THE RESILIENCE AND SUSTAINABILITY OF *SURANGA* IRRIGATION IN THE WESTERN GHATS OF INDIA

Sudhir Chandra Tripathi

Submitted to the University of Hertfordshire

in partial fulfilment of the requirements of the degree of

Doctor of Philosophy

May 2021

Abstract

This study focused on a little known traditional water management system, known as *suranga*, historically used by marginalised agricultural communities in the remote foothills of the Western Ghats in India to evaluate the resilience and sustainability of the *suranga* system. A hill irrigation analytical framework was used to provide a pragmatic epistemology. The research methodology was interdisciplinary, incorporating mixed methods taken from both the physical and social sciences to answer five research questions about *suranga* linked to their history, distribution, design principles, operational characteristics, governance, and organisation. Results suggest that *suranga* originate from the early 20th century. A field survey, supported by in-depth interviews of *suranga* users (n=173), found 700 *suranga* mainly distributed in fourteen villages in the Dakshin Kannada and Kasaragod districts. Data from previous studies, including this study, suggest there are a minimum of ~3000 *suranga* in the region as a whole. *Suranga* were defined as a groundwater collection gallery filtration tunnel system sourced from perched aquifers. Key strengths of the system were found to be the basic design principles, flexible excavation approaches, adaptability, clear use boundaries, relatively low construction and maintenance costs, self-regulated discharge, private ownership and management, and ease of access. Weaknesses of the system were a laborious and risky excavation process, limited water yield, non-collaboration, the absence of governance, and low earnings for *suranga* workers. *Suranga* were also found to be vulnerable to pollution, forest cover loss, and the impacts of climate change. However, *suranga* have contributed to a resilient and sustainable community in the past when the population, water demands, and the size of the irrigated area were low, and farm choices were limited. Currently, the *suranga* system may soon be unable to meet increased water demands because of population increase, intensification and reorientation of agriculture, alternative borewell technology and improved socioeconomic conditions. However, *Suranga* do retain some humanitarian relevance to farmers in the study area having improved the quality of life for many low-income families, but new emerging endogenous and exogenous pressures may make them vulnerable to changes in the future that cause the collapse of the system unless further adaptation occurs.

Acknowledgements

Life is beautiful not because of the things we see or do. Life is beautiful because of the people we meet." — Simon Sinek

I would like to start by expressing my gratitude to my parents and teachers at various stages of my life. They laid the foundations of my journey to knowledge. The roots of my academic aspirations to undertake a PhD were initially fostered by my father, who has always stressed the importance of knowledge in one's life. I must thank my brother Nirmal, who encouraged me to take further studies in the UK, and it has been the cusp of my life.

In the summers of 2008, I accidentally came across a fascinating online article on *suranga* written by Mr Shree Padre of Kasaragod. So I decided to do my MSc dissertation on *suranga*. Thus, Shree became my first point of contact into the world of *suranga*. I am very thankful to Shree Padre because Shree facilitated my first trip and helped me develop contacts in the study area. I am also highly grateful to my host Mr M Govind Bhat and his whole family in Manila village. They supported and accompanied me in the field and arranged field guides and interpreters when needed. I almost became a part of their extended family in South India. I would also like to thank Swami Ji at Manila, Mr Murva Mahabal Bhat, Mr Satya Sankar Bhat, Mr Shri Krishan Bhat, Mr Anantram Bhat, Ms M Uma, Mr Harsha Narayan, Mr Achyut Bhat Pelataje, Mr Vivek, Mr Venkatesh, Mr Uday from the study area for their invaluable suggestions and help during the field survey. I would also like to thank Dr Sudhakar Isaac and Mr Govindan Kutty for visiting me in the study area and providing their professional advice. I would also like to thank the respondents for taking part in the survey and in-depth interviews.

I must also thank colleagues and friends at the University of Hertfordshire. I would like to thank Dr Tim Sands, Dr Ronni Brown, Prof Bruce Fitts, and Dr Richard Southern, Dr Yangu Huang, Dr Arohi Srivastava, Emily, Alexandra, and Genevieve Fernandes. My thanks also go to the team at UH Doctoral college. I also thank the Royal Geographical

Society (with the Institute of British Geographers) for awarding me the Dudley Stamp memorial award for supporting me for a field trip for this PhD. I would like to thank the colleagues at Luton Sixth Form College, where I worked during this PhD. I want to mention specifically Mrs Sandra Robinson and Mr Tony Freeston. Their interest in my PhD has helped me reach the goal of finishing my thesis.

I would like to show my honest gratitude to Dr Darren Crook for his patience, continued encouragement, and guidance in supervising this PhD. Even in my difficult times, Darren has shown enormous confidence in me that has helped me finish this research project. Dr Avice Hall is the next person whose encouragement, supervision and interest kept me motivated to complete my thesis. I would also like to thank Dr James Jenkins for his supervision and honest feedback on my work, which helped improve the quality of my work. At this point, I would like to remember Dr Richard Jones, who was with us when I started this PhD but is not with us anymore. Richard has been a source of motivation for me because of his high intellect and simplicity.

When I embarked on my journey to this research project, my knowledge and experience of people, places, and cultures was limited, but now when I look back, I have met hundreds of people who directly and indirectly helped me during the course of this research across India and the UK. I want to thank all individuals I cannot list here, but their support has helped me achieve my aim.

Finally, this PhD wouldn’t have been viable without the support of my wife Megha, who has been a source of inspiration and unconditional support in my endeavours. Our daughter, Haaril, was born midway through this journey, and she filled my monotonous PhD life with new colours of joy and hope for a brighter future.

Thank you to all of you for playing your parts wonderfully in my research journey.

Sudhir Tripathi
May 2021

Contents

Abstract ii
Acknowledgements iii
Contents v
List of figures ix
List of tables xiv
Glossary xvi

Chapter 1– Background 1
1.1 Water scarcity in India 3
1.1.1 Groundwater shortage in India 9
1.1.2 Past climate change and civilisations 12
1.1.3 Current climate change and its impact on India 14
1. 2 Traditional water management in India 18
1. 3 The *suranga* system and the genesis of this project 28
1.3.1 Rationale for the study 30
1.4 Chapter summary 34

Chapter 2 – Research frameworks, aim and objectives 35
2.1 Hill irrigation analytical framework 35
2.1.1 Definition, debates, designs, and issues 37
2.1.2 A typology of hill irrigation systems 43
2.1.3 Managing irrigation systems in mountainous and hilly regions 48
2.2 Community management of commons 52
2.3 Resilience and sustainability framework 58
2.3.1 A resilience framework for *suranga* 60
2.3.2 A sustainability framework for *suranga* 64
2.4 Aim and objectives 69
2.5 Chapter summary 69

Chapter 3 – Methodology and the study area 70
3.1 Mixed methods methodology 70
3.2 Research design 75
3.3 The study area 79
3.4 Chapter summary 83

Chapter 4 – Origin and development of *suranga* **84**
4.1 Methods: Oral history and archival analysis 84
4.2 Results: The antecedents of *suranga* development 92
4.2.1 A brief history of the study area 95
4.2.2 The age and origin of *suranga* 110
4.3 Chapter summary 119
Chapter 5 – Spatial distribution and design principles **120**
5.1 *Suranga* survey 121
5.1.1 Field measurement methods 123
5.2 Spatial distribution of *suranga* 125
5.3 Physical characteristics of *suranga* 127
5.4 Structural classification 150
5.4.1 Elevated *suranga* 150
5.4.2 *Suranga* in a dug well 153
5.4.3 *Suranga* with vertical airshafts 157
5.4.4 Semi-natural *suranga* 161
5.5. Construction and maintenance costs 164
5.6 Flora and fauna in *suranga* 169
5.7 Chapter summary 172
Chapter 6 – Hydrogeological and hydrological characteristics of *suranga* **173**
6.1 Hydrogeology of the study area 174
6.2 Groundwater assessment 179
6.2.1 Radiocarbon dating results 181
6.3 Reframing the hypothesis of *suranga* hydrology 184
6.4 A new hypothesis for *suranga* geohydrology 186
6.5 Water supply in *suranga* 188
6.5.1 *Suranga* discharge results 191
6.6 Water quality analysis 197
6.6.1 Water quality results 199
6.7 Chapter summary 203
Chapter 7 – Socioeconomics of the community **204**
7.1 Method: Survey research 205
7.1.1 Multiple correspondence analysis (MCA) 211

7.1.2 Agglomerative hierarchical clustering (AHC) 213
7.2 Method: In-depth interviews 214
7.2.1 Thematic analysis 217
7.3 Results: Socioeconomic characteristics of the community 221
7.3.1 Multiple water harvesting strategies 232
7.3.2 Pragmatic irrigation approaches 240
7.3.3 Autonomy, conflict, causes, and resolution 244
7.3.4 Status of suranga development 248
7.4 Chapter summary 252
Chapter 8 – Discussion **253**
8.1 A new origin theory of *suranga* 253
8.2 Appraisal of the analytical framework 262
8.3 Comments on vulnerabilities and resilience 268
8.3.1 Agricultural dynamics in the study area 268
8.3.2 Land reforms 272
8.3.3 Poverty and migration 273
8.3.4 Cash crops and water resources 275
8.3.5 Impact of pollution on *suranga* 279
8.3.6 Rigidity traps 280
8.3.7 Climate change 281
8.3.8 The dynamic history of *suranga* based on Hollings's adaptive cycles 285
8.4 Comments on sustainability 293
8.4.1 *Suranga* and poverty alleviation 293
8.4.2 Structure and function 298
8.4.3 (Geo) hydrology of *suranga* 299
8.4.4 Ecological impact of *suranga* 300
8.4.5 Water rights and *suranga* ownership 301
8.4.6 Intervention or no intervention? 304
8.4.7 Technology transfer 305
8.4.8 Overall quality of life 306
8.5 Limitations of the study 314
8.6 Recommendations for future work 317
Chapter 9 - Conclusion **319**

References 324

Appendices 364

Appendix A: TWM systems in India 365

Appendix B: The documents consulted at various archives 367

Appendix C: The population of South Canara (1871-2011 CE) 372

Appendix D: Risk assessment 373

Appendix E: Suranga survey questionnaire 378

Appendix F: Geohydrology of laterites 380

Appendix G: Socioeconomic survey questionnaire 392

Appendix H: A summary of the socioeconomic survey data 399

Appendix I: Interview transcripts, three examples 405

Appendix J: Qualitative analysis codebook for in-depth interviews 417

Appendix K: MCA of socioeconomic characteristics 425

Appendix L: MCA of agricultural practices 432

Appendix M: MCA of water resources 438

Appendix N: MCA of irrigation practices 445

List of figures

Figure 1.1: Average annual rainfall in India 4
Figure 1.2: Average monthly temperature and rainfall in India from 1901-2016 5
Figure 1.3: Views from inside of an abandoned *qanat* in Bidar, in northern Karnataka in India 22
Figure 1.4: Picture of an underground rectangular, covered tank in the Thar Desert, with access at the centre through steps, and water is lifted manually through a rope and a bucket 25
Figure 1.5: A view of an open, stepped-well accessed through the stone steps, in the ancient Hampi town in Northern Karnataka 26
Figure 1.6: The *suranga* have been mainly found in a small region in southern India 29
Figure 2.1: The analytical framework for this study based on key characteristics of a typical hill irrigation system 36
Figure 2.2: Resource ownership rights with reference to stakeholder's position and their hierarchy 56
Figure 2.3: Dynamics of a system based on Holling's concept of the adaptive cycle and its four phases 62
Figure 2.4: A sustainability wheel used in this study to assess the sustainability of the *suranga* system 66
Figure 3.1: Example of two traditional research approaches and their philosophical backgrounds 71
Figure 3.2: Mixed methods approach of research 72
Figure 3.3: A customised, mixed methods research design used in this study 76
Figure 3.4: A funnelling approach of data collection involving three individual research designs 77
Figure 3.5: The map and the location of the study area villages 82
Figure 4.1: A view of the personal archive of a farmer in the study area 88
Figure 4.2: A land registry record from a personal archive dating back to

1876 CE 89
Figure 4.3: A map of India in 1805 CE 96
Figure 4.4: Francis Buchanan's field survey published in 1807 provides a detailed account of life in Canara 98
Figure 4.5: Distribution of Madras Presidency and location of South Kanara in 1907 CE 99
Figure 4.6: Adjusted population density of South Kanara between 1871-2011 CE 100
Figure 4.7: A copy of the first cadastral map of Manila village in 1905 CE, showing large land pockets 102
Figure 4.8: A cadastral map of Manila village in 1997 CE, showing small land pockets caused by land fragmentation 102
Figure 4.9: A view of paddy fields and plantations situated on flatlands in Puttur town in the study area 105
Figure 4.10: A view of a typical areca nut plantation in a valley in the study area 106
Figure 4.11: A traditional water lifting method known as *kaidambe* from South Kanara 111
Figure 4.12: Paddy and sugarcane fields with a *kaidambe* in the picture in the study area 111
Figure 4.13: A map of a farmstead from the study area from 1896 CE 114
Figure 4.14: The entrance of the *Possadigumpe* cave in Bayar village 118
Figure 5.1: A news article covering this study in a Kannada daily newspaper, *Vijayavani*, on 29 Oct 2012 122
Figure 5.2: A map of the core study area with the number of *suranga* surveyed 126
Figure 5.3: Inside view of a typical *suranga* tunnel, during excavation of a *suranga* 128
Figure 5.4: According to locals, *Melastoma malabathricum* grows in water-rich spots 130
Figure 5.5: A *suranga* worker during the excavation of a *suranga* 131
Figure 5.6: Tools used for *suranga* excavation 133
Figure 5.7: Pickaxes of different sizes used for digging inside a *suranga* 133
Figure 5.8: Excavation inside a *suranga* and removal of debris 134
Figure 5.9: A farmer constructing a wooden sledge to be used for *suranga* construction 135
Figure 5.10: The excavated soil from a *suranga* being removed

on a wooden sledge 135
Figure 5.11: Internal structures of three different observed *suranga* 137
Figure 5.12: Design of a complex *suranga* with several water sources 138
Figure 5.13: A worker using a mirror to cast light inside a *suranga* 139
Figure 5.14: A traditional wooden pipe (*dumbe*) made of an areca nut tree 141
Figure 5.15: Water from a *suranga* being transported with a pipe 142
Figure 5.16: A drinking water *suranga* covered with a net for safety 143
Figure 5.17: A drinking water *suranga* covered with a metal gate 143
Figure 5.18: Earthen pond to collect *suranga* water 144
Figure 5.19: Earthen pond to collect *suranga* water through a pipe 145
Figure 5.20: A pond situated at the highest elevation within a farmstead 145
Figure 5.21: Schematic diagram of a farmstead with *suranga* systems 146
Figure 5.22: An overhead water tank under construction on a hilltop 146
Figure 5.23: Water recharge pits on a hillslope 147
Figure 5.24: Types of *suranga* according to water availability 148
Figure 5.25: A dry *suranga* being used for storage 149
Figure 5.26: Entrances of two separate elevated *suranga* 151
Figure 5.27: Schematic diagram of an elevated *suranga*, not to scale 151
Figure 5.28: Drinking water supply with a pipe from an elevated *suranga* 152
Figure 5.29: A typical drinking water supply system 152
Figure 5.30: An elevated *suranga* in the backyard of a house 153
Figure 5.31: A *suranga* inside a circular well 154
Figure 5.32: Schematic diagram of a *suranga* in well 155
Figure 5.33: A *suranga* inside a stepped dug well 155
Figure 5.34: Two submerged *suranga* inside a stepped well 156
Figure 5.35: A schematic diagram of an aerial view of a dug well
with five *suranga* in Manila village 157
Figure 5.36: Schematic diagram of a *suranga* with airshafts 158
Figure 5.37: An outside view of an airshaft, which opens into a working *suranga* 159
Figure 5.38: Looking down an airshaft in a dry *suranga* 159
Figure 5.39: Looking down an airshaft with a submerged *suranga* 160
Figure 5.40: View from inside a *suranga* through an airshaft 160
Figure 5.41: Schematic diagram of a semi-natural *suranga* with syphon system 161
Figure 5.42: A farmer preparing to enter a semi-natural suranga with a
bamboo stem used as a ladder 162

Figure 5.43: Inside view of a natural cavity caused by soil piping 163
Figure 5.44: Roots emerging from the ceiling of a *suranga* 167
Figure 5.45: A worker coming out from a *suranga* after completing maintenance 168
Figure 5.46: Two structurally unsafe *suranga* 169
Figure 5.47: Two typical suranga covered with dense vegetation during monsoon 170
Figure 5.48: A *Hipposideros* bat from a *suranga* 171
Figure 6.1: Top two layers in a laterite profile in Manila village 175
Figure 6.2: The exposed ferricrete patches on the *Possadigumpe* hill in the study area 176
Figure 6.3: A *suranga* with exposed, black, permeable, hard ferricrete layer 176
Figure 6.4: Laterite block cut from the mottled clay zone 177
Figure 6.5: Variation in hydraulic conductivity in a laterite lithological profile 178
Figure 6.6: Sample sites for radiocarbon dating of various subsurface waters 180
Figure 6.7: Adjusted residence time of various water samples collected from multiple elevations 182
Figure 6.8: A schematic diagram of *suranga* hydrology 184
Figure 6.9: Water availability in a theoretical laterite profile 187
Figure 6.10: Schematic map of a hillslope farmstead used for water discharge measurements from *suranga* 189
Figure 6.11: A view of the hillslope farmstead used for water discharge Measurements 189
Figure 6.12: Average annual rainfall and water discharge from five different *suranga* between January 2014-January 2015 193
Figure 6.13: Water-efficient drips and foggers are used by farmers in the study area to improve water efficiency 196
Figure 6.14: pH value variation of all the water samples 202
Figure 7.1: Sub-categories in the survey database 212
Figure 7.2: A frequency word cloud produced from the interview transcripts 218
Figure 7.3: A screenshot of the codes used for the analysis of the in-depth interview 219
Figure 7.4: A view of Manila village in the study area from the hilltop 221
Figure 7.5: The main themes that emerged from the qualitative analysis of interviews, and their relationships to each other 222
Figure 7.6: Correspondence plot of socioeconomic variables 224
Figure 7.7: Correspondence plot based on the economic status

of the respondents 225
Figure 7.8: Primary occupation of the respondents in the study area 227
Figure 7.9: Land distribution between APL and BPL families in the study area 229
Figure 7.10: Correspondence plot of agriculture characteristics in the study area 231
Figure 7.11: An elevated *suranga* excavated into a hill slope in the backyard of a house 232
Figure 7.12: Another *elevated* suranga excavated in the backyard of a house 233
Figure 7.13: A typical dug well in the study area 234
Figure 7.14: Water resources used in the case study area, in addition to *suranga* 235
Figure 7.15: Makeshift dug wells on a seasonal riverbed 236
Figure 7.16: A temporary check dam made of soil and rocks on a seasonal stream 237
Figure 7.17: A temporary check dam on a seasonal river made by sandbags 237
Figure 7.18: Correspondence plot of water resources in the study area 239
Figure 7.19: A typical paddy field in a valley with coconut trees on the boundary 241
Figure 7.20: Correspondence plot of irrigation characteristics in the study area 243
Figure 7.21: A borewell being constructed in Manila village in 2013 CE 245
Figure 7.22: A typically completed borewell in the study area 245
Figure 7.23: A neglected shared water tank in need of maintenance 247
Figure 7.24: An abandoned small length *suranga* with hard rock dead-end 251
Figure 8.1: An improved hill irrigation model based on the *suranga* system 262
Figure 8.2: A new model of hill irrigation framework based on this study 267
Figure 8.3: The process of development of an agrarian community in the study area 269
Figure 8.4: The development dynamics of the agrarian community in the study area with the key events 271
Figure 8.5: A multi-adaptive cycle concept to explain the dynamic of the *suranga* system 287
Figure 8.6: Water resources with water discharge, management level, command area, water rights, and impact on the environment 290
Figure 8.7: Sustainability wheel for the *suranga* system until the end of the 20th century 311
Figure 8.8: Sustainability wheel for the *suranga* system until the mid-21st century 312

List of tables

Table 1.1: Typology of TWM systems in India 23
Table 1.2: Geography of some popular Indian TWM systems 23
Table 2.1: A classification of natural landscapes based on elevation and relief roughness 38
Table 2.2: A list of common crops from mountain regions compared to the crops in the study area 40
Table 2.3: Cultural adaptation examples from the mountain regions 42
Table 2.4: Challenges faced by communities living in mountain and hilly regions 44
Table 2.5: Common types of irrigation methods found in mountain and hilly regions 46
Table 2.6: Conceptual models of irrigation management in the mountains and hills 50
Table 2.7: The sustainability framework for the *suranga* system 67
Table 3.1: Research questions and proposed methods of research 74
Table 3.2: Field trips and associated objectives 78
Table 4.1: Archives visited in India and the UK 86
Table 4.2: The list of documents consulted at various archives 93
Table 4.3: Average annual crop distribution 1924-1928 CE in the Madras Presidency 104
Table 4.4: Government land proportions in 1938 CE in South Canara 108
Table 4.5: Periods of *suranga* construction in the case study area 115
Table 5.1: Structural properties of a *suranga* 124
Table 5.2: Summary of *suranga* surveyed in the study area 125
Table 5.3: Relative costs of construction and usage of water resources in the study area 165
Table 5.4: Flora and fauna commonly found inside *suranga* in the study area 168
Table 6.1: Location of water samples for radiocarbon dating 180
Table 6.2: Radiocarbon dating results of various subsurface water samples 181
Table 6.3: *Suranga* water discharge in cubic metre per day between Jan 2014-Jan 2015 191

Table 6.4: Rainfall data in DK district between Jan 2014-Jan 2015 191
Table 6.5: The water storage ponds and tanks in the study area 194
Table 6.6: Water samples for the water quality analysis 198
Table 6.7: Drinking water permissible limits in India 199
Table 6.8: Water quality analysis of water samples from various sources in three different seasons 201
Table 7.1: A summary of the various questions in the survey questionnaire 206
Table 7.2: Landholdings and the percentage of respondents 228
Table 7.3: Summary of the economic status of families, landholding, and cultivated area 230
Table 7.4: Usual climate pattern of Manila village 241
Table 7.5: Future water plans of the survey respondents 249
Table 8.1: Key differences between *qanat* and *suranga* systems 260
Table 8.2: The past and potential pressures and disturbances on the *suranga* system 284
Table 8.3: Various phases and key events in explaining the dynamics of *suranga* 288
Table 8.4: A summary of strengths and weaknesses of the *suranga* system 308

Abbreviations

α	Reorganisation (see Holling & Gunderson, 2002)
Ω	Release/collapse (see Holling & Gunderson, 2002)
^{14}C	Carbon-14, a radioactive isotope of carbon
AHC	Agglomerative Hierarchical Clustering
AMS	Accelerator mass spectrometry
APL	Above poverty line
bavi	An open well or a dug well
BCE	Before the Common Era
BPL	Below poverty line
cal BP	Calibrated/Calendar years before the present
CAMPCO	Central Arecanut and Cocoa Marketing and Processing Cooperative Limited
CBNR	Community-based natural resource management
CE	Common Era
CGWB	Central Ground Water Board
CFCs	Chlorofluorocarbons
CMIP-3	Third Coupled Model Intercomparison Project
CPRs	Common-Pool Resources
CSE	Centre for Science and Environment, New Delhi, India
CWRDM	Centre for Water Resources Development and Management
DK	Dakshin Kannada (a district in south India)
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GHGs	Greenhouse gases
GIS	Geographic Information System
GPS	Global Positioning System
GOI	Government of India
GWh	Gigawatt-hours (to measure electric energy)
IMR	Indian monsoon rainfall
IPCC	Intergovernmental Panel on Climate Change

ISM	Indian summer monsoon
KACMS	Kasaragod Agriculture Cooperative Marketing society
KVK	*Krishi Vigyan Kendra*
LULC	Land use and land cover change
MCA	Multiple Correspondence Analysis
MMR	Mixed Methods Research
MNREGA	Mahatma Gandhi National Rural Employment Guarantee Act
MPN/100ml	Most Probable Number per 100 ml
NABL	National Accreditation Board for Testing and Calibration Laboratories
NTU	Nephelometric turbidity unit
OCPs	Organochlorine pesticides
PVC	Polyvinyl chloride
RR	Relief roughness, maximum minus minimum elevation per cell divided by half the cell length in meters/kilometre, or ‰ (from Meybeck *et al.*, 2001)
SC	Scheduled Cast
SD	Sustainable development
SKACMS	South Canara Agriculture Cooperative Marketing Society
SST	Sea Surface Temperature
ST	Scheduled Tribes
TWM	Traditional water management
WCRP	World Climate Research Programme
WHO	World Health Organization
WWC	World Water Council

Chapter 1 – Background

Thousands have lived without love, not one without water.

W H Auden[1]

The world population has increased by approximately 400% over the last two millennia (Roser *et al.*, 2019), and it has surged exponentially since the end of the 17th century (Hara, 2020, pp. 11-30). The most significant growth in world population in human history was recorded in the second half of the 20th century when it surged from 2.5 to 6.1 billion inhabitants between 1950-2000 CE (Rockström *et al.*, 2014, p. 47). Some of the crucial impacts of population growth and associated development are land conversion, agricultural intensification, and overexploitation of water resources (Rockström *et al.*, 2014, p. 55). Freshwater demand from an ever growing global population is continually increasing because of agriculture development and intensification to achieve food security and to increase industrial production (Rockström *et al.*, 2014, p. 47; Leridon, 2020; Molotoks *et al.*, 2020; Bahar *et al.*, 2021). A significant amount of world water is used in growing grains, vegetables, fruits, dairy products, and meat (Pimentel & Pimentel, 2003; Hoekstra, 2012; Chriki & Hocquette, 2020). Economic development and improved living conditions have further pushed up the consumption of these products (Rockström *et al.*, 2014, pp. 47-49), and as a result, global water consumption is almost doubling every 20 years at a rate far faster than human population growth (Bhattacharya, 2015). Thus, approximately 80% of the global population is on the verge of facing water stress (Lasage & Verburg, 2015; WaterAid, 2017, p. 5), which means a situation when water

[1] W H Auden (1907-1973 CE) in 'First Things First' (1957).

demand exceeds the freshwater availability (Reynard *et al.*, 2014). The number of water stressed countries worldwide is expected to increase from seven in 1955 to approximately 35 by 2025 (Misra, 2014), and approximately 4 billion people are likely to face moderate or severe water stress by 2025, and most of the affected population is likely to be in arid and semi-arid regions in Africa, South America, and Asia (Steffen *et al.*, 2004; p. 25; Wisser *et al.*, 2010). Overall, there may be enough freshwater available to meet the current water demands of the world, but the temporal and uneven spatial (geographical) variation of water resources availability and demand causes acute and chronic water scarcity worldwide (Mekonnen & Hoekstra, 2016). In addition, current freshwater supplies are also stretched and stressed by anthropogenic activities such as urbanisation, deforestation, land use change, intensive farming, soil degradation, pollution of the natural environment, over-abstraction of water resources, and surface water diversion (IPCC, 2007; Wisser *et al.*, 2010; Bunclark *et al.*, 2011, p. 82; Reynard *et al.*, 2014; Rockström *et al.*, 2014, p. 47; Coyte *et al.*, 2019; García *et al.*, 2020; Molotoks *et al.*, 2020; Ghorbani *et al.*, 2021).

Environmental changes caused by climate change has started to show sign of altered water cycles, causing natural disasters such as droughts and floods, resulting in reduced food supplies, health issues, economic and social disturbances around the world (Rockström *et al.*, 2014, p. 69; Masroor *et al.*, 2020). Altered water cycles are highly likely to further decrease freshwater availability and affect the life of 663 million people around the world with no access to clean water. More than 40% of the global population is likely to face severe water stress by 2050 (Misra, 2014; WaterAid, 2017, p. 3), with the highest impact being seen in developing countries (Shanmugasundaram *et al.*, 2017) with high population density and large areas of irrigated agriculture, such as found in India (Saleth, 2011), eastern China, and the Nile delta; and arid regions with already deficient freshwater availability such as the Sahara and deserts of Australia (Mekonnen & Hoekstra, 2016). Global water scarcity has also been attributed to poor water resources management, social inequalities and poverty, amongst existing climate variability (WaterAid, 2017, p. 4). For example, the Arabian Desert has the highest water scarcity level because of low freshwater availability, high population density, and irrigated agriculture (Mekonnen & Hoekstra, 2016).

Water scarcity can have a high impact on livelihoods in urban and rural areas in these water stressed regions (FAO & WWC, 2015) because water is essential for economic development, food security, and alleviating poverty (WHO, 2009; Bhattacharya, 2015). For example, agricultural prosperity also depends on freshwater availability for irrigation. Therefore, the economic value of water is usually high, and water becomes a prized commodity in the agricultural regions situated in arid and semi-arid zones such as in India, an agricultural country with seasonal water availability and high population density (Berking, 2018, p.12). India constitutes approximately 17.7% of the world population (Government of India, 2012; India Population, 2021) and is likely to be the world's most populous country by 2027. Therefore, the management of increasingly scarce water resources in India is crucial, as the next section will illustrate.

1.1 Water scarcity in India

India is a developing country and ranks 133rd in the development ranking index based on human development, life-course gender gap, women's empowerment, environmental sustainability, and socioeconomic sustainability by the United Nations Development Programme [UNDP] (UNDP, 2020, pp. 333-394). By area, India is the seventh-largest country in the world, lying within a large peninsula bounded by the Bay of Bengal to the east and the Arabian Sea to the west (Pletcher, 2011). It is commonly accepted that the Indian peninsula was formed because of a collision between a part of the Gondwanaland, and the Eurasian plate in the Early Cenozoic period, which resulted in the formation of the Himalayas (Le Fort, 1975; Kale, 2014). The Himalayas orogeny, followed by the onset of the monsoon climate, has mostly moulded the geography and the climate of the Indian subcontinent (Kale, 2014). India is a classic example of monsoon climate, creating distinct dry and wet seasons, and extreme climates, because of diverse geography, including mountains, rivers, extended plateaus, sweeping plains, deserts, and a long coastline (Jain *et al.*, 2007; Chakraborty & Shukla, 2020). The Asian monsoon is the main source of annual rainfall in the Indian subcontinent, and it is significant because it affects a large region that inhabits approximately one-fourth of the world population (Gadgil, 2007; Attri & Tyagi, 2010; Chakraborty & Shukla, 2020; Mahendra *et al.*, 2021). The seasonal monsoonal rainfall and glacier fed rivers constitute the primary source of fresh water in the Indian subcontinent, but there is a high geographical variation in precipitation across India (see Figure 1.1).

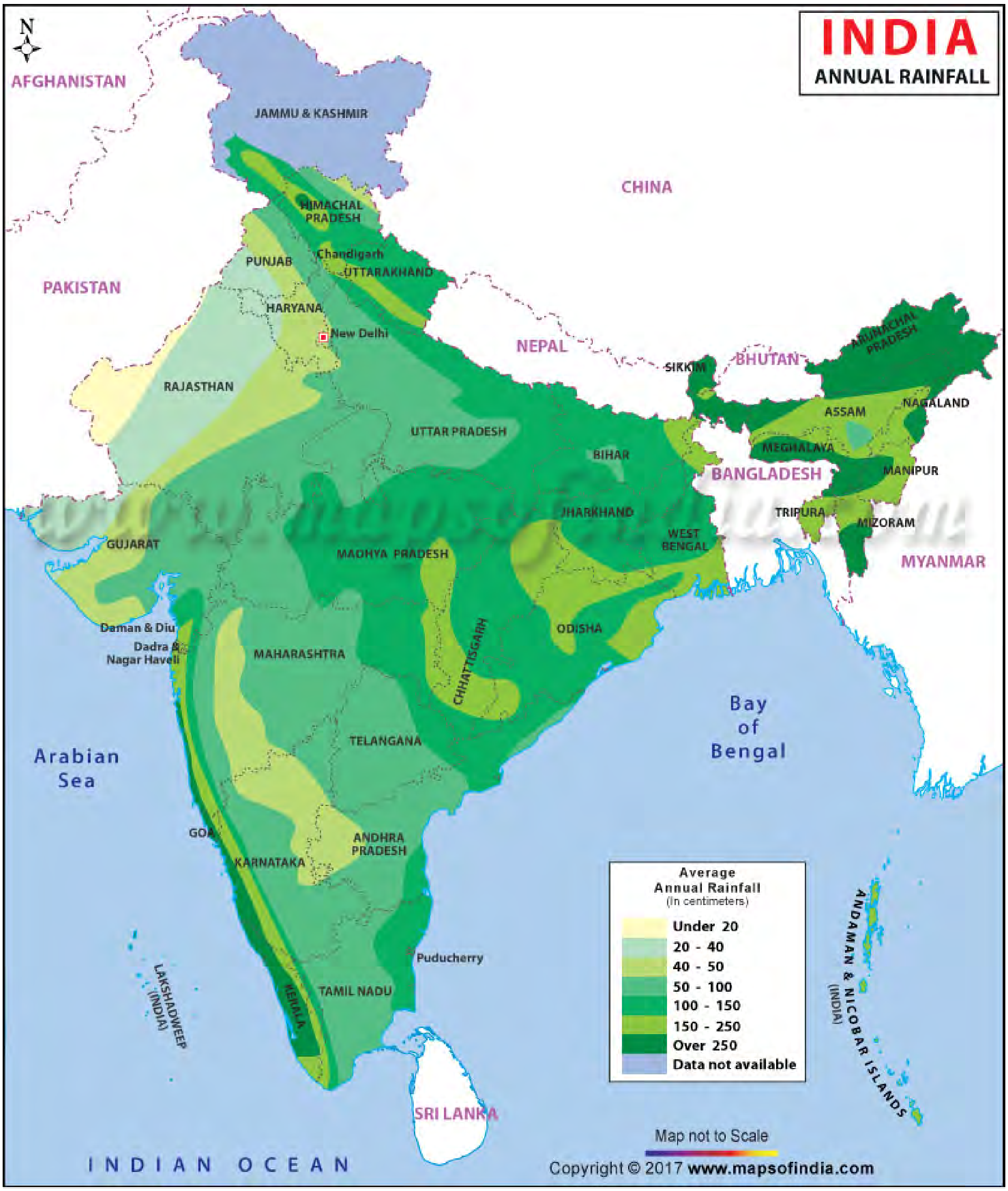


Figure 1.1: Average annual rainfall in India

(Source: Annual Rainfall Map of India, 2021).

The driest area in India is Jaisalmer, with an average annual rainfall of 13 cm, and the wettest area in India is Cherrapunji, with an average annual rainfall of 1141 cm (Attri & Tyagi, 2010, p. 1). More importantly, the interannual variation in monsoon causes distinct wet and dry seasons, as seen in Figure 1.2 the major wet season lasts from late May to early November, and mostly dry season prevails from mid-November to late May.

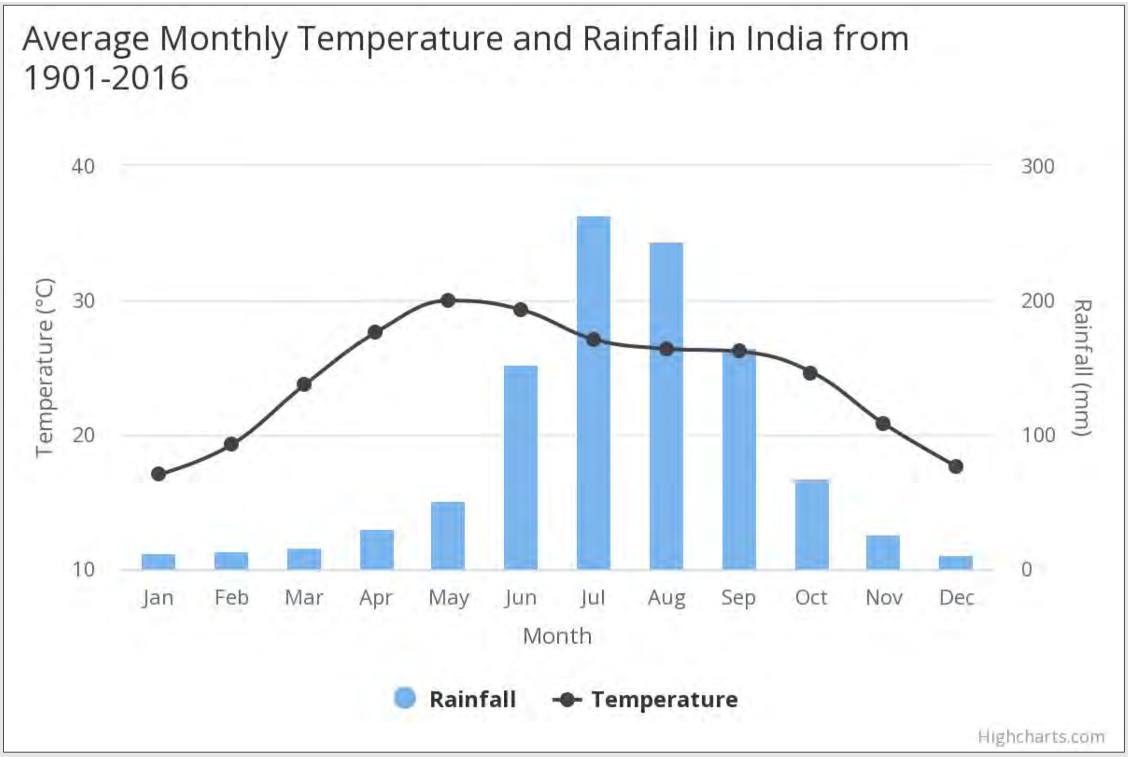


Figure 1.2: Average monthly temperature and rainfall in India from 1901-2016
(Source: World Bank, 2020).

This interannual variation in rainfall causes extreme climatic conditions in India every year (Mahendra *et al.*, 2021). Most states face water stress between January-April until the onset of monsoon in late May (Chakraborty & Shukla, 2020) when seasonal precipitation causes widespread runoff and floods around India between June-September (Joseph *et al.*, 2020). The northeast regions of India receive a large amount of seasonal rainfall, and are flooded during the rainy season but face acute water scarcity during the summer months, while areas such as the Thar Desert are dry the whole year (Agarwal & Narain, 1997; Attri & Tyagi, 2010; Chakraborty & Shukla, 2020). Moreover, especially in the Indian subcontinent, the importance of monsoonal rain to these regions can be highlighted by the increased surface water vulnerability and scarcity in river basins caused by any decrease in annual precipitation (Varis *et al.*, 2012; Rakhecha, 2016; Chakraborty & Shukla, 2020).

Historically the Indian agricultural economy has been dependent on monsoonal rain (Chakraborty & Shukla, 2020; Karnawat *et al.*, 2020), and any long term monsoon failures in the recent past have caused widespread droughts and famines in India (Whyte, 2013, p. 338; Surendran *et al.*, 2015; Karnawat *et al.*, 2020; Mahendra *et al.*, 2021**)**. The everyday life, agrarian pattern, culture, and festivals of the Indian society were historically shaped over millennia by the seasonal variability of monsoonal precipitation or the monsoon cycle (Gadgil, 2006; Chakraborty & Shukla, 2020; Singh, Dey *et al.*, 2020). There prevails a dry season in India between January to May, and temperature surges post-March until the onset of monsoon; therefore, the arrival of the monsoonal rain in June is a highly significant event for agricultural communities in India (Gunn, 2010, p. 2; Chakraborty & Shukla, 2020). Therefore, the monsoon season in India is also commonly known as the wet season and the rest of the year as the dry season. Rice, which is the chief crop and the staple diet of Asia, is mainly a rain fed crop therefore it directly depends on monsoon rain (Barker *et al.*, 1985, pp. 22-23; Gunn, 2010; p. 4). High dependence on monsoonal rain for rain-fed agriculture occurs because a slight variation in annual monsoon rain has a high impact on overall crop production (Gadgil, 2003; Singh, Gupta *et al.*, 2020) and impacts on the Gross Domestic Product (GDP) of India (Karnawat *et al.*, 2020; Mahendra *et al.*, 2021; Vijay *et al.*, 2021). In summary, the Asian monsoon is the primary source of precipitation, but uneven geographical distribution and seasonality in precipitation are among the leading causes of water scarcity in the Indian subcontinent.

India has approximately 17.7% of the world population, but only 4% of the world's freshwater useable resources (Government of India, 2012; Kumar, 2019; Joseph *et al.*, 2020; India Population, 2021). According to Mekonnen & Hoekstra (2016, p. 3), 66% of the world population (4.0 billion people) faces severe water scarcity at least for a month every year, and approximately one billion of this population live in India, followed by 0.9 billion people in China. Moreover, a monthly spatial analysis suggests that countries in the Indian subcontinent face moderate to severe physical water scarcity from February to

June (Mekonnen & Hoekstra, 2016, p.1). Riparian water issues over large hydroelectric projects, transboundary water governance and allocation of surface waters from various rivers originating in India have caused international and interstate transboundary issues with neighbouring countries such as Pakistan, Bangladesh, and China (Kolvankar, 2019; Kumar, 2019; Mukherji *et al.*, 2019) and internal water conflicts between states in India (Acharya *et al.*, 2019; Kolvankar, 2019). It shows the level of freshwater stress in India and the uneven geographical distribution of surface water resources in India (GOI, 2018; Kumar, 2019; Bogra & Bakshi, 2020; Katyaini *et al.*, 2020).

Water scarcity is a relative term as freshwater scarcity is the difference between freshwater availability and freshwater demand (Saleth, 2011). According to the government of India, approximately 93% of the urban population has access to clean water (GOI, 2018, pp. 123-124), but the rising population density and more intensive water use have increased the gap between water supply and demand (Misra, 2014; Rakhecha, 2016; Kumar, 2019; Bogra & Bakshi, 2020; Katyaini *et al.*, 2020). To illustrate this point, freshwater supply in India in 2008 was 650 billion cubic metres (bcm), with freshwater supply predicted to be 744 bcm by 2030, but the water demand is expected to be 1498 bcm by 2030, nearly double the available freshwater supply (GOI, 2018, p. 28; Joseph *et al.*, 2020). As a result, the planning department of the government of India suggested that 40% of the Indian population may face extreme potable water scarcity by 2030 (GOI, 2018, pp. 123-124), and this water supply and demand gap may detrimentally impact India’s large population and economy (Bhattacharya, 2015; Rakhecha, 2016; Chakraborty & Shukla, 2020).

According to the Government of India, approximately 600 million people are already suffering from high to extreme water scarcity (GOI, 2018, pp. 27-30). Usually, 40 litres of water per person per day availability is taken as a standard in India (Salve, 2017) compared to a minimum of 50-100 litres of water suggested by WHO for basic needs (Gleick, 1996; United Nations, 2021). The actual water demand for domestic water is so significant that water is rationed in most Indian cities and towns and provided at set regular intervals by the government using pipe supplies (Kumar, 2019, p. 18). In some highly water deprived, remote regions, water is also provided by road and rail networks, while well off families often source their regular water directly from private suppliers through water tankers (Kumar, 2019, p. 18; Chatterjee & Kundu, 2020). The level of overall water scarcity in India is so grave that the supreme court of India has recognised water as a right for life, and the national water policy of the federal government designate water as an economic good that must be used efficiently (GOI, 2018, p. 28).

Water scarcity can affect the quality of life of individuals and communities. Quality of life is a broad concept, and it covers a range of factors that can impact an individual life, including the physical and psychological state of an individual; their social wellbeing; the level of physical, economic, and social independence; and the surrounding environment (Cai *et al.*, 2021). For example, a chronic scarcity of drinking water may cause health issues related to metabolism, various membranes, temperature regulation, kidney and circulatory function in the human body (Armstrong & Johnson, 2018). Thus, the communities may have to rely on low-quality water, available from any natural water source such as rivers, streams and lakes, and sometimes contaminated piped government water supplies[2], causing serious health issues such as hepatitis and cholera (Kumar, 2019), significantly when a high number of rivers in India are highly polluted from industrial wastes and sewage (Kumar, 2019; Panigrahi & Pattnaik, 2019; Sarkar *et al.*, 2020; Shaji *et al.*, 2021). Furthermore, drinking water shortages and related water borne issues can negatively impact the education of children and the empowerment of women, especially in developing and underdeveloped regions. In low income families living in a rural area, women, girls, and children are usually responsible for fetching drinking water from rivers, streams, and wells situated far from the family home (WaterAid, 2017, p. 7; Yadav & Lal, 2018; Kumar, 2019). Besides this, water scarcity for agriculture can lower soil moisture, change temporal crop patterns leading to non-cultivation and affecting crop production, which in turn may lead to food scarcity and hunger amongst vulnerable communities and an increased dependency on the government for rationed food (Singh *et al.*, 2018, p. 2423). In addition, water scarcity can also cause livelihood issues, economic disturbances, and mass migrations, leading to social unrest and increased poverty (Saleth, 2011; Graham *et al.*, 2020). Water scarcity can also lead to over-abstraction from existing

[2] Tap water in India is usually potable, but often leakage in sewerage can contaminate government water supplies.

water resources, which can further reduce water availabilities and flow in surface water resources, and deplete groundwater levels, especially during dry periods, leading to long term irreversible impacts on natural ecosystems (Mekonnen & Hoekstra, 2016). Thus, water scarcity in many ways can affect the quality of life for families and communities and their economic prosperity.

1.1.1 Groundwater shortage in India

When the well is dry, we know the worth of water.

Benjamin Franklin[3]

India is one of the largest groundwater extractors, and the Indian population is highly dependent on groundwater for irrigation and water supplies in rural and urban areas (Sowthanya & Shanmugam, 2019; Patel *et al.*, 2020; Shaji *et al.*, 2021). Over 75 billion m^3/year groundwater is abstracted in India, constituting around 30% of global groundwater abstraction (Coyte *et al.*, 2019, p. 1217). Groundwater resources account for 40% of India's water resources (GOI, 2018, p. 27), and in the arid state of Rajasthan, 90% of its drinking water and 70% of its irrigation water supplies are received from groundwater (Coyte *et al.*, 2019, p. 1217). In India, groundwater for irrigation is abstracted through traditional systems such as dug wells and privately owned borewells, and by high capacity deeper borewells (often known as tube wells) for drinking and household water supplies to towns and cities by the local governments (Kumar, 2019; Shrestha & Dahal, 2019; Patel *et al.*, 2020).

The recent development of Indian agriculture is often attributed to Indian economic development after independence in 1947 CE when agriculture shifted from rainfed and traditional water management (TWM) based irrigation to hydropower projects,

[3] Benjamin Franklin (1706-1790 CE) in 'Poor Richard's Almanac' (1746).

reservoirs, and groundwater abstraction through borewells to increase water availability (Naz & Subramanian, 2010; Bharucha *et al.*, 2014; Kumar, 2019). The onset of the Green Revolution[4] in the 1960s in India, supported by technological advancements in agriculture and water abstraction (Naz & Subramanian, 2010; Balasubramanya & Stifel, 2020), boosted crop production from 50 billion kilograms to 203 billion kilograms between 1950-1999 (Joseph *et al.*, 2020, pp. 1-2). At the same time, groundwater abstraction surged from 87 km^3 to 190 km^3 between 1960 to 2000 in India because of this rapid agricultural growth (Joseph *et al.*, 2020, pp. 1-2). Nevertheless, the total irrigated area in India is still relatively small in comparison to other Asian countries, and monsoonal rain is still the primary irrigation source in India (Gunn, 2010; Surendran *et al.*, 2015), with over half of the agriculture in India rainfed (GOI, 2018, p. 27). In India's Rajasthan state, surface water flows have been affected by overexploitation, pollution, and limited storage capacity, thus people with access to groundwater turn more to bore well systems because water storage structures are not required, but water can be directly pumped to the place of need (Coyte *et al.*, 2019, p. 1217). According to Bassi (2017), the irrigated area from wells in India increased by 185% between 1980 (17.7 million ha) and 2008 (50.4 million ha), and this surge in interest can be attributed to the popularity of electric and diesel pumps (Bassi, 2017; Bahinipati & Viswanathan, 2019), which were underpinned by highly subsidised (or free) electricity and fuels for agriculture by local government authorities. As a result, electricity consumption for agriculture also increased from 4470 GWh to 160,000 GWh between 1970 and 2014 (Bassi, 2017).

Easy year round access facilitated by pumping, non-regulation, and subsidised electricity in rural areas further accelerated the over-abstraction of groundwater, causing considerable damage to groundwater levels in India (Saleth, 2011; Kumar, 2019, p. 7; Patel *et al.*, 2020; Vij *et al.*, 2021). In addition, the subsidised electricity approach has

[4] The Green revolution in India was an agricultural revolution to increase agriculture production in the 1960s, based on the use of the latest agriculture technologies mainly imported from the USA, involving hybrid seeds, chemical fertilizers, increased irrigation by use of groundwater, and use of chemical pesticides (Naz & Subramanian, 2010; Fisher, 2018; Balasubramanya & Stifel, 2020).

increased the overall carbon footprints of energy production, and the subsidies have caused revenue loss for government owned energy organisations in India (Bassi, 2017, pp. 134-135).

Densely populated urban areas face severe groundwater scarcity in India because of increased water demands caused by technological development, improved lifestyles, and a high reliance on groundwater resources for drinking and household water supplies (Bhattacharya, 2015; Joseph *et al.*, 2020). For example, the city of Bengaluru in 1885 was full of interlinked lakes (~1452) to store precipitation and runoff (Ramachandra, 2017). In addition, there were approximately 1960 wells in parts of Bengaluru that used to harvest groundwater from shallow aquifers primarily for drinking water (Yadav & Lal, 2018). However, over time, with an exponential increase in population, a reduction in the agricultural area, and urbanisation that led to encroachments onto lake catchment areas and sewage and untreated waste entering the lakes, these water bodies gradually disappeared or became highly polluted (Ramachandra, 2017; Yadav & Lal, 2018). Forest cover decreased by 89% as the built area increased and the number of lakes was reduced to ~193 (Ramachandra, 2017). As the popularity of borewell increased, the number of traditional, shallow depth wells also reduced to 49 in 2014 (Yadav & Lal, 2018). Currently, Bengaluru relies heavily on the Kaveri River and groundwater abstraction for its water requirements, with depleted and polluted groundwater (see Unnikrishnan *et al.*, 2017). Similarly, other highly populated settlements such as New Delhi, Chennai, Hyderabad, and 17 other Indian cities are close to exhausting their groundwater resources soon (GOI, 2018, p. 123-124). The groundwater water levels have decreased significantly in India's northern and northwest regions because of the over-abstraction of groundwater resources to meet increased water demands (Coyte *et al.*, 2019; Kumar, 2019; Joseph *et al.*, 2020, p. 18). As a result, approximately one-sixth of India's groundwater resources are overexploited because of unregulated over-abstraction (WaterAid, 2017, pp. 14-15).

Groundwater quality is also found to be affected by anthropogenic activities such as over-abstraction abstraction of aquifers (Shukla & Saxena, 2020), leaching of subsurface contaminants, infiltration of wastewaters, improper waste management, irrigation return flow, and excessive use of pesticides, herbicides, chemical fertilisers; and geogenic factors such as aquifer characteristics, mineral weathering, residence time; and carbonate dissolution, reverse ion exchange and evaporation (Mukherjee & Singh, 2018; Kurwadkar, 2019; Singh *et al.*, 2019; Subba Rao *et al.*, 2019; Kurwadkar *et al.*, 2020; Lone *et al.*, 2020; Karunanidhi *et al.*, 2021a; Shaji *et al.*, 2021). Groundwater quality issues caused by nitrate (NO_3^-) and fluoride (F^-) contamination have been reported in Punjab (Singh *et al.*, 2019), Tamil Nadu (Aravinthasamy *et al.*, 2019; Karunanidhi *et al.*, 2021a; Karunanidhi *et al.*, 2021b), Telangana (Subba Rao *et al.*, 2019), and Maharashtra (Nawale *et al.*, 2021). Fluoride contamination of groundwater is a significant groundwater quality issue in India, affecting ~66 million people, mainly in Rajasthan, Andhra Pradesh, Gujarat, and West Bengal (Mukherjee & Singh, 2018).

Thus, water scarcity in India is likely to become worse in the coming years with increasing water demands (Saleth, 2011), excessive dependency on groundwater, unregulated abstraction and mismanagement, slow replenishment, and depleted resources (Bhattacharya, 2015; Mekonnen & Hoekstra, 2016; GOI, 2018, p. 27, Kumar, 2019, p. 7). Therefore, government policies have a pressing need to regulate groundwater abstraction in India's already stressed and overexploited states (Bassi, 2017, pp. 134-135). Thus, in response, India's government has attempted to regulate groundwater extraction through introducing policies such as the Groundwater (Sustainable Management) Bill 2017 (Cullet, 2018) to increase state control over groundwater (GOI, 2018, p. 28). Still, demand management policies are required to improve the efficiency of groundwater management (Saleth, 2011), not least because of the lessons learnt from the impacts of past global climate change on ancient civilisations as discussed in the following section.

1.1.2 Past climate change and civilisations

Historically, climate change phases ranging from interannual to decadal and up to multi-century have drastically affected the resilience and longevity of ancient civilisations by changing the temporal and geographical patterns of monsoon precipitation and causing prolonged droughts and severe floods (deMenocal, 2001; Peiser, 2003; Drysdale *et al.*, 2006; Fagan, 2010; Middleton, 2012). For example, the Holocene climate change around

4.2 kiloyears BP[5] is linked to prolonged monsoon failure of Centennial and Millennium range in the Indus valley that reduced the water flow in the Indus (Dixit *et al.*, 2014a). The Indus river was the only freshwater source for the Indus civilisation, resulting in multi-centennial droughts and collapse of the highly advanced, ancient cities and agrarian communities of the Indus civilisation (Staubwasser *et al.*, 2003; Giosan *et al.*, 2012; Dixit *et al.*, 2014b; Fisher, 2018, p. 40). Similarly, the ancient rain fed irrigation based communities of northern Mesopotamia also collapsed when crop production diminished because of fluctuation in rainfall and resulted in prolonged droughts induced by the Holocene climate change (Weiss *et al.*, 1993; Wilkinson, 1997; Middleton, 2012). Furthermore, the ancient but highly advanced civilisation of Egypt, known as the gift of Nile, is also believed to have collapsed between 2200-1900 BCE in part because of the low flow in the River Nile and dry periods resulting from long term variability in the monsoon patterns leading to famine and conflict (Hassan, 1997; Peiser, 2003; Middleton, 2012; Welc & Marks, 2014). More recently, the end of Tang, Yuan, and Ming dynasties in China are also attributed to several decade long monsoon failures (Whyte, 2013, p. 338). Similarly, altered monsoon patterns are believed to be the key reason for the termination of the great Mayan city of Tikal in Guatemala, in addition to population increase and deforestation (e.g., Hodell *et al.*, 1995; Scarborough, 1998; deMenocal, 2001; Haug *et al.*, 2003; Peiser, 2003; Lucero *et al.*, 2011; Drysdale *et al.*, 2006; Middleton, 2012; Scarborough *et al.*, 2012). Recently, the demise of the hydrologically advanced Angkor city of the Khmer kingdom in Cambodia in the 14-15th century is also ascribed to long term monsoon variability, causing cyclicity of droughts and intense precipitation seasons (Buckley *et al.*, 2010), resulting in crop failures and acidification of soil (Singh, Gupta *et al.*, 2020). The above evidence points to the severity of past climate changes on the stability and survival of past civilisations across the world. Therefore, it is essential to reflect on how current global climate changes may impact vulnerable societies like those found in India today to understand their resilience to these changes better. First, though, it is crucial to understand the potential climate change impacts.

[5] Before the present, and according to radiocarbon dating convention 1950 CE is the present reference point.

1.1.3 Current climate change and its impact on India

Climate change, primarily caused by anthropogenic activities, is one of the biggest challenges of the 21st century because it has significantly increased the number of extreme climate events such as shifted monsoon and precipitation patterns, droughts, intense precipitation, cyclones, floods, and heatwaves, melting of ice and glaciers, rising sea levels, and irreversible changes in ecosystems around the world (e.g., Peiser, 2003; WHO, 2009; Tripathi & Mishra, 2017; van Oldenborgh *et al.*, 2018; Krishnan & Dhara, 2020; Masroor *et al.*, 2020; Rao *et al.*, 2020; Saranya *et al.*, 2020; UNDP, 2020; Vijay *et al.*, 2021). The global average temperature has increased by 1^{o}C since pre-industrial times, and it is often attributed to anthropogenic activities such as the emission of greenhouse gases (GHGs), use of Chlorofluorocarbons (CFCs), changes in land use and land cover (van Oldenborgh *et al.*, 2018; Krishnan & Dhara, 2020). The global temperature is likely to increase by 3^{o}C by the end of the 21st century, increasing the melting of glaciers and ice and changing ecosystems in mountain regions around the world (Kohler & Maselli, 2012; UNDP, 2020, p. 4). In addition to the impact on the natural environment, the high temperatures and heatwaves caused by climate change also affect the overall development of societies by causing issues such as crop failures, increased mortalities, economic growth, and stress on infrastructures and governance (UNDP, 2020, p. 218). Increased heatwave spells may also cause or worsen various health issues such as heat strokes, exhaustion, cramps, and any existing cardiac, kidney, and pulmonary conditions (van Oldenborgh *et al.*, 2018). Large scale land use and land cover change can further alter the climatic pattern by changing surface albedo and changing the energy conversion between surface and atmosphere, resulting in changed water cycle dynamics, biodiversity loss and consequent socioeconomic changes (Jose & Padmanabhan, 2015; Chakraborty & Shukla, 2020; John *et al.*, 2020; Saranya *et al.*, 2020), which may further increase the inequalities in human development across the world especially in developing and underdeveloped regions (UNDP, 2020, pp, 218-219; Vijay *et al.*, 2021). Though climate change is a global phenomenon, the impact of climate change is not likely to be uniformly distributed across the Earth, but some of the regions are more vulnerable to climate change than others (Krishnan & Dhara, 2020).

India is a large country, with several climatic and geographic zones, which causes the uneven geographical distribution of natural and human resources, thus, the impacts of climate change are likely to vary between the regions in India (Krishnan & Dhara, 2020; Deepa & Gnanaseelan, 2021). The average temperature in India has already increased by 0.7^{o}C from 1901-2018, and this change has been attributed to historical emissions of greenhouse gasses, use of Chlorofluorocarbons (CFCs), land use and land cover changes (Krishnan & Dhara, 2020; Rao *et al.*, 2020; Vijay *et al.*, 2021). Moreover, by the end of the 21st century, the average temperature over India is likely to increase by 4.4 ^{o}C (Krishnan & Dhara, 2020), which is higher than the global average increase of 3 ^{o}C (UNDP, 2020, p. 4). Similarly, the sea surface temperature (SST) of the Indian Ocean has also increased by an average of 1^{o}C between 1951-2015 and is projected to increase further, which is higher than the global averages of 0.7 ^{o}C for the same period (Krishnan & Dhara, 2020). Moreover, by the end of the 21st century, the sea level rise in the North Indian Ocean is expected to be ~300 mm, which is significantly higher than the predicted 180 mm global mean sea level rise (Krishnan & Dhara, 2020; Rao *et al.*, 2020; Deepa & Gnanaseelan, 2021).

Since the mid-20th century, India has started to observe the implications of human induced climate change in the form of a significant increase in average temperature, heat waves, retreating glaciers, changed precipitation pattern, droughts, extreme precipitation and harsh cyclonic conditions, followed by extreme flooding, affecting water and food availability in India, and the vulnerability is increased as the population of the Indian subcontinent heavily relies heavily on annual monsoons to recharge their water resources (van Oldenborgh *et al.*, 2018; Chakraborty & Shukla, 2020; Krishnan & Dhara, 2020; Rao *et al.*, 2020; Wang *et al.*, 2021). A weakening trend in the global monsoon precipitation has been reported in the second half of the 20th century (Zhou *et al.*, 2008), especially in the Northern Hemisphere summer monsoon, which is widely attributed to warming associated with anthropogenic emissions (Wang & Ding, 2006; van Oldenborgh *et al.*, 2018). However, Zhisheng *et al.* (2015) have reported strengthening global summer monsoon rain trends in the northern hemisphere over the past thirty years. Kripalani *et al.* (2003) and also did not find a direct association between global warming and the variation in Indian monsoon rain for a longer term dataset between 1871-2001. According to a climate projection based on the Third Coupled Model Intercomparison Project (CMIP-3), climate change caused by anthropogenic activities will increase the overall precipitation caused by the monsoon, and seasonal variation will increase with more intense rainfall but also longer dry periods over India (WCRP, 2017; Chakraborty & Shukla, 2020; Rao *et al.*, 2020). Any regime shift in the current monsoon pattern may cause droughts, floods, risk of crop failure, and health issues (Rockström *et al.*, 2014, pp. 72-72; Chakraborty & Shukla, 2020; Rao *et al.*, 2020), as has happened in the past in India (Singh, Gupta *et al.*, 2020). India was found to be highly vulnerable to drought situations between 1951-2000 (Vijay *et al.*, 2021), and climate change seems to have further increased the frequency of droughts in India in the last two decades (Chakraborty & Shukla, 2020; Masroor *et al.*, 2020; Poonia *et al.*, 2021), which is associated with decreasing rainfall intensity, the long temporal gaps between the dry and rainy seasons, and increasing temperatures (van Oldenborgh *et al.*, 2018; Rao *et al.*, 2020; Poonia *et al.*, 2021; Vijay *et al.*, 2021). For example, the regions around the Western Ghats and Chennai faced severe drought in 2016 caused by changing monsoon pattern, followed by devastating floods in 2018 and 2019, and floods were also observed in other 13 states in India induced by heavy spells of monsoon rain (Menon *et al.*, 2020; Saranya *et al.*, 2020; UNDP, 2020, p. 120; Poonia *et al.*, 2021).

Approximately 67% of the Indian population live in rural areas, and 7% (63.4 million) have no access to clean water (WaterAid, 2017, pp. 14-15). Furthermore, according to the Government of India, India has the highest rural population without access to clean water (GOI, 2018, p. 121), and climate change is likely to further stress any existing drinking water supplies in the rural areas (Bhagawati *et al.*, 2017; Saranya *et al.*, 2020). Furthermore, the women, girls, and children in rural areas in India are highly vulnerable to climate change mainly because of extra household and work responsibilities, including time spent in fetching water from long distances, fodder, fuel and wood collection, gender discrimination, sanitation issues, low income, and low education opportunities (WHO, 2009; Yadav & Lal, 2018). Moreover, India is in the top 38% of the most vulnerable and least ready countries to adapt to climate change and other significant weather events (Salve, 2017; WaterAid, 2017, pp. 14-15). Thus, India is highly vulnerable to climate change (UNDP, 2020, pp. 2018-219; Rao *et al.*, 2020; Vijay *et al.*, 2021); so, the Indian government initiated its National Action Plan on Climate Change in 2008 and signed the Paris Agreement to reduce fossil fuel emissions significantly and increase its reliance on solar energy for power generation by 2030 (UNDP, 2020, p. 83). Besides these recent initiatives to mitigate or reduce the impacts of climate change in India, it is essential to recognise that India has a large historical legacy of traditional water conservation and harvesting methods designed to ameliorate or prevent water scarcity problems in the past. The following section explores the traditional water management methods used by these communities in India in response to water scarcity and geographical and temporal variations in water availability.

1. 2 Traditional water management in India

Similar to other ancient civilisations and communities living in arid and semi-arid regions around the world, the ancient communities in India developed several traditional water management (TWM[6]) systems to overcome the issues of freshwater scarcity for drinking, household, and irrigation usage by conserving excess water from monsoonal rains and by harvesting surface and groundwater (e.g., Ron, 1985; Agarwal & Narain, 1997; Chakravarthy *et al.*, 2006; Kokkal & Aswathy, 2009; Rawat & Sah, 2009; Schelwald-van der Kley & Reijerkerk, 2009; Ferrand & Cecunjanin, 2014; Lasage & Verburg, 2015; Yannopoulos *et al.*, 2015; Ein Mor & Ron, 2016; Dahmen & Kassab 2017; Gautam *et al.*, 2017; Baba *et al.*, 2018; Khorramrouei & Nasiri, 2019; Megdiche-Kharrat *et al.*, 2020; Singh, Dey *et al.*, 2020; Singh *et al.*, 2021; Yechezkel *et al.*, 2021). Historically, these diverse TWM systems were indispensable for community survival because they protected communities against seasonal water shortage caused by temporal and spatial monsoon variation (Agarwal & Narain, 1997; Kokkal & Aswathy, 2009; Naz & Subramanian, 2010; Baba *et al.*, 2018; Singh, Gupta *et al.*, 2020). These TWM systems also provided water security for agriculture production, allowing communities to grow (Yannopoulos *et al.*, 2015; Baba *et al.*, 2018). The main advantages of these TWM systems were that they were flexible in design and construction whilst construction and maintenance costs were minimal because locally available materials were used for their construction, and these systems could be implemented locally using basic technical knowledge according to local geography and climate (Wisser *et al.*, 2010; Yannopoulos *et al.*, 2015; Singh *et al.*, 2021). The typical water sources in Indian TWM systems are groundwater and surface runoff during the wet seasons (Agarwal & Narain, 1997; Wisser *et al.*, 2010; Bhattacharya, 2015). Therefore, some TWM systems, for example, inundation canals in Bengal and the irrigation tank systems of south India, also helped in minimising the effects of floods by directing floodwater to agricultural fields, or the excess water was often saved in massive storage structures for use in dry periods (Agarwal & Narain, 1997;

[6] In this study traditional water management (TWM) has been used as an overarching theme, that includes traditional methods of water harvesting and/or allocation of water among the stakeholders based on collective or individual basis.

Mosse, 1999; Chakravarthy *et al.*, 2006; Shah, 2008; Wisser *et al.*, 2010; Shanmugasundaram *et al.*, 2017; Baba *et al.*, 2018).

India's rich history of TWM systems is recorded in ancient Vedic, Buddhist, and Jain texts and found on inscriptions, culture, and archaeological remains (Mate, 2006; Mujumdar & Jain, 2018). The first record of dams, bunds, reservoirs, wells, and network of canals, private baths, and well developed sewage system in the Indus civilisation (also known as Harappa civilisation) in the north-west of the Indian subcontinent in the early Bronze age, between ~3000-1500 BCE (Mate, 1969; Jansen, 1989; Kenoyer, 1991; Mate, 2006; Baba *et al.*, 2018; Singh, Dey *et al.*, 2020). The earliest references to the use of wells in India are found in the *Rigveda*, composed around 1500-1200 BCE (Müller, 1965; Gokhale, 2006). Some other ancient hydraulic systems were canals, tanks, and embankments (Pande, 1997; Singh, Dey *et al.*, 2020). The ancient philosophers and religious preachers may have known the importance of water for life in India's diverse geography and climate seasonality. Therefore, the association between water and environment with culture, spirituality, and religion is often noticeable in ancient Indian religious and mythological texts (Mujumdar & Jain, 2018; Singh, Dey *et al.*, 2020). For example, in India's ancient Hindu culture, water was worshipped as one of the five essential elements of life, including air, soil, fire, and space. The *Varuna* and the *Indra* were the respective deities of water and rain. The *Indra* was worshipped because he defeated the *Vritra*, the demon of drought. Various inscriptional evidence and standard mythological literature suggest that any kind of water harvesting for the society, especially for drinking water, was deemed a commendable act in ancient Indian society (Gokhale, 2006).

There is a rich history of water tanks in south India, and these are found in assorted sizes and scales that stored the diverted water from rivers and monsoonal runoff to be used for irrigation during the dry season (Agarwal & Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008). The construction of several types of tanks was also mentioned in the inscription of *Kharavela* in Orissa (Jaiswal & Banerjee, 1929-30). Private ownership and cooperative use of water tanks and wells have been mentioned in Kautilya's *Arthashastra* during the Mauryan period in 300 BCE (Gokhale, 2006; Naz & Subramanian, 2010), which is often credited as being a period of one of the most developed hydraulic civilisations in India (Singh, Dey *et al.*, 2020). *Setubandha* embankment, *prapa* storage of drinking water, and *aharyodakasetu* are other water harvesting structures mentioned in Kautilya's *Arthashastra* from the Mauryan period (Kangle, 1963; Singh, Dey *et al.*, 2020). A dam named *Sudarsana,* constructed on the river *Suvarnasikata* and *Palasini* by the *Mauryan* ruler *Chandragupta Maurya* (320 – 298 BCE), has been mentioned in the inscription of *Rudradaman* at *Junagadh* in Gujarat (Gokhale, 2006; Singh, Dey *et al.*, 2020). Inscriptional evidence from the period of the Mauryan King Ashoka (268 – 232 BCE) in Delhi suggests that the construction of planned water structures for drinking water for the communities were one of the prime responsibilities of a ruler (Hultzsch, 1969). A dam known as *Sudarsana* became so popular that king *Devasena* of *Vakataka* constructed another dam in 458 CE near *Vatsagulma* (Gokhale, 1968), and Queen Prabhavati Gupta built another dam near *Ramtek*, with both dams named *Sudarsana* (Jamkhedkar, 1992).

Several large tanks in south India were constructed to store the diverted river flow during the *Pallava* kings between 275 CE- 891CE and *Chola* kings between 850-1300 CE (Sutcliffe *et al.*, 2011, p. 785; Shanmugasundaram *et al.*, 2017). The rise of the *Chola* kingdom as a significant political and economic power in south India, during the long term monsoon irregularities, such as floods and droughts, between 850-1300 CE, has been attributed to timely use and largescale promotion of TWM such as tanks (Shanmugasundaram *et al.*, 2017; Singh, Dey *et al.*, 2020). There are various references to the construction of wells by the rulers during and after the *Yadava* period between 850-1334 CE (Gokhale, 2006). *Anicuts* (diversions dams) were used to divert runoff to reservoirs in the historical regions of Vijayanagar and Seringapatam (Sutcliffe *et al.*, 2011, p. 782). Over eight hundred Buddhist rock caves at Kanheri on the Western coast of Maharashtra have water tanks (*podhi)* that collect rainwater from the artificial water channels excavated on the roof of the caves (Gaikwad, 2010). Inscription records suggested a dam on a stream, and the remains of this dam have been reported, which might have been used for irrigation by the dwellers of these caves (Gokhale, 1991).

Another ancient form of irrigation found in India is *qanat* (Raghuwanshi, 2006; Wahurwagh & Dongre, 2015; Mishra, 2017). *Qanat* is an underground gallery (tunnel) system. A mother well is dug in an aquiferous region by users who need water for drinking and irrigation in dry areas, these groundwaters are conveyed in tunnels along distances from several hundred metres up to 100+ kilometres (Yazdi & Khaneiki, 2012; Mahan *et al.*, 2015; Khorramrouei & Nasiri, 2019). A *qanat* harvests water from alluvial fans by intercepting the water from an aquifer through water-saturated soil layers that flow down gently sloping tunnels under gravity (Yazdi & Khaneiki, 2012). There are various origin ideas to *qanat* that have been suggested in the texts, such as Roman, Jewish, Arab, and Persian (e.g., Wulff, 1968; Stiros, 2006; Al-Ghafri, 2012; Boualem & Rabah, 2012; Yazdi & Khaneiki, 2012; Fattahi, 2015; Mahan *et al.*, 2015; Nasiri & Mafakheri, 2015; Ein Mor & Ron, 2016; Dahmen & Kassab 2017; Manuel *et al*., 2017; Mokadem *et al.*, 2018; Khorramrouei & Nasiri, 2019; Yechezkel *et al.*, 2021), but the *qanat* technology has also spread further afield to places like China and India. These water tunnels were probably introduced to India by Arab and Persian traders, who settled on India's western coast, from Middle Eastern countries via the sea route during the 7th century (Nazimuddin, & Kokkal, 2002; Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Mujumdar & Jain, 2018). Over time these traders moved inland into semi-arid and arid zones. It is then likely that inland technology transfer occurred as Indian *qanats* are typically found in semi-arid or arid plateaus proximal to wetter uplands. The *qanat* of Burhanpur town in Madhya Pradesh is an example of a working *qanat* in India (Mishra, 2017). This gravity based, complex water system of underground tunnels, wells, and airshafts, locally known as *bhandara* (Wahurwagh & Dongre, 2015), harvests the groundwater from the *Satpura* hills. The rectangular *bhandara* was used to collect water, carried to the town in an underground tunnel. The underground tunnel has regular air shafts, each ~20 metres, with a diameter of 1.2-1.8 metres (Raghuwanshi, 2006). The *qanat* system of the UNESCO heritage city of Burhanpur was constructed between 14th -17th century CE by the Mughal emperors under the Persian geologist Tabkutul Arz. This *qanat* system was one of the primary sources of water for the army and residents of ancient Burhanpur town, and part of this *qanat* still provides water today (Raghuwanshi, 2006; Wahurwagh & Dongre, 2015). A few *qanats* are also found in central India in Bidar town, northern Karnataka (Figure 1.3). Persian architects constructed these *qanat*s during the Tughlaq dynasty, the Bahamani kingdom, and later during the Mughal empire in India (Doddamani, 2007; Halemane, 2007).

Figure 1.3: Views from inside of an abandoned *qanat* in Bidar, in northern Karnataka in India[7].

Tanks (*Hauz*) are another key characteristic of Mughal architects in north and central India (Wahurwagh & Dongre, 2015). By the 18th century, a diverse range of community water management systems such as cascading ponds, reservoirs, check dams, weirs, and open channels were used for drinking water, household use and irrigation (Fisher, 2018, pp. 117-120). These community managed water resources were also the centre of social and religious activities (Mishra, 2012). For example, the community water structures such as a tank or reservoir often had a temple (Sutcliffe *et al.*, 2011), which might serve the structure's communal purpose. Most TWM techniques use similar hydrological principles to divert water through channels to store in tanks. However, nomenclature varies because of design, geography, culture, and language. For example, tanks are found through India, with different names, *eri* in Tamil Nadu and *kere* in Karnataka (Agarwal & Narain, 1997;

[7] All diagrams and photos without a source are author's work.

Mosse, 1999; Narayanamoorthy, 2007). Nevertheless, India's TWM systems can be broadly classified into four categories based on the underlying technique (Table 1.1).

Table 1.1: Typology of TWM systems in India

(Agarwal & Narain, 1997; Pant & Verma , 2010; Mukherji *et al.*, 2019).

Types of TWM	**Type of structures**	**Rationale**	**Benefits**	**Some examples (Location)**
Diversion based	Conduit, Channels, Canals	To direct water from a large water source To distribute and regulate water.	Avoid floods during wet seasons. Transport water from a high water availability area to a waterless area	Canals G*uhls* *Kuhls*
Storage Based	Tank, Pond, reservoir, Lake, Stepwell, Bunded tanks	To store water at the water source To store transported water from other water sources To harvest rainwater	Reduced rainwater runoff Groundwater recharge Flood control Prevent soil erosion	Systems tanks, *Eri* (Tamil Nadu) *Kere* (Karnataka) *Madaka* (Karnataka *Zing* (Ladakh) *Khal* (Uttarakhand) *Naula* (Uttarakhand)
Temporary storage	Earthen dams, Check dams	Water storage in the dry season Create a water gradient.	Decreases runoff. Groundwater recharge	*Katta* (Karnataka) *Korambu* (Kerala)
Groundwater abstraction	Dug well, Open well Qanat	To harvest groundwater	Regular water supply for drinking	*Bavi* (Karnataka) *Keni* (Kerala) *Koop* (North India) Qanat (Karnataka, Madhya Pradesh)

TWM systems in India can also be summarised into four primary categories according to India's broad geography and water use, as shown in Table 1.2.

Table 1.2: Geography of some popular Indian TWM systems

(Agarwal & Narain, 1997; Raghuwanshi, 2006; Kokkal & Aswathy, 2009; Bhattacharya, 2015; Wahurwagh & Dongre, 2015).

Geographical region	Systems for drinking water	Systems for irrigation
Hill and mountain	Streams Spring water Rainwater harvesting Transportation of spring water through channels, bamboo pipes	Water diversion from spring, streams, and rivers through channels and a network of canals, for example, the *Apatani* system of Arunachal Pradesh, G*uhls*, and *Kuhls* in the Western Himalayan region. To water storage structures for dry periods. Example *Zings* of Ladakh. Bamboo pipe irrigation network used to transport water from springs from hilltop to lower areas, used in Meghalaya.
Arid and semi-arid	Wells and stepwells to harvest from groundwater aquifers, for example, *baoli* of Rajasthan. Rainwater harvesting from rooftops, for example, *tankas* of Pali Rainwater harvesting through artificial catchment into wells, for example, *kunds* of Rajasthan Water harvesting through a *qanat*	Rainwater stored in a tank at an extensive catchment area A runoff system made of a series of tanks, for example, *bandharas* of Maharashtra, *keres* of Karnataka Runoff water storage structures, which recharges the groundwater and increases the moisture of the land and later used for agriculture, without irrigation. Example *khadins* of the Jaisalmer and *johads* of the Alwar district of Rajasthan.
Plains	Dug wells	Floodwater diverted to the agricultural field through inundation channels built on flood plains of rivers. An example of floodwater irrigations systems of West Bengal. Storing rainwater in the agricultural field by constructing bunds, for example, the *haveli* system of Madhya Pradesh.
Coastal	Dug wells	Community water tanks of Tamil Nadu. *Khazana* lands of Goa uses regulatory systems to control the ingress of saline river water to maintain agriculture in coastal plains.

Thus, India’s traditional water management systems are mainly made up of community managed tanks, reservoirs, wells, seasonal dams, and feeder channels (Agarwal and Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Sutcliffe *et al.*, 2011). For example, the centuries-old *tanka* is found in the arid region of Rajasthan with an annual rainfall of 160 mm. A *tanka* or *kund* is usually an underground tank that collects filtered rainwater with the structure covered to avoid contamination and minimise loss through evaporation. A typical tanka has been shown in Figure 1.4, with access from the centre of the catchment to stored water through steps, and water is lifted through a rope and bucket (Mishra, 2012). Another example of groundwater collection is open, stepped wells (*baoli*) that harvest groundwater and runoff and are also accessed through a series of steps (Sutcliffe *et al.*, 2011). Such *baolis*, with design variation, are in significant numbers in parts of India (Mishra, 2012). A stepped-well (*baoli*) is shown in Figure 1.5.

Figure 1.4: Picture of an underground rectangular, covered tank in the Thar Desert, with access at the centre through steps, and water is lifted manually through a rope and a bucket (Image source: Mishra, 2012).

Figure 1.5: A view of an open, stepped-well accessed through the stone steps, in the ancient Hampi town in Northern Karnataka

(Image source: Creative Commons, 2019).

Thus, India has had a rich history of hydrological knowledge and medium scale community managed TWM systems (see Mishra, 1993; Agarwal & Narain, 1997; Chakravarthy, Badam & Paranjpye, 2006; Iyengar, 2007). A summary of some of the most popular TWM systems in India has been presented in Appendix A. However, failed attempts to centralise TWM systems and the start of the canal revolution during the British Raj impacted India's community water management discourse (Naz & Subramanian, 2010). It continued post-independence in India in 1947 CE as the population increased in the last centuries, and borewell and water pumping technologies were gradually introduced in the mid and late 20th century, which lead to the further neglect and abandonment of TWM systems (Agarwal & Narain, 1997; Naz & Subramanian, 2010). The centralisation of drinking and domestic water supplies for the household, and government interventions on water management post-independence in India, further created an indifferent society towards TWM of water resources (Unnikrishnan *et al.*, 2017). Cities became more urbanised, the agriculture area decreased, and agricultural water demands decreased (Agarwal & Narain, 1997). These community managed TWM systems effectively mitigated floods and droughts until recent times; after that, they gradually became moribund or were abandoned (Agarwal & Narain, 1997; Naz & Subramanian, 2010 Unnikrishnan *et al.*, 2017; Yadav & Lal, 2018), making places vulnerable to floods (Shanmugasundaram *et al.*, 2017). These TWM systems, evolved over generations based on accumulated historical community water knowledge, can be useful to mitigate current water issues. Thus, there is an urgent and timely need to study these TWM systems to increase understanding of their design and organisational principles, as the use of TWM systems diminish further under the pressure of modern competing technology-based water abstraction systems such as borewell.

Furthermore, experiences from these TWM systems may help develop a sustainable water approach in India and other parts of the world with similar environmental and social characteristics. Aside from these points, several small scale TWM systems used by marginalised communities in India have not received much academic or official attention, and knowledge has been underexposed to the outer world. The reason for this lack of attention is that these systems have been officially ignored by the national, regional, and local government despite these water systems appearing to have helped some remote frontier communities grow and develop. Some examples of these small scale TWM systems are *suranga, keni, madka,* and *katta,* mainly found around India in the Western Ghats (Doddamani, 2007; Halemane, 2007; Iyengar, 2007). Thus, there is an even greater need to study and learn about these little known and understood traditional water harvesting systems before they vanish and indigenous knowledge and adaptations are lost (UNDP, 2020, p. 150). This study looks at one of these less known small scale TWM systems found in the foothills of the Western Ghats, known colloquially as *suranga*. The following section introduces the *suranga* water management system and the need for this study.

1.3 The *suranga* system and the genesis of this project

The word *suranga* is of Indo-Aryan descent, and it means an underground tunnel; however, it is also found in the Kannada and Malayalam languages of Dravidian origin (Pathak, 2007; Bahri, 2009). The *suranga* system was first discovered by the researcher on the Flickr website in the year 2008 as a series of photographs and articles published by a water journalist from Kasaragod district in India (Padre, 2002; Padre, 2006a; Padre, 2006b; Padre, 2008a, Padre, 2008b). A preliminary survey of *suranga* was undertaken in part required to complete a master's in science taught programme (Tripathi, 2009). This doctoral research germinated from the need for further research into *suranga* because the preliminary survey identified a dearth of documented information about the origin, age, development, and management of the *suranga* system (Nazimuddin, & Kokkal, 2002; Doddamani, 2007; Tripathi, 2009).

Previous studies portray *suranga* as hand-hewn horizontal dug tunnels usually excavated on hillslopes to harvest water from the subsurface. These tunnels are used for drinking, household, and irrigation activities by the local farmers on farm units that are often viewed as marginal in their geography, environment, and farm output (Basak *et al.*, 1997; Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Tripathi, 2009). Although the exact spatial distribution and the total number of *suranga* were unknown, *suranga* in the preliminary surveys were primarily found throughout parts of the foothills of the Western Ghats (see Figure 1.6), specifically in the villages of Dakshin Kannada (DK) district in Karnataka, and Kasaragod district in Kerala (Prasad *et al.*, 1991; Basak *et al.*, 1997; Nazimuddin, & Kokkal, 2002; Doddamani, 2007; Halemane, 2007).

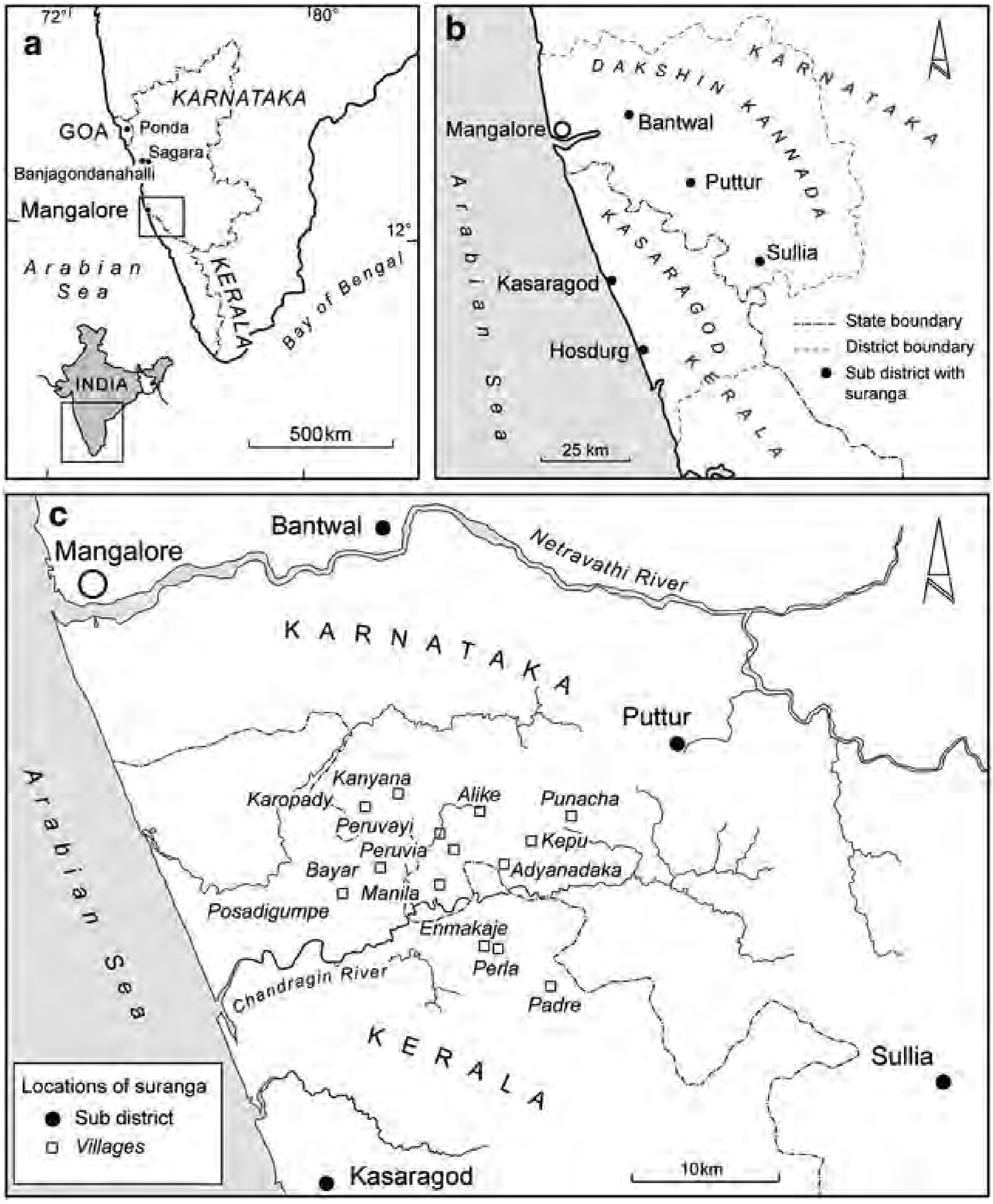


Figure 1.6: The *suranga* have been mainly found in a small region in southern India (from Crook *et al.*, 2015).

The *Bayar* village in Kasaragod district, situated on the slope of the Possdigumpe hill, is thought to have the highest density of *suranga* (Doddamani, 2007; Halemane, 2007). Other neighbouring dispersed and non-nucleated villages with large numbers of *suranga* were *Manila* and *Padre* (Tripathi, 2009). Agriculture in these villages was often located in deep cut valleys and terraced fields on steep hillslopes (Suseelan, 2008).

1.3.1 Rationale for the study

The *suranga* water harvesting system has been relatively little explored in the academic literature, and only a small number of studies document and quantify the total number of *suranga*, and there is an absence of any complete database on the spatial distribution of *suranga* (Prasad *et al.*, 1991; Basak *et al.*, 1997; Nazimuddin, & Kokkal, 2002; Tripathi 2009; Balooni *et al.*, 2010). These data gaps can be attributed to the difficulty of collecting data from dispersed settlements in remote regions with hilly and mountainous topography (Shannikodi, 2013) that are susceptible to extreme weather. The initial descriptions of *suranga* (Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Tripathi, 2009) were based on personal accounts drawn from small and partial surveys. As a result, the data available on *suranga* come across as shallow, erroneous, and widely repeated, and unable to explain or expand on unanswered concepts related to *suranga*, such as the discrete hydrological functioning of the *suranga* system that makes *suranga* different from other methods of water harvesting and storage. A local journalist, named Shree Padre from Kasaragod district, published several online and offline English articles on *suranga* (Padre, 2002; Padre, 2006a; Padre, 2006b; Padre, 2008a, Padre, 2008b; Padre, 2009). Several early film documentaries and newspaper articles on *suranga* were also published (CSE, 1998; Doddamani, 2007; Halemane; 2007; Doordarshan, 2008; Jayan, 2012). These articles on *suranga* mostly contain recycled and rephrased information on *suranga* from previously available information. For example, the idea of *suranga* technology owing to its existence to *qanat* technology has become popular anecdotal mythology because it was mentioned in many popularised and academic articles, including Prasad *et al.* (1991), Doddamani (2007) and Halemane (2007). However, in none of these articles are these claims, of *suranga* origin from *qanat*, substantiated; therefore, there was a need to collate evidence to provide a more rigorous explanation for the origin and spatial distribution of *suranga* to fill the knowledge gap. The key differences found between a *suranga* and a *qanat* from this study have been summarised in Table 8.1 and discussed in detail in Chapter 8.

Basak *et al.* (1997) try to explain the hydrogeology of *suranga* with a vague diagram based on *qanat* hydrogeology that has been subsequently redrawn and used by other academic authors who have no practical experience of *suranga*. Other studies on *suranga* include Suseelan (2008) and Tripathi (2009), who attempted to quantify the structural parameters and excavation rates of *suranga*, but only a small number of respondents acknowledged the broad spatial distribution of *suranga*. A small body of work constitutes rhetoric on the sustainability of *suranga* without providing a sustainability framework and supporting evidence (Doddamani, 2007; Halemane, 2007; Suseelan, 2008). Issues of generalisation, overall rigour, and reliability also seemed to creep into past work. For example, the number of airshafts and the number of interconnected, tiered *suranga* mentioned in Balooni *et al.* (2010) could not be verified in the field by Crook *et al.* (2015).

To understand the prospects of a water management system in detail, Reynard *et al.* (2014, p. 12) suggest using a study combining natural and social aspects. In the case of *suranga*, a couple of more extensive studies were undertaken, but these were focused on the spatial distribution, construction details, and supply of water to *suranga* but were lacking in the human and social perspectives of *suranga* users (Prasad *et al.*, 1991; Nazimuddin, & Kokkal, 2002).

Furthermore, the rapid rise in population has resulted in increased water demands for daily household and agriculture requirements, followed by increased deforestation and informal settlements, which may have increased the environmental and ecological pressure on fragile but globally significant natural forest reserves (Chitale *et al.*, 2015; Reddy *et al.*, 2016). The case study area is situated in the foothills of the Western Ghats, designated as one of the world's biological diversity hotspots (Chitale *et al.*, 2014; Marchese, 2015). These mountains and hills of tropical evergreen forests are home to a diverse range of endemic flora and fauna, with many of these species being listed as endangered (Chitale *et al.*, 2015; Sarvalingam & Rajendran, 2016; Arumugam *et al.*, 2018; Chitale *et al.*, 2020). Thus, it was crucial to understand the impact of *suranga* construction on local flora and fauna.

It is crucial to understand why farmers adopted *suranga* technology and how they have adapted it over time to exogenous and endogenous demographic, agricultural market, and political forces to understand the system's resilience to these perturbations. For example, groundwater over-abstraction caused by new technologies like borewells may negatively affect various traditional water systems in India, including *suranga*. Thus, in this instance, there was a need to enhance understanding of the complicated geo-hydrological relationship between *suranga* and borewell water supplies to understand community vulnerability and resilience with respect to existing water shortage, increasing water demands and climate change.

It is also essential to understand the significance of the *suranga* system in helping to buffer the consequences of climate change as the onset and length of monsoon threatens to be radically changed under current scenarios (Bhagawati *et al.*, 2017; Vijay *et al.*, 2021; Wang *et al.*, 2021), especially as water resources, particularly groundwater resources, are already critically scarce in the region (Bhattacharya, 2015; Mekonnen & Hoekstra, 2016; GOI, 2018, p. 27; Coyte *et al.*, 2019). Water scarcity caused by a change in monsoon pattern because of climate change is likely to affect the mountain communities' environmental, ecological, agricultural, and socioeconomic conditions (Bhagawati *et al.*, 2017; Tripathi & Mishra, 2017). Therefore, it was essential to ascertain if *suranga* technology is resilient to the predicted perturbations of climate change and thus help poor and marginalised families cope with environmental uncertainty and change. This will test whether *suranga* can be viewed as sustainable and potentially transferable into new marginal locations, provided that their design principles and governance models can be replicated.

So far, the literature available of *suranga* shows several knowledge gaps, which can be summarised in the form of the following research questions, which this study attempted to answer:

> **Research Question 1:** What is the origin and development history of *suranga* in the study area?
>
> **Research Question 2:** What is the spatial distribution of the *suranga* system in the study area?
>
> **Research Question 3:** What are the design principles, governance and management systems underpinning *suranga* use in the study area?
>
> **Research Question 4: Research Question 4:** What are the key geohydrological and hydrological characteristics of *suranga*?
>
> **Research Question 5:** What socioeconomic conditions in the study area promote the use of *suranga*?

Thus, this study attempted for the first time to fill the knowledge gap about the origin, geographical distribution, structural classification, design principles, hydrogeology and hydrology, and governance and organisation of *suranga*. This study also provided a scientific evaluation of a little known water harvesting system in context to the broader issues of the agrarian system dependent on the *suranga* systems (Padre, 2006). This can help in a better understanding of community vulnerability and resilience supported by *suranga* with reference to the broader water issues, such as decreasing groundwater availability in the region, water quality issues, and the impact of climate change on the monsoon and water resources on the study area.

1.4 Chapter summary

India heavily relies on seasonal monsoon rains for agriculture and recharge freshwater resources during the dry seasons. India is progressively approaching a nationwide crisis linked to critical water scarcity because of increased water demand from both household and agriculture sectors. Groundwater resources in India are already showing signs of a critical decrease in level because of over-abstraction caused by the unregulated use of groundwater pumping technologies for drinking, household, and agriculture use. Moreover, climate change is likely to make the water shortage worse in India. However, historically communities in India have relied on several localised TWM systems to achieve water security that minimised disturbance to the environment. An unknown TWM system called *suranga* has been traditionally used by the communities in the foothills of the Western Ghats in India to harvest water. This research aims to study the *suranga* system to understand its characteristics and impact on the environment and the local communities. The increased understanding of the *suranga* system can help in knowledge transfer to combat water scarcity issues in other parts of India, or in any other arid and semi-arid regions of the world with similar geographical circumstances. However, in the absence of previously documented information on *suranga*, there was a need to place this work within a workable conceptual framework for focused analysis of *suranga* based on the researcher’s limited and partial knowledge of the system at the start of the project, which is presented in Chapter 2.

Chapter 2 – Research frameworks, aim and objectives

An introduction to the *suranga* water harvesting system and justification for this study was presented in Chapter 1. Following this, an analytical framework to study *suranga* was required to set an overarching research framework that collected data logically and systematically to answer the research questions. *Suranga* is an example of a TWH system used principally by agricultural communities living in the foothills of the Western Ghats in India. Therefore, this study used an analytical framework centred on water and agriculture development in a hilly region, based on the work of Vincent (1995). Despite being somewhat dated, this text has been used because it still provides the best published overview of different mountain and hill irrigation types across the globe. This chapter introduces the concept of hill irrigation and presents a hill irrigation model that is believed to have utility and enables a rigorous exploratory study of *suranga* systems to be carried out (section 2.1). This section is followed by section 2.2, which critically focuses on the community management aspects of TWM systems to evaluate their efficacy. Moving on, section 2.3 presents a resilience and sustainability framework to assess the *suranga* system. The chapter concludes by presenting the project aim and the objectives for this study in section 2.4 and a chapter summary in section 2.5.

2.1 Hill irrigation analytical framework

The analytical framework provides a theoretical foundation that guides the course of the study and sequence of data collection, leading to developing new emergent concepts essential for understanding a topic (Andrew & Halcomb, 2009; Coral & Bokelmann, 2017). The analytical framework employed in this study is based primarily on an interpretation and application of Vincent's (1995) definition of a hill irrigation system with conceptual inputs from studies conducted in other mountain regions (Ron, 1985;

Gerrard, 1990; Crook & Jones, 1999; Crook, 2001; Meybeck *et al.*, 2001; Kreutzmann, 2011; Kohler & Maselli, 2012; Knez & Eliasson, 2017; Dörre & Goibnazarov, 2018; Suri, 2018; Wilson *et al.*, 2018; Mukherji *et al.*, 2019). The hill irrigation analytical framework, coupled with the findings from the initial exploratory analysis of *suranga* (Tripathi, 2009), seemed to offer the potential to study the system in depth. Thus, five overarching analytical components emerged (see Figure 2.1) from these readings to define a hill irrigation system, which are, history, design principles, hydrology and hydrogeology, governance and organisation, and community (Vincent 1995; Gerrard, 1990; Crook & Jones, 1999; Crook, 2001; Meybeck *et al.*, 2001; Kreutzmann, 2011; Kohler & Maselli, 2012).

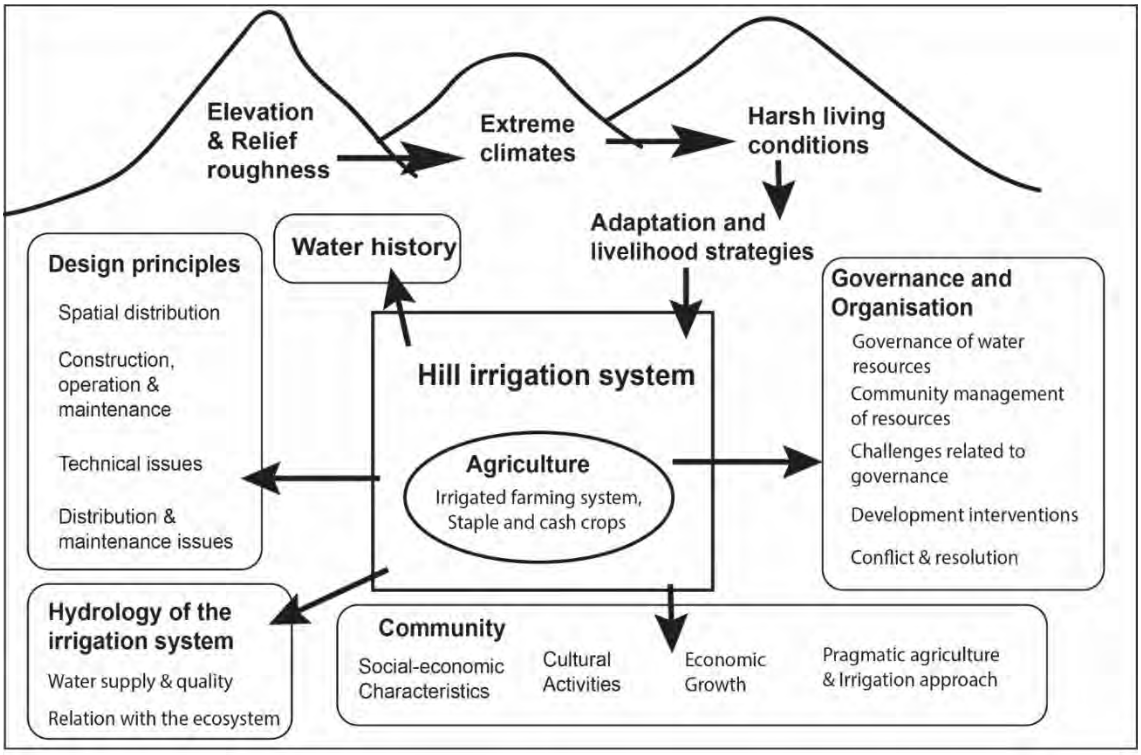


Figure 2.1: The analytical framework for this study based on key characteristics of a typical hill irrigation system (adapted from Vincent 1995; Gerrard, 1990; Crook & Jones, 1999; Crook, 2001; Kreutzmann, 2011; Kohler & Maselli, 2012).

These five components were explored further in the following sections through the definitions, debates, and typologies around hill irrigation systems. This analytical process brought a deeper understanding of the *suranga* system and provided justification based on evidence for an improved understanding of the *suranga* system. The data collection structure was also designed to allow for both a quantitative and qualitative data driven analysis (Vincent, 1995; Reynard *et al.*, 2014) of the resilience (section 2.3.1) and sustainability (section 2.3.2) of the *suranga* system.

2.1.1 Definition, debates, designs, and issues

Mountains cover ~25% of the Earth's total land area and account for 32% of surface runoff; therefore, mountains are among the largest providers of global freshwater supplies, with water originating in mountainous areas coming mainly from surface runoff, snow and ice melt, and underground aquifers (Meybeck *et al.*, 2001; Kohler & Maselli, 2012; Mukherji *et al.*, 2019). Approximately 26% of the global population live in mountain regions (Meybeck *et al.*, 2001). In the absence of universally accepted definitions (Gerrard, 1990), the terms mountains and hills are often used interchangeably (Vincent, 1995; Meybeck *et al.*, 2001; Fang & Ying, 2016). Efforts have been focused on categorising mountains and other regions according to the physical and environmental parameters, such as altitude, geomorphology, climate, vegetation cover, ecology (Vincent, 1995), slope, elevation, and relief data based on GIS and a global database (Kapos *et al.*, 2000; Meybeck *et al.*, 2001). Elevation is a widely used characteristic to define mountains and hills and characterise mountains and other natural landscapes. Meybeck *et al.* (2001) used elevation and relief roughness (RR in ‰)[8] at a global scale with a grid resolution of 9.14x9.14 square metres (Table 2.1). The RR (‰) is the difference between the highest and the lowest points in a grid, divided by half the cell length, and the dimension of RR is meters/kilometre (Meybeck *et al.*, 2001). According to this classification, the elevation is the prime difference between a mountain (500-6000 m) and a hill (200-500 m) region because both can have high roughness (20‰ < RR), however, plateaus can be found at higher altitudes but have lower roughness (Meybeck *et al.*, 2001). This classification provides a reference to classify landscapes, but it does

[8] ‰ = part per thousand, also known as per mille

not always universally define and set clear boundaries between hills and mountains because of non-uniform variation in natural land formations.

Table 2.1: A classification of natural landscapes based on elevation and relief roughness (adapted from Meybeck *et al.*, 2001).

Landscape	***Total area***	***Mean elevation in any cell***	***Relief Roughness (RR)***	***Examples***
Mountains (Extremely dissected - poorly dissected)	33.3 Mkm^2	Very-high altitudes: 4000–6000 m or higher	40‰ < RR	Most of the Himalayas Parts of the European Alps
		High altitudes: 2000–4000 m	40‰ < RR	European Alps Pyrenees The Western Ghats New Zealand Alps
		Low-medium altitudes: 500–2000 m	20‰ < RR	Ural Australian Alps
Hills (Highly dissected - poorly dissected)	30.5 Mkm^2	200–500 m	20‰ < RR < 160‰	Arthur's seat, Scotland Crook hill, England Foothills of the Western Ghats
Platforms		200–500 m	20‰ < RR	
Plateaus (Poorly dissected)	16.8 Mkm^2	500–6000 m	5‰ < RR <40‰	Tibet and the Altiplano
Lowlands (Flat)	19.2 Mkm^2	0-200 m	5‰ <RR <20‰	Thar desert Great Erg Kimberley Plateau Gobi Desert Brittany South Sweden
Plains (Subhorizontal)	33.2 Mkm^2	Three types: Low, midaltitude, and high plains Usually, the non-glaciated, subhorizontal surface	RR < 5‰	Western European plains Great China plain Indo-Gangetic plain Mesopotamia Congo Basin Gulf of Mexico Murray Basin

According to the classification in Table 2.1, the foothills of the Western Ghats, where *suranga* are found, are classified as hills because the elevation of these foothills often ranges from 100-300 metres with steep elevation and some small scale plateaus.

Rugged terrain, unique climate, and harsh living conditions in the mountain regions have forced mountain communities to develop various social and cultural responses and adaptative techniques that may have evolved over the *longue durée* (Vincent, 1995; Braudel & Mayne, 2005; Mukherji *et al.*, 2019). The mountain communities around the world developed and adapted responses over generations to sustain life on rugged mountain landscapes, example of some of these adaptations include unique community managed traditional water harvesting systems for drinking and agriculture, terraced farms, raised bed agriculture, mixed farming, agro pastoralism and vertical control practices (Vincent, 1995, p. 5; Kreutzmann, 2011; Yannopoulos *et al.*, 2015; Mukherji *et al.*, 2019; De, 2021; Singh *et al.*, 2021, pp. 21-22). Vertical control systems are a coordination strategy for livelihoods adopted by communities to adapt to graduating altitudes along slopes (Kreutzmann, 2011; Mukherji *et al.*, 2019). They are a crucial characteristic of mountain communities because they demonstrate that social relations and local actions in mountain regions are essential (Vincent, 1995, pp. 6-7; Leibundgut, 2004, p. 79) and include such things as collaborative practices of water management for irrigation, soil erosion, pest control, and interaction between communities in mountain regions and the lowlands (Kreutzmann, 2011). Therefore, different interest groups may perceive development strategies in mountain regions in diverse ways (Mukherji *et al.*, 2019). For example, natural scientists may use environmental factors such as altitude, vegetation, physical fragility, and the vulnerability of mountains to draw up development plans, rather than vertical control, cultural adaptation, and continuity within the communities, as prioritised by social research (Vincent, 1995). For a comprehensive and holistic approach, this project collected both types of data to understand farmers' strategies towards using *suranga* and look for any patterns of vertical control.

Vincent (1995, pp. 12-13) suggests that cultural adaptation in mountain regions is usually based on two practices: principles and values, rationality and pragmatism. The theme of principles and values means general practices where communities are indirectly driven by a set of practices guided by the principles, such as humanity, conservation of the natural environment, and social harmony, usually reflected in a community's socioeconomic and cultural aspects (Knez & Eliasson, 2017; Mukherji *et al.*, 2019). The second theme, rationality and pragmatism are primarily based on economic subsistence and the exploitation of natural resources as required to support survival and improve livelihoods. Mountain communities usually show a combination of both the theme of practices, principles and values, rationality and pragmatism. For example, mountain communities found in India (De, 2021), Pakistan, Nepal (Gautam *et al.*, 2017), Bhutan, Peru, Bolivia, and Ecuador, rely mainly on the mixed crop farming system through a combination of livestock rearing, crop cultivation, and agroforestry for their subsistence (Vincent, 1995, p. 15; Yannopoulos *et al.*, 2015; Rajan & Shah, 2020). Crops such as various grains, vegetables, fruits, and fodder for the cattle are the main crops (Rajan & Shah, 2020) in mountain environments. Farmers often sell these commodities in the nearest markets to earn money to purchase commodities and requirements (*ibid*.). Table 2.2 demonstrates how the study area fits within this mountain crop typology.

Table 2.2: A list of common crops from mountain regions compared to the crops in the study area
(Vincent, 1995, p. 15; Kumar & Krishna, 2015).

Type of crops	Crops	Crops in the study area
The staple food, residue used for livestock	Paddy Grains: Wheat, buckwheat, barley, corn, millet, sorghum	Paddy
Staple and cash crop	Potatoes, other tubers, vegetables, fruits, herbs, spices, medicinal plants Various types of beans Sugarcane	Tubers, seasonal vegetables, fruits, spices Sugarcane
Agroforestry	Fruits, nuts, timber, silk, coffee, rubber, banana, cocoa, cotton	Areca nut, coconut, coffee, rubber, banana, cocoa

Land terracing for agriculture has been used as an adaptation feature on mountain and hilly geography since ancient times to conserve soil and water by stabilising the hill slopes and reducing flood, runoff and soil erosion (Widgren *et al.*, 2016; Wei *et al.*, 2016; Mukherji *et al.*, 2019), and to accumulate sufficient depth of soil for agriculture, accumulate biomass, conserve water in dry regions by control of irrigation and drainage in wet areas, and increase agricultural yield (Vincent, 1995, pp. 22-23; Deng *et al.*, 2021). In wetter regions, raised bed agriculture is practised to provide drainage and temperature protection. The irrigation in terraced farms is usually done with canals. The various cultural adaptation examples from the mountain regions predominantly identified by Vincent (1995, pp. 78-87) and others (Mukherji *et al.*, 2019; Deng *et al.*, 2021) have been summarised in Table 2.3. This study searched for evidence of cultural adaptation in the *suranga* system, observing such practices as terracing and soil and water conservation to see where they fit this typology.

Table 2.3: Cultural adaptation examples from the mountain regions
(Vincent, 1995, pp. 78-87; Mukherji *et al.*, 2019; Deng *et al.*, 2021).

Adaptation strategies in mountain agriculture	**Explanation**
Vertical control	Vertical control is the primary adaptation strategy in the mountain region, for example, the riparian rights of water resources for irrigation in mountain regions.
Mixed farming strategies	Traditionally, livestock and agriculture have been used complementarily in mountain agriculture; however, this nexus is changing, for example, land-use change, technology development for agriculture and irrigation, use of inorganic fertilisers, and grazing restrictions in forests, and availability of fodder in the market have weakened this dependency.
Acclimatisation of crops and cattle	The crops and livestock in mountains regions are accustomed to the local climate conditions, thus form an integral part of mountain agriculture. For example, yak and alpaca are the most favourable livestock in very high altitudes. Similarly, specific tubers and pulses are grown in mountain regions, which can withstand low temperatures.
Indigenous techniques and technologies	The development of locally suitable agriculture, land management, water harvesting and irrigation, is a response to challenging environments in mountain regions. Terraced and bunded farms, manuring and composting, and the development of traditional water harvesting systems are examples.
Community management	Cultural, communal management of resources, especially using forests for grazing and other resources, human resources, and water resources for irrigation across catchments, is the crucial adaptation strategy to minimise risk and protect resources in mountain territory.
Religious or mythical association to local history and natural resources	Communities in the mountain regions often have religious and mythological beliefs, which are predominantly interlaced in the society in the form of ritual and beliefs, and often implicitly governs their social, cultural, and agriculture patterns. For example, the religious seats and sites of gods and goddesses are often associated with the natural resources within the geographical boundaries, such as forests and water, and are of paramount importance to society.
Sex specific allocation of responsibilities in agricultural communities	Traditionally, in agricultural communities, specific responsibilities are usually allocated to men and women. However, in high mountain regions, such allocation may not be distinguishable. For example, women are mostly assigned household duties, while the men usually assigned management of agriculture and irrigation in the farms. However, the absence of male members, because of migration for trade and off farm employment, allows women to take charge of man dominated jobs. This division gradually disappears with increased access to roads and means of transport to other communities, access to education, and economic development and opportunities.
Off farm employment as an additional source of income	In addition to agriculture, part-time or full-time off farm employment is another common source of food and income in mountain communities; however, migration can cause farmworkers' scarcity.
Strong association with their land	Economic limitations may force migration from mountain regions, but strong cultural links and community spirits have often been observed in mountain communities, which manifest in affection for their land and culture (Knez & Eliasson, 2017; Mukherji *et al.*, 2019).

The development approaches for hill and mountain regions are usually different from lowlands because mountain regions are characterised by high physical, environmental, and cultural diversity. However, the development lessons from other mountain regions around the world can be used to design strategies for development because there are often environmental and social commonalities that can facilitate the exchange of ideas for the development of mountain regions (Vincent, 1995, p. 1). These commonalities were integrated into the model of hill irrigation presented in section 2.1 that was used to provide an analytical framework for this study to understand the development trajectory of *suranga*. The next section presents the need for irrigation in mountain regions and a typology of hill irrigation systems.

2.1.2 A typology of hill irrigation systems

Mountain crops are often rainfed; however, precipitation can be seasonal, irregular, or scarce in arid and semi-arid mountain regions. In such conditions, irrigated crops are cultivated (Kreutzmann, 2011). Irrigation is essential for crop growth to maintain soil moisture for crops during the dry periods (Vincent, 1995, p. 15; Hussain, 2007; Majumdar, 2014, p. 7). Thus, irrigation is an integral part of mountain and hill farming systems because it is linked directly to livelihood strategies of agriculture, either to sustain life or to earn money by selling crops in the market to buy commodities for subsistence (Kreutzmann, 2011; Mukherji *et al.*, 2019). Sometimes, trees and fodder are grown on common lands, either rainfed or irrigated using shared water resources. In high altitudes, irrigated agriculture also protects against frost and low temperature (Perry, 1998; Vincent, 1995, p. 15; Mukherji *et al.*, 2019). However, excess irrigation can cause various soil issues such as waterlogging, increased anaerobic conditions, soil erosion, loss of soil fertility, and nutrient imbalance (Hussain, 2007; Majumdar, 2014, pp. 14-15). An efficient irrigation supply, in association with other crop improvement strategies such as high yield varieties, organic and chemical fertilisers, use of technology, mixed cropping, and plant protection, can significantly improve the yield and economic returns (Vincent, 1995; Perry, 1998; Hussain, 2007; Majumdar, 2014, pp. 7-8). However, there can be construction and management challenges for farms and irrigation infrastructure on rugged mountain geography that can all impact the efficiency of a system (Table 2.4). All the above characteristics and challenges were explored in relation to improving the present knowledge of the *suranga* system.

Table 2.4: Challenges faced by communities living in mountain and hilly regions (Vincent, 1995; Mukherji *et al.*, 2019).

Type of challenges	**Examples**
Construction operation	Lack of appropriate technology, resources, and skills in the construction of an irrigation system
Technical issues	Issues related to maintaining gradient and headworks with rugged and steep slopes Water storage or distribution capacity
Distribution and maintenance issues	Frequency of distribution Regular maintenance issues

Thus, hilly regions make a hill irrigation system a complex social and environmental phenomenon (Mukherji *et al.*, 2019). For example, hill topography usually does not allow the construction of large water storage structures; therefore, networks of small cisterns and ponds are widely found in hill irrigation systems, which collect water either during the night and are used for irrigation in the morning or *vice-versa* (Vincent, 1995, p. 54). The hill hydrology is influenced by natural geographical features such as slope, elevation, drainage, geology, and artificial features such as land terracing, bunding of streams, water recharge, and water storage structures (Vincent, 1995, p. 45; Wei *et al.*, 2016; Mukherji *et al.*, 2019). For example, in very high altitude mountain regions, surface water is found in meltwater and glaciers, and in lower altitudes, precipitation and river flows are the prime sources of surface water in hilly regions (Mukherji *et al.*, 2019). Therefore, geographical location and scale of *suranga* are essential to study alongside the sources of water that are captured.

Any irrigation system is composed of physical and social infrastructure. The physical infrastructure includes water distribution and control structures and the water harvesting technique (Mukherji *et al.*, 2019). The social infrastructure includes the rules and procedures for fair distribution of the irrigation system (Vincent, 1995: Crook & Jones, 1999; Mukherji *et al.*, 2019). Hill irrigation systems can be broadly grouped into eight categories according to the source of water and transportation infrastructure (Table 2.5).

However, other classification systems based on hydraulic and physical characteristics are placed into a broad category of lift, gravity, diversion, and water harvesting systems.

Table 2.5: Common types of irrigation methods found in mountain and hilly regions (adapted from Vincent, 1995).

Type of irrigation systems	Main characteristics with examples
Offtake/diversion	This is the most common irrigation systems found in hilly regions. Water is usually diverted through canals and weirs from water sources situated on high altitudes such as rivers, glaciers, high altitude lakes, and springs. These flexible and minimal design systems are made of local raw material, with maintenance, are overall highly efficient systems, but water loss through seepage in long canals may occur. These are of two types, river valley offtake and slope offtake systems. *Muang faai* system in Thailand, *Zanjeras* systems in the valleys in the Philippines, Irrigation systems in Nepal, Peru and Indonesia, Rift valley slope systems in Kenya and Tanzania, Irrigation systems in the Colca Valley in Peru, Hill canals in India, Bhutan, Pakistan, various meadow irrigation techniques in European Alps (Leibundgut, 2004) including *bisses* irrigation systems (Crook & Jones, 1999) are an example of offtake irrigation systems.
Underground canal	Underground tunnel with vertical shafts at regular intervals harvest water from shallow depth, subsurface aquifers. Water loss because of evaporation is low because water is transported underground. These tunnels are primarily found in hill slopes, valleys, and foothills areas, and the construction of these canals requires skilled people in excavation and hydrology. *Qanat* is an example of underground canals systems found in Asia, the middle east, and Africa.
Spate	In Spate systems, water is harvested from seasonal rivers and ephemeral streams during the flooding season by diverting water through canals at higher altitudes, flooding fields and bunding fields in the valleys, and seasonal rivers and streams (seasonal check dams) according to the altitude. These are mainly found in foothills and valleys in arid regions with seasonal water scarcity for agriculture. These systems are like offtake systems, but there are fundamental differences in hydraulic, institutional, and operational characteristics between spate and offtake systems. These systems have intricate designs because of seasonal uncertainty in water flow, complex water rights, and prone to disputes. Example of spate systems are Wadi Dahr, and Wadi Rima in Yemen, Oaxaca and Teohuacan valleys in Mexico, the Sonoran Desert in North America
Collection	In collection systems, water from small water sources, such as a spring, is collected in small cisterns and ponds, and the water is utilised daily. Sometimes, the springs are excavated to increase the supply of water (Ein Mor & Ron, 2016; Yechezkel *et al.*, 2021). Irrigation systems in Yemen and Morocco are an example of collection systems.
Storage	In storage systems, water is usually stored annually in a reservoir and large tanks for dry seasons. Storage systems are not popular in high altitudes but mainly in valleys, foothills, and low elevation dissected terrain. The largescale storage systems require support from the broader community for smooth institutional and technical management, while

	small storage systems are often privately owned. The scale of these systems is often governed by geography, water catchment, and management. Some example of storage systems is tank systems in India and Sri Lanka, large storage systems in the valleys in Bolivia, Peru, Ecuador, Chile, Mexico, China, Pakistan, and Afghanistan.
Lift	Lift irrigation systems are mostly of two types: open channel lift systems that lift water from a surface water source such as rivers and streams; groundwater based lift systems that lift from a subsurface water source such as well, well on a riverbed, and river terraces (Yannopoulos *et al.*, 2015). Low initial cost, but the running cost may be higher because of electric or fuel pump to lift water. Lift systems are not popular in hilly regions. Irrigation systems in Himachal Pradesh in India, wells in Altiplano in Bolivia are examples of lift irrigation systems.
Combination	These systems are mainly extensions of offtake systems. A combination system may use water from more than one sources, such as rivers, streams, springs, and runoff (Yechezkel *et al.*, 2021). Combination systems are often seasonal and are primarily found in arid regions. Some examples are Pimampiro in Ecuador, Lari in the Colca Valley in Peru, Quinua system in the Ayacucho valley in Peru.
Wetland	Wetlands usually do not require any irrigation because of sufficient moisture available in the soil because of the availability of water table at low depths. Wetlands are found in mountain agriculture in flooded depressions, raised beds, and recession agriculture. *Bas-fonds* system found in highlands of Madagascar, valley swamps in hilly regions of Rwanda, *khadins* in Northern India, and wetlands of Ethiopia are some examples of wetlands.

It is important to understand where *suranga* fit within this hill irrigation typology because the existing knowledge of hill irrigations systems, coupled with the findings from this study could be utilised to improve the current management and organisation of the *suranga* system.

Non-irrigation uses of water resources in hilly areas are another aspect of the hill irrigation system, such as water mills, drinking, domestic water supplies and renewable energy through hydro-electric power (Vincent, 1995, p. 52; Crook 2001; Megdiche-Kharrat *et al.*, 2020). Drinking water sources are usually separate from irrigation water supplies to maintain water quality and avoid conflicts (Vincent, 1995, p. 52; Crook 2001). Maintenance costs are usually high in hill irrigation systems, especially with long canals; therefore, the use of traditional and modern water lifting devices (Yannopoulos *et al.*, 2015), plastic pipes, drips, and sprinkler systems were reported to be increasingly used by Vincent (1995, pp. 55-57). Water losses through evaporation from open conveyance channels can be high, and on steep slopes, it can cause soil loss; moreover, rodents and crabs can cause further damage to the water channel by digging holes leading to seepage water loss. Invasive grasses can reduce the dimensions of the channel, further decreasing the conveyance efficiency of the whole water distribution system, especially in long canal networks (Mukherji *et al.*, 2019). Thus, there is a need for careful management of these channels. From this interpretation, there is the expectation of finding evidence of careful management of conveyance channels in the *suranga* system to minimise water loss and increase water availability. The following section explores this question, further understanding of how to manage irrigation systems in mountain regions.

2.1.3 Managing irrigation systems in mountainous and hilly regions

Collective action is a key characterises of mountain and hill communities as the demand for collective action is more pressing in agrarian mountain and hill communities and their irrigation systems because of geographical complexities in highlands result in individuals usually not being able to develop and run an irrigation system without help (Vincent, 1995; Kreutzmann, 2011; Dörre & Goibnazarov, 2018; Suri, 2018; Mukherji *et al.*, 2019). Moreover, the construction cost of mountain/hill irrigation systems can be high, making it impossible for an individual to bear all the costs. Collective action results in an investment in land to achieve food security and potentially to produce a surplus and raise profit by increasing productivity (Vincent, 1995; Dörre & Goibnazarov, 2018). Therefore, the stakeholders in a collectively managed irrigation system are usually committed to looking after their irrigation systems because of the economic incentives and the externalities involved (Vincent, 1995, p. 95; Kreutzmann, 2011). Therefore, mountain and hill irrigation systems are usually found to be collective systems with a set of rules and procedures for their management, including the fair allocation and scheduling of water for different crops (Kreutzmann, 2011; Dörre & Goibnazarov, 2018; Mukherji *et al.*, 2019). However, the working of a collective system in mountain and hilly regions can be challenging because of the high number of resources required to develop and maintain the irrigation systems and water allocation to small fields distributed over steep hill slopes (Vincent, 1995, p. 92; Dörre & Goibnazarov, 2018). From this interpretation, there is an expectation of finding evidence of collective action and management in the *suranga* system. If the *suranga* system is found to be community managed then data from other community managed water systems from across the globe can be used for comparison and or can be applied to this study in order to improve the current management of the *suranga* system.

Irrigation systems usually have two aspects of governance, operational and institutional: the former deals with the development and management of irrigation systems, while the latter are the stakeholders or communities who run these irrigation systems (Vincent, 1995, p. 92; Suri, 2018). The institutions also directly or indirectly develop rules and procedures for the smooth running of the irrigation systems (Kreutzmann, 2011; Dörre & Goibnazarov, 2018). These local institutions may have evolved because of water crises or water conflicts (Dörre & Goibnazarov, 2018) or may have originated from more critical cultural institutions within the communities (Alokhunov, 2021). These irrigation institutions may be easily recognised as a distinct body within a community or may be highly interlaced within the communities' cultural organisations (Vincent, 1995, pp. 92-93; Mukherji *et al.*, 2019). The typical vital principles underpinning a collective action are religion, economic interest, kinship, and ecology (Vincent, 1995, p. 93; Dörre & Goibnazarov, 2018). For example, a community may come together to build a cooperative irrigation project to improve their agriculture and economic condition (Dörre & Goibnazarov, 2018) but also to control and allocate the water resources amiably (Kreutzmann, 2011). Therefore, two different social and economic domains (Vincent, 1995, p. 92) are involved in any cooperative project. However, a real life cooperative system may have multiple and usually interwoven underpinning principles (Dörre & Goibnazarov, 2018). The basic conceptual models of irrigation systems that can be applied to hill irrigation systems such as *suranga* are summarised in Table 2.6.

Table 2.6: Conceptual models of irrigation management in the mountains and hills (adapted from Vincent, 1995).

Conceptual models of management	Components	Focus of inquiry
Irrigation management	Water use Design principles Control structures Organisation	Why is water harvested or controlled? How is water harvested? What is the source of water? How is water allocated or shared? What are the design principles and structural properties of *suranga*? How these structures are made, and who make these structures? How is this irrigation system operated and maintained? What is the decision making process in these systems?
Hydraulic tenure	Property and water rights Tenure principles	Who gets the water? How is water shared? What are the properties of water rights? Can water rights be conferred, claimed, or sold? Are water rights transferrable? Are water rights transferred over generations with the land?
Governance of irrigation systems	Making of institutions for irrigation Legal framework Constitutional principles of the groups Regulation Conflict resolution	Are there any institutional structures associated with *suranga* irrigation? Do *suranga* have any legal protection How one can be eligible to get water from these irrigation systems, and who will decide this? What are the rules and procedures for the functioning of these systems, and how these rules are decided? Is there a conflict resolution system?

The conceptual models mentioned above of irrigation management indicate that irrigation systems usually have rules and procedures to avoid conflicts and efficient conflict resolution procedures. Thus, it is essential to search for evidence of these types of organisational arrangement in the management of *suranga*. In some cases, state interventions are found to weaken the collective management systems by indirectly overtaking them, with stakeholders not having any obligation for the upkeep of an irrigation system but just paying for their use, which weakens the collective management of the systems. In other cases, an intervention may not be able to meet the expectations to set and define the tenure and governing rules for the systems because of limited understanding of the existing systems (Dörre & Goibnazarov, 2018), which may cause apathy among the collective users and destroy the existing community dynamics for the management of the irrigation systems. Therefore, this study explored the levels of government intervention into the *suranga* system alongside the tenurial arrangements linked to ownership.

Similarly, changing agrarian pattern, interventions such as migration and change in demographic and technological advancements can negatively impact the community management of irrigation systems (Vincent, 1995, p. 95; Kreutzmann, 2011). In addition to the restrictions placed on hill irrigation systems by the physical environment, they can also have complex socioeconomic arrangements developed over a long duration (Mukherji *et al.*, 2019). There may be various objectives for the development of irrigation systems in an area, such as to increase food security for the community, to prospect new lands and to increase the cultivable area to increase income or food security, increase water availability for the community, and to increase individual agricultural outputs (Vincent, 1995, pp. 96-97; Alokhunov, 2021). If water sources are developed collectively, then water rights are shared (Dörre & Goibnazarov, 2018); however, the rights still may be prioritised for staple crops in specific seasons or during droughts (Vincent, 1995, p. 97). Similarly, the water rights may vary according to the elevation and location on a hill slope. Thus, analysis of the legal framework for water right allocation and scheduling is a key component of any water management system, therefore it becomes essential to explore the legal framework for water right allocation and scheduling in the *suranga* system.

In summary, community management is an essential characteristic of hill irrigations systems; therefore, the next section focuses on the theoretical concept of community management of the commons to better understand how to analyse the management of *suranga*.

2.2 Community management of commons

As seen in the previous section, community management is a crucial aspect of hill irrigation systems (Vincent, 1995; Crook 2001; Kreutzmann, 2011; Dörre & Goibnazarov, 2018; Mukherji *et al.*, 2019; Alokhunov, 2021); however, some significant issues are often associated with the community management of natural resources. In the concept of the tragedy of the commons, Hardin (1968) suggested that with the increasing demand for natural resources caused by population increase, the users of a commons attempt to increase their profits, but the loss is shared by all the users, which is a fraction of the individual profit for the user who would be overexploiting the commons. Thus, unfair users get an advantage at the loss of fair playing users. As a result, all the users attempt to minimise their loss by maximising their commons' exploitation in an unfair way (Hardin, 1968; Dietz *et al.*, 2003). Therefore, the users of a commons will be trapped in an economic dilemma where individual profit and loss will outweigh the community action, leading to the collapse of the common. For example, in India's present context, groundwater as a shared resource is readily available for exploitation by the users. In this case, the absence of effective groundwater abstraction policies will mean that users will try to abstract as much water for their use and irrigation to maximise their economic returns. As a result, all the groundwater will be exhausted at some point, which is a classic example of the tragedy of the commons. The commons' tragedy can only be avoided by relinquishing commons or having private management, such as government rules, or permit allocation with a fee (Hardin 1968). The idea of relinquishing the use of commons is not practical in the present scenarios, when the world population has surged from 3 billion in 1960 to 7.7 billion in 2019 (Roser *et al.*, 2019) and is projected to be over 9 billion by 2050 CE (Leridon, 2020; Molotoks *et al.*, 2020), and ~11 billion by 2100 CE (Hara, 2020), and the demands of natural resources utilisation are at the highest level ever. Thus, according to Hardin (1968), the tragedy of commons is an inevitable stage of every common.

However, Ostrom (1990) refutes the idea of the universality of the tragedy of commons but suggests that the tragedy of common pool resources (CPRs)[9] can be avoided by allowing stakeholders, in the form of groups, to manage their CPRs. The users in the group may still devise ways to evade the guidelines to maximise their profits (Dietz *et al.*, 2003), therefore supporting interventions and interactions in the form of a set of rules and procedures are necessary (Ostrom, 1990). These rules and procedures allow the group users to interact and cooperate (Basurto & Ostrom, 2009) to manage their CPRs efficiently, with the aim of avoiding the commons dilemma (Meinzen-Dick *et al.*, 2002; Dietz *et al.*, 2003; Gerber *et al.*, 2008). For example, the collaboration of different countries at the global levels has shown positive results, especially in environmental conservation, and attempts to decrease carbon emissions globally, and global attempts to eradicate diseases (Dietz *et al.*, 2003), such as poliovirus, and the recent covid-19 virus. However, in the present world, absence of robust governing rules in institutions, CPRs are likely to collapse against the challenges presented by increasing human population, consumption, and development in technologies (Hardin, 1968; Dietz *et al.*, 2003, p. 1907). For example, groundwaters in several developing countries, including India, have already decreased to an alarming level because of increased demand by a growing population coupled with technological developments that have made this water abstraction possible. Ostrom (1990, p. 90) identified a set of following design principles that were often found in successful community managed systems.

[9] Hardin (1968) says it "commons", Ostrom has used the term Common-Pool Resources (CPRs), and other (Fabricius & Collins, 2007) have referred as Community-based Natural Resource Management (CBNRM).

1. Clearly defined boundaries
2. Congruence
3. Collective choice arrangements
4. Regular monitoring
5. Graduated sanctions
6. Conflict resolution system
7. Minimal recognition of rights to organise
8. Nested enterprises

These eight principles were further modified into five key characteristics to effectively manage commons, which are: easy and cost efficient monitoring of resources and their consumption by the users; the steady rate of changes of resources, users, social, economic, and technology conditions; regular interaction, and strong social networks among users and remaining stakeholders; a system, to add new users, and to prevent nonusers (outsiders) from harvesting the common resource; and effective monitoring and rule enforcement (Dietz *et al.*, 2003, p. 1908). However, that even community based management based on the above principle is not the universal solution for the problems of the commons, but a continuously diagnostic, transformative approach, based on the above design principles can help avoid potential conflicts (Basurto & Ostrom, 2009, pp. 55-56).

Success stories of community management of CPRs made decentralisation policies globally prevalent in the mid and late 20th century, and the aim of decentralisation of power, especially in developing countries, is to achieve development, conservation of natural resources, and to provide government services to the public (Agrawal & Ostrom, 2001; Meinzen-Dick *et al.*, 2002; Mishra *et al.*, 2011; Chaudhry, 2018, pp. 15-17; Mukherji *et al.*, 2019; UNDP, 2020, p. 150). Decentralisation is associated with the devolution of power and rights from the state to the local governments and indirectly communities[10] to increase overall efficiency and equity by providing increased privileges

[10] A village is usually the most primary unit in decentralisation process (Agrawal & Ostrom, 2001).

to the stakeholders (Agrawal & Ostrom, 2001; Meinzen-Dick *et al.*, 2002; Nagrah *et al.*, 2016). The key idea was to let the communities manage their shared resources locally and more effectively than a state owned system (Parthasarathy, 2000; Agrawal & Ostrom, 2001; Meinzen-Dick *et al.*, 2002). In decentralisation, the state cedes rights of decision making and implementation to the users and their institutions at lower levels in an administrative hierarchy, and now these users can make policies and can take decisions about managing these shared sources (Agrawal & Ostrom, 2001, pp. 489-489; Mishra *et al.*, 2011).

The main types of property rights associated with a common pool resource can be withdrawal; management; exclusion; alienation (Agrawal & Ostrom, 2001, pp. 489-493). The right of withdrawal means access to a shared pool resource to harvest, for example, the individual right to take water from a community managed water resource. When the users have a further right to make policies and implement these policies to manage the shared resources, the right is known as management. Furthermore, exclusion rights mean the right to decide how and to whom the withdrawal can be provided. Alienation is the right to sell or lease individual withdrawal, management, and exclusion rights (Agrawal & Ostrom, 2001, p. 489). In a hierarchy arrangement, withdrawal is the least powerful of the four property rights, while alienation is at the highest property rights level (Agrawal & Ostrom, 2001, p. 490). Withdrawal is mainly the right at the operational level of a resource, and for example, in a centralised water system, anyone can apply and get the right to withdrawal after paying a set fee to the provider, which is usually the state. In such a centralised system, the management, exclusion, and alienation rights are highly likely to be with the state, not with the users. However, in decentralised water or community water systems, the local users or community may decide the withdrawal property right criteria (Mukherji *et al.*, 2019). This group may have the rights to set the management, exclusion, and alienation of property rights. Therefore, in this case, withdrawal property right may not be achieved by a user just only by paying a fee, but it may require a regular contribution in the form of cash or kind. In a private resource, all four property rights are usually vested in the ownership (see Figure 2.2).

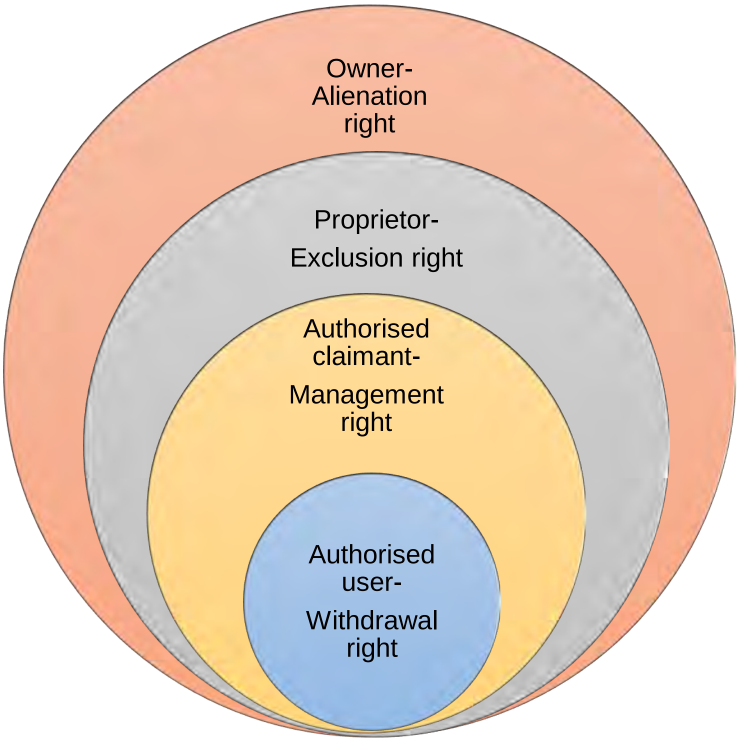


Figure 2.2: Resource ownership rights with reference to stakeholder's position and their hierarchy
(Adapted from Agrawal & Ostrom, 2001, p. 491).

A system can be fully decentralised if the state devolves all four ownerships to the users, which is an ideal case of decentralisation because in this case, the users can make, decide, and implement their policies, which are likely to be highly efficient because these are usually based on local circumstances (Agrawal & Ostrom, 2001, pp. 489-490; Meinzen-Dick *et al.*, 2002). However, it has been found that successful community systems and often decentralised systems usually have only proprietary level rights, which are enough for an efficient operation and management of a shared resource in the long term (Agrawal & Ostrom, 2001, pp. 489-493). In the real world, community managed systems are often found to have minimum proprietary level rights so that they can design, implement, manage, and enforce their rules (Agrawal & Ostrom, 2001, pp 489-490). However, in proprietary level rights, users cannot sell or lease their proprietary (including withdrawal) rights, but the rights can be bequeathed to the family members (*ibid.*). Occasionally, an individual, a private corporation, a government, or a community group may have an owner level of property rights, which means that in addition to the proprietary level, the user(s) can sell or lease their property and associated rights (Agrawal & Ostrom, 2001, pp. 489-492).

In summary, the best results of decentralisation can only be achieved by bestowing the users' maximum property rights to allow them to design, manage, and undertake enforcement in their community managed system. (Agrawal & Ostrom, 2001, pp. 508-509). Furthermore, active participation of users in community managed systems is necessary for the efficient and smooth functioning of a community system (Meinzen-Dick *et al.*, 2002; Dietz *et al.*, 2003), which can be achieved by devolving the management rights and power to users, which is also the quintessence of the community management (Agrawal & Ostrom, 2001, pp. 508-509).

Some other factors, such as scale, temporal changes, and uniqueness of commons, play a critical part in the success of community managed systems (Meinzen-Dick *et al.*, 2002). The scale of a commons is critical in deciding the scale of the institution; for example, the oceans cannot be managed by a village level group. Likewise, global and transboundary issues, such as climate change, cannot be solved at local levels (Dietz *et al.*, 2003). Similarly, some of the centuries old community systems failed because they could not evolve to the rapid changes when exposed to the outer world (Dietz *et al.*, 2003, p. 1907). Therefore, there are some basic principles but no universal approach that will successfully apply to all commons, but a customised, diverse, adaptive management approach must effectively manage the commons (Dietz *et al.*, 2003). Continuous dialogues can only achieve such an adaptive approach among the stakeholders, supported by continuous experiments with the design of institutions, continuous learning from failure and success are necessary for any thriving community institutions at any level (Dietz *et al.*, 2003, p. 1907).

Freshwater availability and water resilience for the community is central for sustainable development, socioeconomic stability, ecological integrity, and sustaining life (Rockström *et al.*, 2014; Singh *et al.*, 2021). Thus, based on the interpretations presented above, the level of community management will provide a measure of the success of *suranga* and insight into the resilience and the sustainability of the hill irrigation system amongst a remote and marginalised rural community in the foothills of the Western Ghats. The following section explains further the concepts of resilience and sustainability that are being embraced in this study.

2.3 Resilience and sustainability framework

This section presents the frameworks used in this study to evaluate the resilience and sustainability of the *suranga* system for present and future. It appears that both the concepts are highly abstract and have various definitions (Gabella & Strijker, 2018, p. 2). A critical difference between the concepts of resilience and sustainability is that resilience aims at flexibility and adaptability of a system at any temporal scale whilst sustainability is implemented to achieve desirable outputs from a system over a longer temporal scale that aims at future generations (Saunders & Becker, 2015; Marchese *et al.*, 2018, p. 1279). Resilience is the characteristics of a system to resist or adapt against unexpected disturbances to remain functional (Wilson, 2018; Walker, 2020), whereas sustainability is also often associated with the desired outcomes and longevity of a system (Marchese *et al.*, 2018). The consequences of resilience are maintaining the operation of a system, irrespective of its outcomes, during and after periods of disturbances (Walker, 2020).

In contrast, a sustainable system is presumed to boost the quality of life, social equality, and improved environmental conditions for future human generations (Marchese *et al.*, 2018, p. 1279). Thus, a water management system is deemed resilient if it can continue to yield water and can avert or minimise the impact of any type of endogenous or exogenous disturbances or changes inflicted upon it; similarly, a water management system can sustain if it can continue to provide water efficiently to the current and future generations without having a significant impact on the environment: (Walker *et al.*, 2004). Past research (for a review, see Marchese *et al.*, 2018) has used the concepts of resilience and sustainability in several combinations with four popular trends found in the literature:

1. Resilience and sustainability often treated as interchangeable concepts, for example, studying communities from the perspective of disaster management (see Rose, 2011) and land use planning (Collier *et al.*, 2013). Similarly, some suggest an approach that integrates sustainability and resilience (Fahimnia & Jabbarzadeh, 2016).

2. Resilience (or adaptive capacity) as a component of sustainability (Reynard *et al.*, 2014, pp. 9-10; Saunders & Becker, 2015; Walker *et al.*, 2004; Schneider *et al.*, 2015; Gabella & Strijker, 2018; Davidson *et al.*, 2019)
3. Sustainability is conceptualised as a subset of a broad resilience theory (Ahi & Searcy, 2013; Bansal & DesJardine, 2014; Wilson *et al.*, 2018)
4. Resilience and sustainability as no interchangeable concepts (Wilson, 2018), which may be correlated (positively and negatively) or non-correlated concepts according to the context (Marchese *et al.*, 2018)

The association between resilience and sustainability has been debatable (Derissen *et al.*, 2011). However, from the above four categories, it seems that there is a similarity between resilience and sustainability (Saunders & Becker, 2015), and the degree of dependences often depends on the (subjective) contexts selected to study. In this study, resilience and sustainability both are used as two individual concepts: the resilience evaluates the capacity of the *suranga* system to maintain its characteristics against any endogenous and exogenous disturbances/changes imposed upon it; while the sustainability of the *suranga* systems based on four components aims to assess the longevity of the system. The detailed reviews of the resilience framework (section 2.3.1) and the sustainability framework (section 2.3.2) used in this study are presented next.

2.3.1 A resilience framework for *suranga*

The term resilience has gained popularity and is used widely in various research disciplines, legislative settings, community levels, and personal contexts (Saunders & Becker, 2015). The resilience of a system defines the capacity of a system to either return to its state after any shocks or disturbances in the short term or how the system adapts to the shocks or disturbances to return to its original equilibrium conditions or a new stable state, still maintaining its original structure, functionality, identity, and feedback characteristics (Holling, 1973; Walker *et al.*, 2004; Saunders & Becker, 2015; Walker, 2020). Resilience is more about how a system, individual, or community, adapts positively or transforms in responses to future changes and disturbances (Holling & Gunderson, 2002; Gabella & Strijker, 2018, p. 14; Walker, 2020).

Resilience in itself may not be a practical term without the frame of references, which lets one evaluate a system's resilience (Thorén & Olsson, 2017), especially as the resilience of a social system or system with a social aspect can be complicated. There is no universal way of assessing the resilience of social systems, but the concept of resilience for a social system is dependent on the key indicators (Saunders & Becker, 2015, p. 74) of norms, values, and observations, that the resilience is construed upon (Thorén & Olsson, 2017). The norms, values, and observations for resilience for a subject usually emerge from the theoretical perspective of the investigation because a social system studied from various perspectives may produce opposite results depending on the selection of norms, values, and observations. Therefore, assessments of the resilience of such systems depend on the presence or absence of specific characteristics that the assessor has construed to be the sign of resilience (Thorén & Olsson, 2017). An ecosystem's resilience can also be characterised by its reinforcing process and stabilising feedback (Walker, 2020), but regime shift can alter the feedback system by changing its identity, structure, and function (Rockström *et al.*, 2014, pp. 69-93).

If consistently, sufficient water availability is assumed as the standard for *suranga* to be resilient, then the system is resilient under both scenarios. However, suppose the norm of resilience is relevance/significance of *suranga* to the society after the disturbances. In that case, *suranga* are resilient in scenario one but not resilient in scenario two. Moreover, the resilience of a traditional water harvesting system (*suranga* in this study) and a community's resilience that depends on the *suranga* system are two completely different notions. For example, *suranga* may not be resilient, but the community may continue to be resilient by adopting new water harvesting methods. In this case, *suranga* may be classed as a resilient system. On the other hand, suppose *suranga* fail to be utilised, either because they fail to produce water or lose their importance in the community. In that case, the community starts to use alternative methods. Then the community may be interpreted to be resilient because the community adapted to the new conditions.

In summary, the concept of a system's resilience is the prediction of facts from a construed perspective. The same system may appear resilient in one set of norms, values, and observations and may not be resilient in another set of norms, values, and observations. Therefore, the resilience results are dominated by perspective (Thorén & Olsson, 2017). There are several definitions and types of concepts about resilience, but the most common is below.

> "*Resilience is the ability of a system S to absorb some disturbance D whilst maintaining property I." (Thorén, 2014, p. 311)*

In the above definition, a system S with a property I may be assessed as a sustainable system, but system S cannot be assessed for resilience without disturbance D. Therefore, the presence of a disturbance is essential for resilience assessment. The property I of the system S can be either qualitative or quantitative, but it requires a clear explanation based on the system's persistence criterion (Thorén & Olsson, 2017, p. 115).

Resilience can also be defined as a descriptive notion of the dynamics of a system (Derissen *et al.*, 2011; Walker, 2020); thus, the resilience of a system can be explained with Holling's concept of the adaptive cycle (also known as panarchy) made of four phases: growth (r), conservation (K), release/collapse (Ω), and reorganisation (α) as shown in Figure 2.3 (Holling & Gunderson, 2002; Walker *et al.*, 2004). A dynamic system at a stable state between growth (r) and conservation (K) cannot remain in equilibrium for always because once the balance of a dynamic system is perturbed by disturbances (or disasters), the system collapses (Ω) in a quick process. A resilient system then attempts to reorganise (α) itself and find a renewing state in the new circumstances. Once a new stable state is achieved by adapting to the circumstances, the system steadily achieves growth (r). It gradually achieves the conservation (K) phase, the highest energy state for a dynamic system. The system attempts to remain in state K until its equilibrium is perturbed again and falls again into a different state. The front loop from r to K, phase from growth to conservation, is a slow, gradual process, while the back loop from Ω to α is a fast phase of fall followed by regeneration (Holling & Gunderson, 2002).

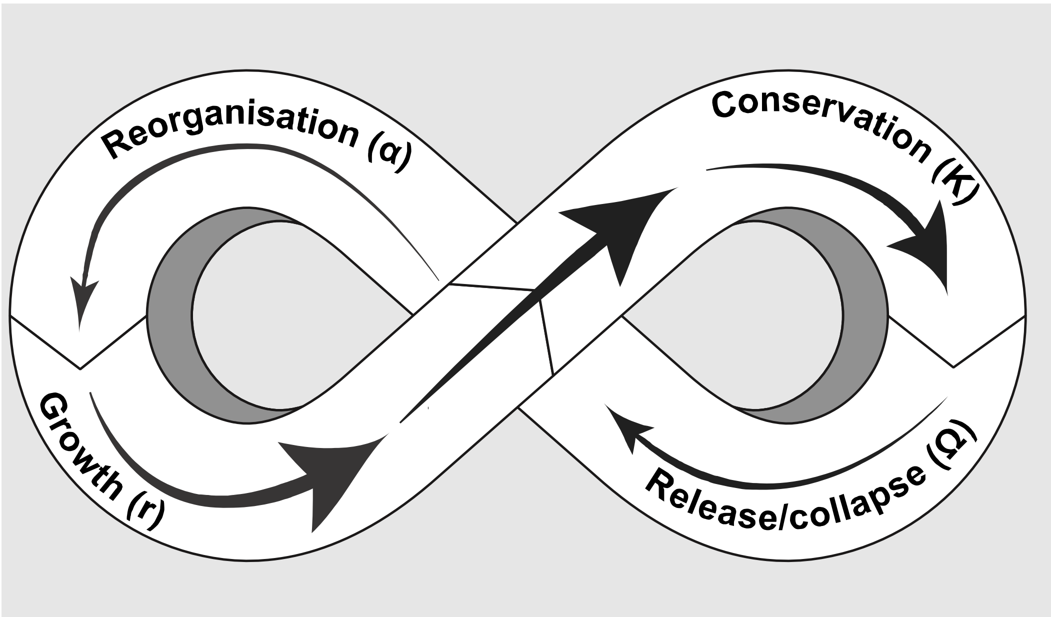


Figure 2.3: Dynamics of a system based on Holling's concept of the adaptive cycle and its four phases (from Holling & Gunderson, 2002).

In this study of a water system, water availability in the *suranga* is the essential criterion for assessing the resilience of *suranga* systems because yielding water is essential to any irrigation system. Therefore, the persistence criteria used in this study for the *suranga* system is based on retaining basic design, function, and feedback properties (Walker & Salt, 2012, p. 3; Thorén & Olsson, 2017, p. 115; Walker, 2020).

I_1 Structural: Will *suranga* survive/adapt their design and structure?

I_2 Functional: Will *suranga* be able to produce water after endogenous and exogenous disturbances?

I_3 Feedback: Will *suranga* still be relevant in the future for water requirements as other water abstraction systems steadily become more popular in the region?

Therefore, the resilience of a water system may be defined as the ability of the *suranga* system to deal with the social, economic, and physical disturbances (Ω) to conserve its functional, structural, and feedback attributes by adapting and reorganisation (α) (Xu *et al.*, 2020). The resilient systems are flexible to absorb the shocks caused by disturbances or changes (Ω), and the flexibility of resilient systems usually appears in the form of adaptation (α) to disturbances to achieve growth (r) and conservation (K) (Thorén & Olsson, 2017; Xu *et al.*, 2020).

There are likely to be several disturbances distributed over a long temporal scale that can cause exogenous perturbation in the *suranga* system, such as climate change (D1) and the change in the community's socioeconomic status (D_2). Data collection and analysis will aim to recognise such disturbances to the *suranga* system. Thus, the resilience of the *suranga* system (S) can be defined as:

> Will a system (S) be able to adapt to the shock caused by disturbances (such as D_1 and D_2) and more to maintain its functions (I_1 I_2 and I_3)?

After the disturbances, *suranga* may remain in the same state. For example, *suranga* may continue to be used as an irrigation system; or may move to a different adaptive cycle, for example, by converting to a different system, or may stop functioning. The pre-disturbance state of the *suranga* system can be made of several characteristics, such as structural, usage, output, and spatial distribution, which must be pre-decided and explained in detail before assessing the resilience of the *suranga* system.

The following section presents the sustainability framework used to evaluate the sustainability of the *suranga* system.

2.3.2 A sustainability framework for *suranga*

> *…that sustainability should not be conceived of as a single concept, or even as a consistent set of concepts. Rather it is more usefully thought of as approach or process of community-based thinking that indicates we need to integrate environmental, social and economic issues in a long-term perspective…*
>
> Robinson (2004, p. 381)

The concept of sustainability is based on a sensible approach to development that does not result in undesirable conditions for future generations (Marchese *et al.*, 2018, p. 1279). However, there is a vagueness to the idea of sustainability as a policy concept with no standard measurement measures in practice, which has resulted in many definitions and interpretations of sustainability (Robinson, 2004; Kuhlman & Farrington, 2010; Holden *et al.*, 2014; Saunders & Becker, 2015, p. 73; Schneider *et al.*, 2015; Hellström *et al.*, 2000; Siebrecht, 2020). The most widely accepted [political] definition of sustainability is of sustainable development, which is "… development that meets the needs of current generations without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987, p. 23). In some studies, both sustainable development and sustainability are used interchangeably (Holden *et al.*, 2014), while some researchers believe that they are two different terms. Moreover, the pressing need for an integrated sustainability approach with the concept of climate change has often been recommended (Cohen *et al.*, 1998; Swart *et al.*, 2003; Siebrecht, 2020). In this study, the term sustainability has been used preferentially to the term 'sustainable development;' see Robinson (2004) for a detailed critical analysis of both terms.

Sustainability in general has three key components: environmental sustainability, social sustainability, and economic sustainability, and to achieve sustainable development, a compromising collaboration of these three is essential (Dzhengiz, 2020, p. 2; Siebrecht, 2020, p. 2). However, economic considerations are often found to be dominating the sustainable development debate (Saunders & Becker, 2015, pp. 73-74). Therefore, the sustainability of a system is not just a binary state, and sustainability is better approached as progress to move towards achieving a balanced state of various sustainability components (Siebrecht, 2020). Therefore, a context based, holistic, interdisciplinary, indicator based approach has been used in this study to evaluate the sustainability of the *suranga* system (Schneider *et al.*, 2015; Hellström *et al.*, 2000; Siebrecht, 2020). This sustainability assessment is based on the quality, quantity, and supply of freshwater resources, design, adaptive capacity, and social frameworks (Wiek & Larson, 2012; Schneider *et al.*, 2015; Hellström *et al.*, 2000; Maurya *et al.*, 2020). According to the context, focus, and subject specific sustainability of a sustainable water management system (Wiek & Larson, 2012; Siebrecht, 2020), the main four components used in this study are:

1. Structural and functional
2. Environmental and ecological
3. Social and cultural
4. Economic benefits

The above four components of sustainability of the *suranga* system were further divided into individual sustainability indicators, which are presented in a sustainability wheel (see Figure 2.4). These indicators were selected, focusing on what and how people do with the *suranga* and water from *suranga*. For example, the *suranga* water has only two primary development uses water for basic needs and water for irrigation; therefore, the regional development component of sustainability has only two sustainability indicators in this study. Thus, the *suranga* system can be termed partially sustainable if *suranga* provides sufficient water for the development of the community, water for drinking and household, and irrigation. Similarly, the four indicators for environmental integrity components are water quality, water discharge, groundwater quantity, and ecological impact of the *suranga*. Overall, fourteen indicators were used to evaluate the sustainability of the *suranga* system, and the resulted were summarised in colour coded wheels of sustainability.

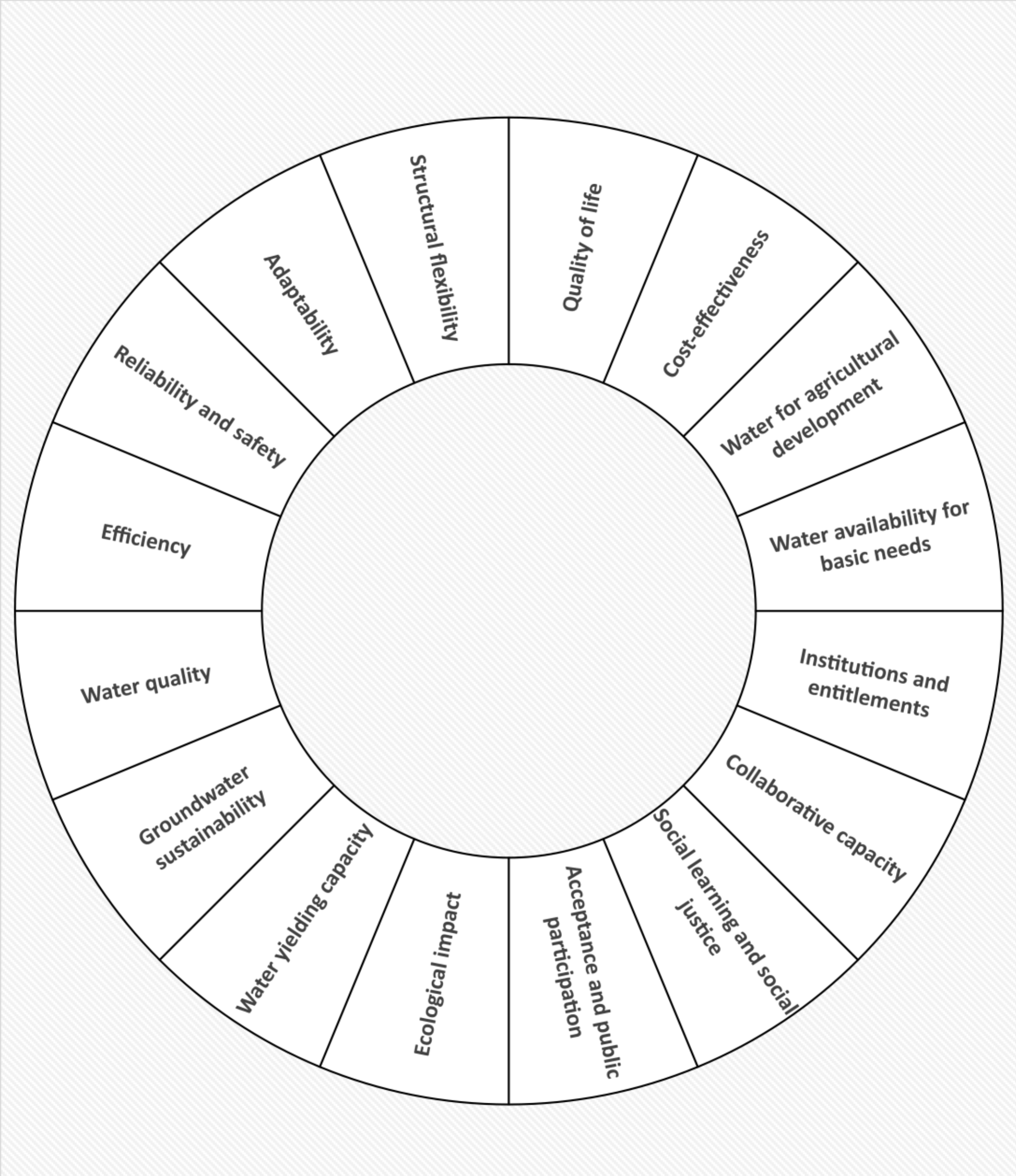


Figure 2.4: A sustainability wheel used in this study to assess the sustainability of the *suranga* system (adapted from Wiek & Larson, 2012; Schneider *et al.*, 2015; Wilson, 2018; Hellström *et al.*, 2000; Maurya *et al.*, 2020***).***

The sustainability indicators for the *suranga* system were allocated associated statements of inquiry in leading research questions. These leading research questions guided the mode and methods of data collection for this study. Table 2.7 summarises the sustainability framework used to evaluate the sustainability of the *suranga* water system.

Table 2.7: The sustainability framework for the *suranga* system

(adapted from Wiek & Larson, 2012; Schneider *et al.*, 2015; Wilson *et al.*, 2018; Hellström *et al.*, 2000; Maurya *et al.*, 2020).

Sustainability components	**Indicators**	**Statement of inquiry**
Structural and functional	Structural flexibility	Does *suranga use a* flexible structural approach?
	Adaptability	Are *suranga* adaptable to changes?
	Reliability and safety	Are *suranga* safe and reliable to construct?
	Efficiency	Are there any effective water demand management process in place? Such as the use of water efficient irrigation techniques, and rules to decide water priority, and practices to minimise water loss during transit.
Environmental and ecological	Water quality	Are basic Indian water health standards met? What is the vulnerability of *suranga* water quality to pollution and contamination?
	Groundwater sustainability	Identification of groundwater sources Estimation of the impacts of *suranga* and competing users exploitation o*f underground a*quifers
	Water yielding capacity	Do *suranga* provide sufficient perennial water supplies for irrigation and household use?
	Ecological impact	What impact does the *suranga* have on the ecology of the study area?
Social and cultural	Acceptance and public participation	Are *suranga* easily available and equally distributed among all the stakeholders for water use and governance?
	Social learning and social justice	Can all users in the community access the *suranga* water? Is *suranga* water availability discriminatory to families above and below the poverty line in the study area? Are new *suranga* workers being trained?
	Collaborative capacity	Has *suranga* technology spread/exchanged into the other parts?

		How is conflict resolution resolved in the system?
	Institutions and entitlements	Are there clear, applicable rules and frameworks for collective decisions and equal engagement from all stakeholders? Are there effective institutions and entitlement levels in property rights, concessions, formal and informal rules for water governance responses to water shortages?
Economic benefits	Water availability for basic needs	Do *suranga* provide water security for drinking and household usage to the community?
	Water for agricultural development	Do *suranga* provide sufficient water supplies for irrigation to the community to practice agriculture sustainably?
	Cost effectiveness	Are *suranga* or finances to make *suranga* easily available to all classes in the society?
	Quality of life	Has *suranga* helped in improving the quality of life?

The questions posed in Table 2.7 for the sustainability indicators were answered from the results of this study, presented in Chapter 4 to Chapter 7. The final discussion of these results to evaluate the resilience and the sustainability of the *suranga* systems is presented in Chapter 8. Based on the knowledge gap and rationale for this study presented above, the following section presents the aim and objectives based on these understandings.

2.4 Aim and objectives

The main aim of this study is to:

> To investigate the resilience and sustainability of *suranga* irrigation in the Western Ghats of India.

The aim of a study is achieved by answering the research questions framed through a series of five key objectives. They arise from the gap in knowledge about the *suranga* system identified in section 1.3 and guide data collection. The five objectives are:

1. To find the origin and history of *suranga*
2. To investigate the spatial distribution and number of *suranga*
3. To critically evaluate the design principles, governance, and management of the *suranga* system
4. To assess the key geohydrological and hydrological characteristics of *suranga*
5. To critically examine the socioeconomic and political context that *suranga* operate in

2.5 Chapter summary

This chapter presented a clear rationale for the analytical framework that is epistemically justified and used to study the *suranga* system. The analytical framework had three main components: an overarching hill irrigation model based principally on the work of Vincent (1995), a concept of community management of a TWH system, and a resilience and sustainability framework. The literature review and the analytical framework's use of the *suranga* system will plug the knowledge gap and data lacunae by focusing on the project aim and five research objectives presented here. The next research stage was to select an appropriate methodology and associated methods to collect the data to answer the research questions, which has been presented in Chapter 3.

Chapter 3 – Methodology and the study area

This chapter outlines the core methodology and research design used for this study and a description of the study area. Section 3.1 introduces a brief discussion on the theoretical foundations of research, leading to the emergence and rationale for using a Mixed Methods Research (MMR) methodology in this study. Section 3.2 presents the research design used in this study, which provided the framework for data sampling, data collection, and data analysis. The research plan was divided into three main research themes: contemporary analysis, historical analysis, and field measurements. Finally, section 3.3 presents a background of the study area, and section 3.4 provides a summary of this chapter.

3.1 Mixed methods methodology

Traditionally, research methods are often associated with specific methodological approaches and philosophical assumptions (Kuhn, 1962; Johnson & Onwuegbuzie, 2004; Nastasi *et al.*, 2010; Creswell, 2015). These philosophical assumptions inform the choice of theories that guide research (Creswell, 2013). For example, survey and field measurement methods are based on a positivist paradigm, mainly used in the natural sciences. In contrast, historical documentary analysis, oral history, and interviews methods are based on interpretivism, widely employed by the social sciences and humanities. Traditionally, these two broad schools of knowledge; positivism, and interpretivism, are often perceived as incompatible because they belong to two different and contrasting research paradigms based around the subjectivity and objectivity of knowledge (see Figure 3.1). This philosophical disagreement among the researchers caused the paradigm war in the 1980s (Kuhn, 1962; Guba & Lincoln, 1994; Morgan, 2007; Alise & Teddlie, 2010; Munoz-Najar Galvez *et al.*, 2019).

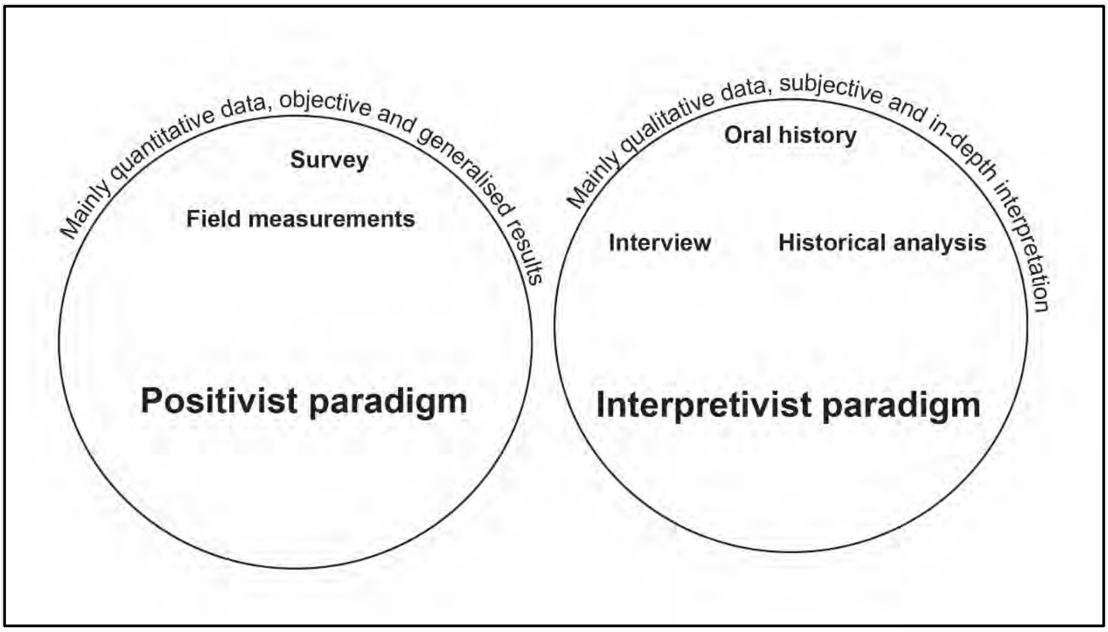


Figure 3.1: Example of two traditional research approaches and their philosophical backgrounds.

MMR is an adaptation to bridge incompatible research paradigms by advocating the use of a mix of research methods to build upon the best of the research methods irrespective of their epistemological origins (Johnson & Onwuegbuzie, 2004; Feilzer, 2009; Alise & Teddlie, 2010; Biesta, 2010; Tashakkori & Teddlie, 2010; Creswell, 2015). MMR is based on the notion that real world knowledge cannot be exclusively objective or subjective but is always a mix of both types (see Figure 3.2). For example, humans and their interactions and interventions with the real world create a primarily subjective truth (Schwandt, 1998), and the information related to the non-human world is usually objective, and both complement each other. The analogy of an apple can explain the nature of reality, where the number of seeds (objective) in the apple is quantitative data. The texture, taste, smell, and colour of the fruit (subjective) is qualitative.

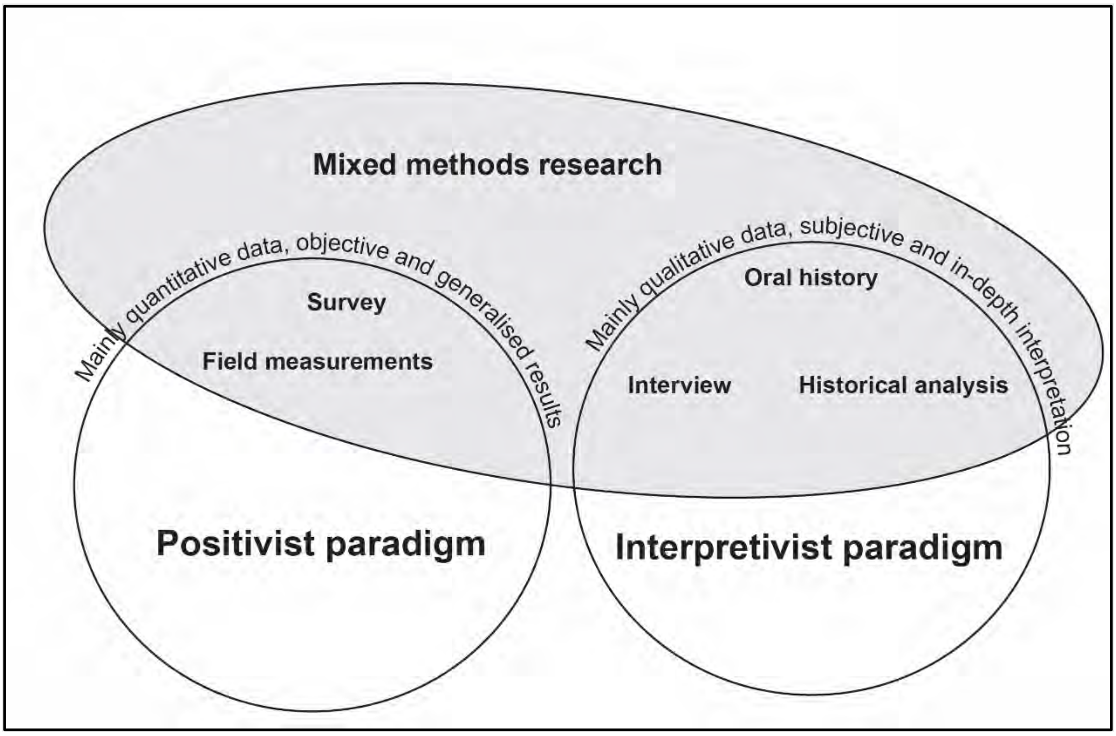


Figure 3.2: Mixed methods approach to research.

However, objective knowledge can be converted into qualitative data, as seeds can be further explained and explored. Similarly, the subjective data about the apple's flesh can also be quantified when many apples are studied. In an ideal, theoretical world of research methods, data collection and analysis should be based on quantitative or qualitative regimes with nearly zero deviation (Johnson & Onwuegbuzie, 2004). However, qualitative and quantitative data are not mutually exclusive but are embedded in each other (Gorard, 2010, pp 244). For example, it is assumed that interviews should only produce no numerical, subjective data to follow its philosophy and maintain its validity. Still, it is not essential that interviews can never produce quantitative data. Thus, the knowledge/truth for the real world is often a combination of objective and subjective knowledge (Brannen, 1992; Schwandt, 1998).

The *suranga* system, a real world phenomenon, consists of subjective and objective truth embedded into each other like the previous analogy of an apple model because *suranga* are a human intervention in nature. This exploratory study is the first empirical and comprehensive study on *suranga*. Therefore, for an inclusive study of the *suranga* system, an MMR approach was the most appropriate. For example, if only quantitative methods are employed to understand the *suranga* water systems, it fails to incorporate and acknowledge the individual perspectives and *vice-versa*. The absence of previously documented information on *suranga* created a greater need for a comprehensive study by integrating multiple methods. An eclectic approach of using diverse, pragmatic methods and an approach beyond boundaries is getting popular in real world research (Bryman, 1988; Brannen, 1992; Thomas, 2013), especially for the expansion studies where information is collected to extend the available depth and breadth of a phenomenon (Feilzer, 2009; Nastasi *et al.*, 2010). The application of various data gathering methods and analysis has the advantage of minimising the drawbacks of individual methods and analysis (Walsh, 2001; Johnson & Onwuegbuzie, 2004).

The selection of a research methodology and methods is often guided by the research objectives (Thomas, 2013, p. 105), but this study used a pragmatic and flexible data collection approach. The five research questions (section 1.3) helped set the research objectives for this study in section 2.4, and the respective data collection methods have been presented in Table 3.1. Therefore, the research methods were selected in their ability to answer the related research questions, not by their allegiance to a specific paradigm (Guba & Lincoln, 1994; Johnson & Onwuegbuzie, 2004; Feilzer, 2009).

Table 3.1: Research questions and proposed methods of research.

Research question	Method of research
Q1: What is the origin and development history of *suranga* in the study area?	Carbon dating Archive analysis Oral history
Q2: What is the spatial distribution and number of *suranga* in the study area?	Survey research Questionnaire
Q3: What are the design principles, governance and management systems underpinning *suranga* use in the study area? Q5: What socioeconomic conditions in the study area promote the use of *suranga*?	Survey research In-depth interview
Q4: What are the key hydrological characteristics of *suranga*?	Field measurement Water provenance Water quality test

As shown in Figure 3.2, MMR allowed for collecting quantitative and qualitative data for this study in an integrative and complementary way (Tashakkori & Teddlie, 2010; Thomas, 2013; Creswell, 2015). The quantitative approach of data collection with an objective form of knowledge provided a broader perspective, while a subjective and in-depth form of data collected from qualitative research methods helped develop additional insight into the *suranga* system (Schoonenboom & Johnson, 2017). Therefore, an MMR approach was the most suitable to achieve the objectives of this study. The following section explains the theoretical process/plan of applying MMR in the form of a research design employed in this study.

3.2 Research design

Studies on TWM systems are often criticised for too much focusing on the physical processes and ignoring the human and social aspects of the water system (Kreutzmann, 2011; Mukherji *et al.*, 2019). Therefore, MMR methodology was employed in this study because it allowed the freedom to create a bespoke research design employing an interdisciplinary approach combining the physical and human aspects employing qualitative and quantitative methods to answer the research questions (Creswell, 2015). In the absence of any previously established theory/hypothesis to explain the geohydrology of the *suranga* systems, this study started with an exploratory, inductive data collection approach. The analytical framework (see Chapter 2) based on a mountain/hill irrigation framework (Vincent, 1995) guided/set the relevancy of the data for collection. Inductive reasoning was further improved with a large dataset that increased the experiences and principles derived from such a dataset (Thomas, 2013). Once a broad understanding of the *suranga* systems was achieved using an inductive approach to data collection, this was followed by using a deductive approach to assess the hydrogeology of the *suranga* system. Multiple methods of data collection have been categorised into three broad research themes. These themes are given below, with their corresponding data collection methods employed in this study.

1. Contemporary analysis
    - Socioeconomic survey
    - In-depth interviews
2. Historical analysis
    - Archival analysis
    - Oral history
3. Field measurements
    - *Suranga* structural survey
    - Discharge measurement
    - Water quality analysis
    - Groundwater assessment

The customised MMR based design for this study has been presented in Figure 3.3.

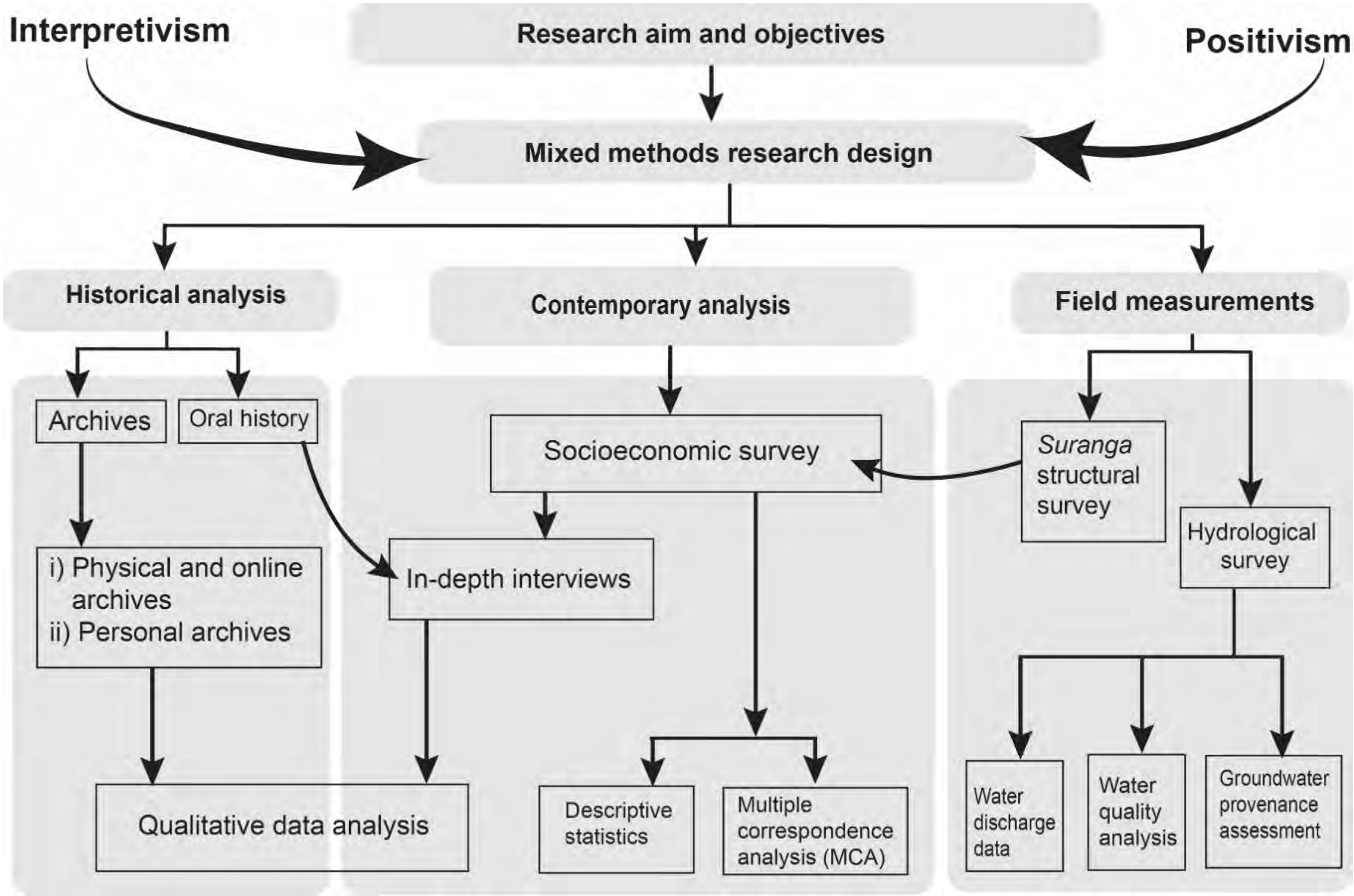


Figure 3.3: The customised, mixed methods research design used for this study.

In this MMR study, the integration of quantitative and qualitative data occurred at various stages, such as during data collection, data analysis, and in the results section (Johnson & Onwuegbuzie, 2004; Tashakkori & Teddlie, 2010; Creswell, 2015). On the spatial level, a funnelling approach for data collection and interpretation was used. The data collection started from a broad regional level and gradually focused down to village and hamlet levels. The scale of data collection and the type of resultant data for each approach has been shown in Figure 3.4.

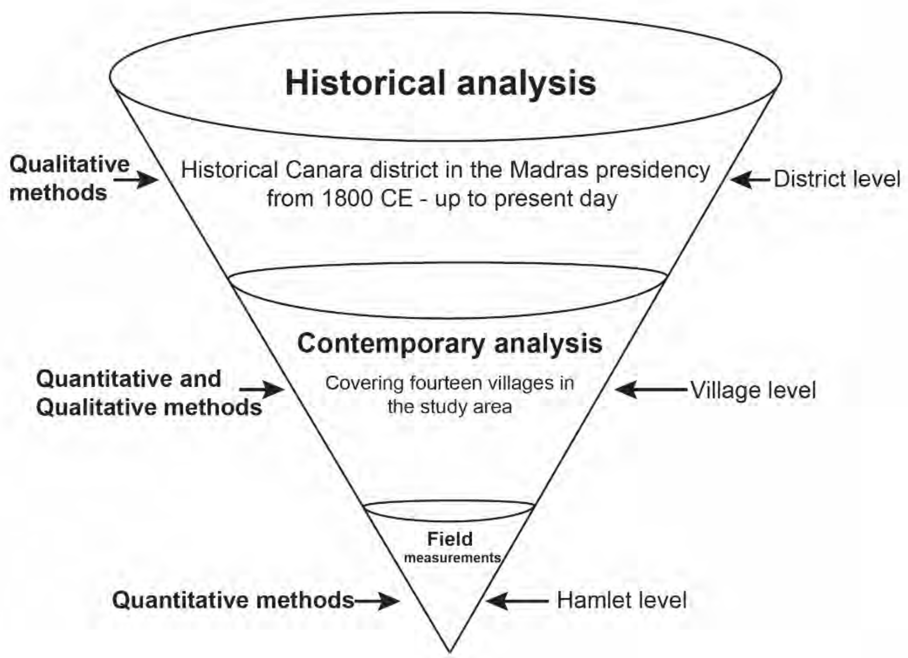


Figure 3.4: A funnelling approach of data collection involving three individual research designs.

Although the three parallel research approaches were employed, however, as shown in Table 3.2, data were often collected simultaneously to optimise resources over four main fieldwork sessions. For example, the qualitative data for historical analysis from the oral history method was often collected during the in-depth interviews and the questionnaire survey for contemporary analysis.

Table 3.2: Field trips and associated objectives.

Date	Location (Districts, cities in India)	Objectives
August-December 2012	DK Kasaragod Bangalore New Delhi North Goa Panaji Kozhikode	*Suranga* field survey In-depth interviews Archival search at states archives in Bangalore, Panaji, and Chennai, and national archives in New Delhi
March-May 2013	DK Kasaragod Bangalore Chennai North Goa Kozhikode Wayanad Madurai	In-depth interviews Archival search Hydrological survey
April 2014	DK Kasaragod Chennai	Hydrological survey
May 2015	DK Bidar	Archival search
May 2018	DK Kasaragod	Hydrological survey Archival search

The overall gain of this iterative fieldwork and data analysis process was an increased understanding of the system, with emerging themes explored after every fieldwork period and during the next visit. For example, the second fieldwork period was planned and underpinned by the data, evidence and review collected from the previous fieldwork. Evolutionary data gathering continued until saturation was reached in the respective data collection methods in five fieldwork periods between 2012 and 2018. The fieldwork periods were followed by an ongoing literature review and testing of various themes of ideas and theories.

To provide greater context to the research, the following section supplies further background information on the study area.

3.3 The study area

The study area, in the villages of DK district in Karnataka, and Kasaragod district in Kerala, is situated in the western foothills of the Western Ghats and is bounded by the Arabian Sea on the west (Prasad *et al.*, 1991; Doddamani, 2007; Halemane, 2007). The Western Ghats produces several rivers, such as Krisha, and Kaveri, flowing towards the east and steadily passing through the large regions of southeast India, in the Indian peninsula, which are the primary water source for agriculture, especially paddy cultivation (Sutcliffe *et al.*, 2011; Kumar & Krishna, 2015). The steep average slope gradient causes high runoff with a general slope ranging from 0.12 to 81 degrees (Sarath *et al.*, 2020). The west side of the Western Ghats also has rivers, but the proximity to the Arabian Sea does not allow full utilisation of rivers before they are discharged into the Arabian Sea (Sutcliffe *et al.*, 2011, pp. 777-779). The geology of the area is mainly Precambrian charnockite, gneisses (GSI; 1993; GSI; 2006; CGWB, 2012; CGWB, 2013; GSI; 2014), pyroxene granulite, Hornblende biotite gneiss, Banded Hematite Quartzite, columnar/mafic dykes, pyroxenite and alkali granitoid (GSI, 1995; GSI, 2005; Sarath *et al.*, 2021). The soil is predominantly thick laterite (GSI, 1981; GSI, 2014), a term coined by Buchannan in 1807 during his visits to Malabar and Canara (Buchanan, 1807; Suseelan, 2008; Shaji *et al.*, 2020). The study area is characterised by undulating topography, including the spatially extensive lateritic plateau, steep hills and hillocks with maximum elevation up to 300 metres, steep valleys with gullies and ravines, rivers with seasonal high discharge (Suseelan, 2008; Kumar *et al.*, 2020, Sarath *et al.*, 2020; Shaji *et al.*, 2020; Sarath *et al.*, 2021). The climate of this region is humid and tropical, with annual precipitation averaging 3500 mm/year (CGWB, 2012; Vijay *et al.*, 2021). The average annual rainfall of the DK district for 1971-2000 CE was calculated as 3789.9 mm (CGWB, 2012). The Indian monsoon system is made of two parts: the south-west monsoon (June-September) causes ~85% of the total annual rainfall in the study area (Kodandapani & Parks, 2019); the returning monsoon, known as the north-east monsoon (October-November), causes the remaining precipitation in the study area (Vijay *et al.*, 2021). The period between December and May is primarily dry and requires irrigation (*ibid.*). The torrential monsoonal precipitation and the undulating geography do not allow for the construction of largescale water storage structures such as large tanks, dams, and reservoirs, unlike flat areas found in the rest of south India (Mosse, 1999; Shah, 2008). Small ponds that collect runoff, locally known as *kere*, are widely found in the valleys. Still, these ponds are not suitable on hill slopes because of the steep gradient and torrential rainfall. Intense precipitation and undulating terrain cause rapid runoff, which leads to acute water scarcity during the dry season. The critical water shortages occur mainly during the summer months from late February to late May and last until the monsoon arrives in the last week of May (Doddamani, 2007; Kokkal & Aswathy, 2009; Balooni *et al.*, 2010).

During the initial stages of this study, a typically dispersed village named *Manila* in the DK district was selected as the main base of this study. In preliminary investigations, this village was found to be highly dependent on the use of suranga in association with other traditional water harvesting systems such as wells and ponds, which were widely used for domestic water supplies and irrigation for subsistence farming and agriculture. Furthermore, exploratory fieldwork was previously undertaken in Manila village during August-September 2008 established contacts that could help in facilitating data collection (Tripathi, 2009). Moreover, focusing on a village level case study allowed for exploring socioeconomic and cultural dynamics (Shannikodi, 2013), which allowed an in-depth analysis framed around resilience and sustainability.

Manila is a small Indian village with an area of 1554 hectares and is situated (N 12.690, E 75.080) in the Bantwal sub district of the DK district in Karnataka, shown in Figure 3.5. The foothill village of Manila, with undulating terrain, steep hills and valleys with gullies and ravines, is geographically situated between the western coastal plains and the Western Ghats (Suseelan, 2008; Shannikodi, 2013). According to the census of 2011, the population of Manila was 3191 and 561 households (Government of India, 2012). Most of the population is Hindu, with a small Muslim and Christian population. There are two Hindu temples and a Mosque in the village that are used for religious functions; and are the focal points of social activities. *Kannada* and *Tulu* are two widely used languages in the village, and the *Karadi* dialect is also widely used in the *Karadi Brahmin* community.

The nearest towns of Puttur, Bantwal, and the cities of Kasaragod and Mangalore are situated in flat regions, while villages are usually situated in and around valleys of the foothills. Most of the homesteads in Manila village were connected to nearby towns by narrow roads cutting across these foothills. Houses are made on the land produced by slicing and stonewalled terraced hillslopes (Wei *et al.*, 2016), and generally, the sliced hill surface is at the back of the house (Suseelan, 2008). Terraced farming is practised on the rest of the hill slope and the valley. Manila village got electricity in the late 1990s. At the same time, an unreliable drinking water pipe supply was made available to only a limited number of families because of the undulating and challenging terrain. In 2018 plans were being made to localise the water supply[11]. Such plans usually consist of a borewell constructed at a suitable place, and water is pumped to a small concrete overhead tank situated at the top of the hill, and then water is provided to the families living around this water tank (personal communication, 2018).

Initially, only Manila village was selected for the fieldwork, but in due course, a network of contacts in twelve neighbouring villages was developed, which allowed for the extension of the research area. A basic map of the region is shown in Figure 3.5 with the villages named where fieldwork was undertaken. Thus, the study area comprises 13 villages found on undulating terrain with steeps hills to a maximum height of 300 metres from the sea level and water rich, fertile valleys with seasonal streams and rivulets (Suseelan, 2008).

[11] During a recent conversation with the host in the year 2020, it was confirmed that the local government water supply projects were still not fully operational in the study area, and a large population still rely on traditional water resources.

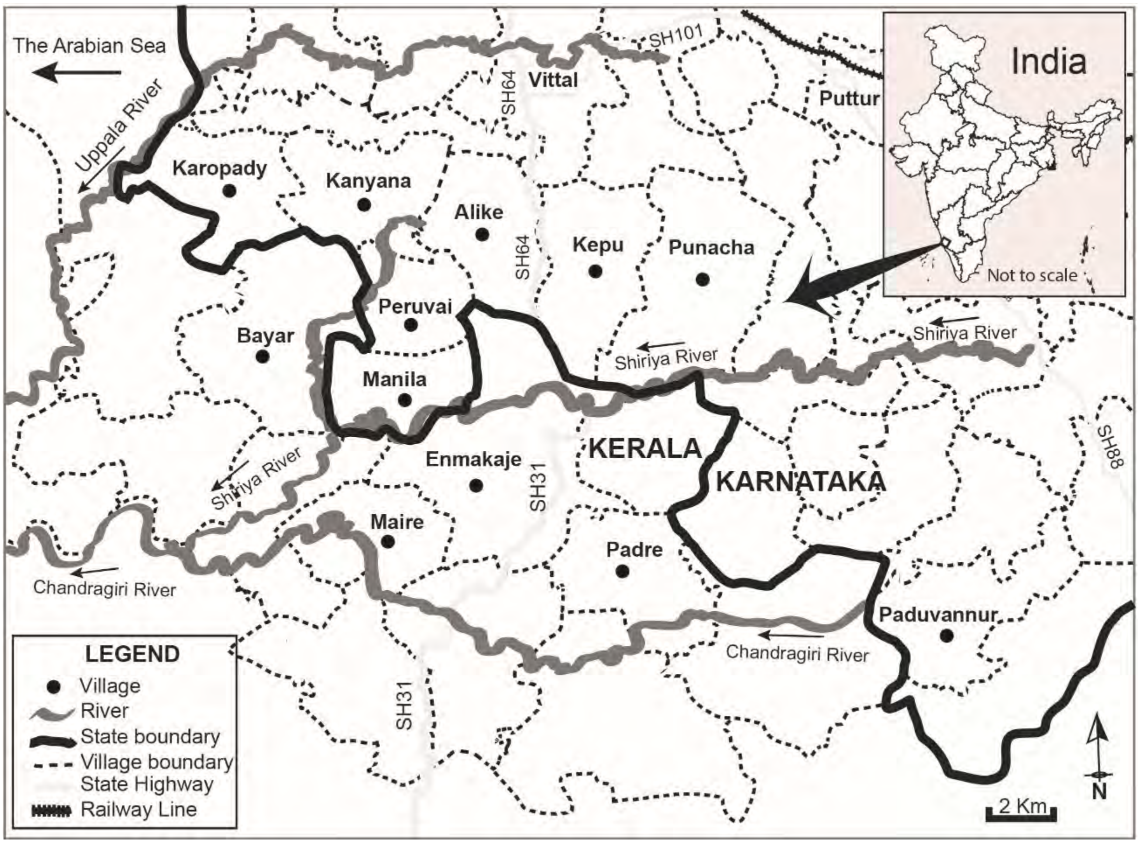


Figure 3.5: The map and the location of the study area villages.

The farmsteads in the study area are sparsely distributed in the small valleys and hill slopes, and houses are often located within the farm boundaries. Presently several people depend on traditional water harvesting methods for their household water requirements and irrigation needs. Rivers, streams, springs, and dug well are the primary water resources (Kokkal & Aswathy, 2009) and borewells were introduced to the region in the 1990s (Bhat *personal communication*). However, the primary source of water in the above water resources is the intense seasonal monsoonal rainfall which lasts five months starting from early June (Kodandapani & Parks, 2019). In the recent historical past, subsistence agriculture (rice and sugarcane) was irrigated with seasonal rainfall (Kumar & Krishna, 2015). The main plantation crops in the study area are coconut, areca nut (also known as betel nut, *supari*), banana, rubber, jackfruit, papaya, cashew, vanilla, black pepper, and cocoa (Kokkal & Aswathy, 2009; Shannikodi, 2013). Historically, paddy and sugarcane were the staple food and main crop of cultivation, but production of both have decreased significantly in the past century (Shannikodi, 2013; Kumar & Krishna, 2015). Presently, paddy is grown seasonally in valleys and in water affluent flattened areas. The cash crops, such as areca nut, rubber, and cocoa, have become increasingly popular among farmers because these do not require intense irrigation nor a large workforce in contrast to paddy and sugarcane plantations; moreover, cash crops provide better economic returns to the farmers (Kumar & Krishna, 2015). Like other rural regions in India, mixed crop based dairy production is used at a family level, where crop by-products were fed to the bovines to produce milk, dung based fuel, and manure (Shannikodi, 2013; Bhagawati *et al.*, 2017; Rajan & Shah, 2020). Historically bovines were a significant part of agriculture, especially for preparing paddy fields and manure; however, farm machines and the use of chemical fertilizers have reduced their use in agriculture in the study area (Shannikodi, 2013), shifting the overall focus of mixed crop based dairy production of milk to solely for domestics usages and for extra income (Rajan & Shah, 2020).

3.4 Chapter summary

In summary, the MMR methodology was employed in this research because it embraced a pragmatic approach to the research beyond the epistemological limitations of different research paradigms. A customised MMR research design was used for data collection and analysis. Three broad themes of data collection were used: contemporary analysis, historical analysis, and field measurements. The contemporary analysis involved a socioeconomic survey method with an in-depth interview approach, which produced quantitative and qualitative data. The historical analysis was used to examine the origin and development history of *suranga* in the study area. Finally, the field measurement theme of data collection was used to perform tests and measurements of various characteristics of *suranga*. Moving on, Chapters 4-7 start with the associated research question(s) and then describe the research method(s) used to answer these questions, followed by the presentation of the results. This approach of presenting research method(s) and associated results together in four individual chapters clarifies and maintains the narrative in this mixed methods research project.

Chapter 4 – Origin and development of *suranga*

At the start of this investigation, the origin, age and development history of *suranga* in the study area were unknown. Therefore, this chapter aims to answer Research Question 1.

> **Research Question 1:** What is the origin and development history of *suranga* in the study area?

This chapter is divided into three parts. The first part (section 4.1) presents the data collection methods used to explain the types of data analysis carried out to answer research question 1. The second part (section 4.2) presents the results. The final part (section 4.3) summarises the key findings from this chapter.

4.1 Methods: Oral history and archival analysis

This project started with a view to finding the origin and age of the *suranga* system by using archaeological, palaeological and sedimentological methods, by exploring proxy data from natural archives, such as fossil pollen and sediments supported by radiocarbon dating techniques (Parducci *et al.*, 2013; Richer & Gearey, 2017; Herrera-Herrera *et al.*, 2020). However, during the first period of fieldwork, it was realised that finding suitable sites for the collection of sediments was not practical because of the regular reworking of land and irrigation structures by farmers and the highly active recycled nature of the semitropical natural landscape[12]. Moreover, no ancient artefacts related to *suranga* history were found because organic materials break down quickly in this environment. While attempting to date similar water tunnel systems, archaeologists have reported similar dating challenges in Israel (Yechezkel *et al.*, 2021) and Mexico (Palerm-Viqueira, 2004, p. 136).

Faced with the methodological constraints on dating the *suranga* system, the focus of the research switched to finding the history of *suranga* by using oral history and testimony. Oral history and testimony play a significant role in historical and contemporary studies, and the tradition of oral history can be traced back to the preliterate times when history was only in oral form (see Freund, 2009; Atkinson & Coffey, 2011; Jessee, 2011; Thompson & Bornat, 2017). The oral history data for this project were collected during the interviews with local research scholars, historians, farmers, religious leaders, and gatekeepers of the community, who had some understanding of the local history, agriculture, and the potential origin of the *suranga* system. The oral histories and testimonies were recorded using a mobile phone, then transcribed later and used to explore the origin and development of the *suranga* system and construct a settlement and agricultural history of the study area (Gray, 2014; Robson & McCartan, 2015). The initial findings from the oral history and testimony transcripts indicated that supporting historical documentary data could be obtained from state and personal archives situated in India and the UK (Table 4.1).

[12] This conclusion was supported by the views of Dr Richard Jones, a respected and well published palynologist now deceased, who visited the study area in 2013.

Table 4.1: Archives visited in India and the UK.

Archives	Address	Visits	Material consulted	Time series (CE)
National Archives, India	National Archives Rajpath Road Area, Central Secretariat, New Delhi, 110001, India	November 2012	Colonial land, revenue, and agricultural records	1836-1942
Goa state Archives, India	Directorate of Archives and Archaeology, Rua de Qurem, Panaji, Goa, India	October 2012	Portuguese land records	17th-19th century
Karnataka State Archives, India	Karnataka State Archives, Room No. 126, First Floor, Vikasa Soudha, Bangalore 560001 India	Oct- Nov 2012 April 2014	Madras land, revenue, agriculture, and forest records	1950-1964
Archives and historical research, Chennai[13], India	No. 51, Gandhi Irwin Road, Egmore, Chennai 600 008 India	April 2013 April 2014	South Canara land and agricultural records, Madras administration records	1871-1940
The British Library, UK	The British Library 96 Euston Road London NW1 2DB, UK	2012 2013 2014	Asian and African studies, Colonial records of India	1881-1998
National Archives, UK	The National Archives Kew, Richmond Surrey TW9 4DU, UK	2013	British colonial records in India	1784-1947
Personal Archives	Murva Mahabal Bhat Manila village	April 2013 April 2014 May 2015	Personal land records Cadastral map Court proceedings	1853-1964
	Manimoole Govind Bhat Manila village	Nov 2012 April 2013 April 2014	Land records Village maps Land tenancy agreements	1905-1997

[13] Madras city was renamed Chennai in 1996.

However, a significant limitation of this archival research was the restricted access to these historic materials in India (Silverman, 2011). There were several bureaucratic hurdles faced in accessing the archives in India, even for an Indian national. In addition, many Indian archives were not catalogued into series following western conventions, which made searching through them time consuming, potentially haphazard and ran the risk of missing information. To overcome some of the access hurdles produced by attempting to consult public archives physically, it became possible to examine traditional government archives in India that had started to be digitalised and made available online, which increased the ease of access to these sources (Skalski *et al.*, 2017). An online archive[14], found to have several relevant documents scanned and uploaded by users, was also consulted. The private archives, usually maintained by local scholars and the seniors of the community (Figure 4.1), were also consulted to search for farmers' old personal and private documents in the study area related to land, tenancy and water rights (Figure 4.2). These private archives helped provide data that added context to the social and cultural history of the study area (Bowen, 2009; Atkinson & Coffey, 2011; Prior, 2011; Gray, 2014).

[14] www.archive.org

Figure 4.1: A view of the personal archive of a farmer in the study area.

Figure 4.2: A land registry record from a personal archive dating back to 1876CE.

The government and personal archives consulted both in India and the UK mainly consisted of various colonial governmental records: gazetteers, land records, enumerations, inventories, technical reports, correspondence, taxation documents, cartographical sources, survey data, forest records, village assessment records, missionary archives, historical and contemporary census data, court proceedings for land and water issues, and travelogues of British travellers and British government officers for the Madras Presidency between 1799-1947 CE (see Table 4.2).

Another methodological issue was the no neutrality of the colonial archives analysed as these documents mainly projected government views (Bhat, 1998), which meant a critical eye was maintained that recognised that these colonial documents at times were upholding and reproducing dominant hegemonic power structures that had little interest or motivation to record a traditional water harvesting system like *suranga*. Therefore, it was necessary to evaluate each archival source for its provenance, dating, origin, authenticity, meaning, context, and relevance to the project (Marwick, 1994; Bowen, 2009; Atkinson & Coffey, 2011; Robson & McCartan, 2015). Thus, the absence of *suranga* from the documentation was not necessarily proof of absence overall. The careful analysis of origin, authorship and users of the archival documents provided the context, transparency, and relevance of the documents; moreover, the intertextuality of the text also helped in finding the referential values of the documents and texts (Freund, 2009; Atkinson & Coffey, 2011; Jessee, 2011).

The data collected from the documents were analysed for their content using thematic analysis (Bowen, 2009; Gray, 2014; Robson & McCartan, 2015) to identify social, economic, agricultural, and water management practices in the past. The aim was also to find a reference or mention of the *suranga* water harvesting system to confirm the origin and age of the system. However, the interpretation of some of these documents became difficult because the old documents were written in old Kannada dialects using historical terminology, so quite often, the owners of these documents could not understand them. Help was sought from local scholars and a language expert in Bangalore to read some of the documents, but the precise meanings could not always be found because of the dated written language and the use of local terminology and languages.

The oral history and testimony interviews were analysed for their content to understand the trends in agricultural development and the social history of the area, with a high level of abstraction used to identify the core requirements for the *suranga* system in the study area. To explore the validity of oral data and various archival documents, the results were compared and corroborated before making any conclusions about the origin and development of *suranga* (Atkinson & Coffey, 2011; Freund, 2014). This complementing approach allowed for a systematic interpretation of old archival sources such as maps, official administrative records, local farmers' archives, and oral history and testimony data (Robson & McCartan, 2015). This analysis provided information on the region's social, economic, environmental, and agricultural history, thereby providing a historical context to the study area and a more reliable agricultural history (Burgess, 2002; Robson & McCartan, 2015). The following section provides the combined results collected from oral history and testimony and the documentary archive analysis.

4.2 Results: The antecedents of *suranga* development

Despite a comprehensive survey of documentary archive sources in India and the UK, and in the personal archives consulted, no evidence was found of the existence of *suranga* systems or any similar water tunnel water system in the study area or the rest of the Madras Presidency from the 19th century up to the end of the 20th century[15]. Although some of these documents, summarised in Table 4.2 (see Appendix B for the complete list), comprehensively cover various aspects of agriculture and life in the region, but no reference to the *suranga* system could be found. Local researchers also supported this observation during oral history interviews, including a renowned scholar of history from the study area (Bhat, 1998; Bhat, 2001), who confirmed that it was difficult to evaluate the exact origin of *suranga* because of the absenteeism of *suranga* systems from historical records related to land and agriculture $_{(R38;\ R55;\ R72)}$[16]. However, the only indirect reference, Hunter (1887, p. 363) has suggested that the local communities inhabiting these hillslopes had skills to utilise the seasonally available water from spring and rivulet by constructing grids channels, feeders, and temporary check dams, which shows the indigenous water skills of the locals. In addition, small, seasonal, or permanent check dams, tanks, and ponds built on hill slopes were often used to irrigate the crops (*ibid.*), but there was no specific mention of *suranga*.

---

[15] To maintain the flow of text in the main body, the archival documents have been referenced in APA 6h format, and the full references have been provided in the References.

[16] The numbers in subscripts are reference to the oral history and testimony interviews.

Table 4.2: The list of documents consulted at various archives.

Document	Year (CE)	Sources (abbreviated)	Archive
Census	1871/1891/1911-1971 1874 1881/1891 1901	Census of India Census Statement of Population of 1871 in each village of the South Canara District. Villagewar Statements of Area, Houses, and Population for the South Canara District. Taluk and Village Statistics. South Canara District. Madras	Archives & historical research, Chennai The British Library, London.
Imperial and District Gazetteers	1855 1866 1905/1915 1908 1938 1983/1985 1997	Gazetteer of South India 1855 The Imperial Gazetteer of India Madras District Gazetteers. South Canara. Provincial Series, Madras II & Vol IX Madras District Gazetteers, Statistical Appendix, together with a supplement to the two District Manuals for South Canara District Gazetteer of India, Karnataka State, South Canara District The Encyclopaedic District Gazetteers of India	Archives & historical research, Chennai The British Library, London.
Inventories/ Taxation	1844 1869 1875	Report on The Medical Topography and Statistics of The Provinces of Malabar and Canara. Madras: Proceedings of the Board of Revenue for the month of November 1875 Vol XI Madras Proceedings of the Board of Revenue for the month of February 1869 Vol II Madras	The British Library, London. Archives & historical research, Chennai
Settlement reports	1858/1862-3/ 1882-3 1894/1895 1905 1940 1950 1964	Settlement Report of South Canara land revenue of the provinces under the Madras Presidency Madras District Manuals, South Canara Manual Vol I Vol II Manila village, Survey Map no 169 Some south Indian Villages: A resurvey by P J Thomas and K C Ramakrishnan Karantha, K. V. (1950). Prosperity for villages. Revision settlement report of Puttur zone- South Canara district	Archives & historical research, Chennai Karnataka State Archives, Bengaluru
Travelogues	1807, 1821 1875 1933 1934	A journey from Madras through the Countries of Mysore, Canara, and Malabar by Francis Buchanan Vols 1-3 London A visit to Madras: Being a sketch of the local and characteristic peculiarities in the year 1811 Canara Past and Present by	www.archive.org The British Library, London

		Samuel Miley. Madras: Picturesque South Canara. By K S Karanth. The Scenery of South Canara by T B Krishnaswami.	
Cadastral and land records	1853 1866 1870 1895 1905 1915 1964 1997	Manila village land document Peruvai village, Murva land contract Land Tenancy agreement Murva farm map Report on the settlement of the land revenue of the provinces under the Madras Presidency for 1903-1904 1913-1914 Land records Manila village map	Personal archives Archives & historical research, Chennai Personal archives
Administration	1895/1913 1902 1915 1919 1933 1938/1942 1998	Report of the administration of the Madras The Economic History of India in the Victorian age by Romesh Dutt Vol 2 London Southern India: History, People, Commerce, and Industrial Resources An Essay on the development of industries in South Canara The Madras Presidency 1881-1931. Madras fortnightly reports South Canara (1799-1860): A study in colonial administration and regional response by N S Bhat	Archives & historical research, Chennai www.archive.org The British Library, London
Agriculture	1918/1931 1917-18/1920-9	Annual report of the four agricultural research stations in Kasaragod taluk Reports on the work of Coconut stations in Kasaragod Taluk	The British Library, London
Other sources	1858 1870 1969 1990	A dictionary, Canarese and English, by the Rev. W. Reeve, Report on Pisciculture in South Canara by H S Thomas. Antiquities of South Canara. Dr P Gururaja Bhatt Basel Mission Industries in Malabar and South Canara 1834 – 1914: By Jaiprakash Raghaviah	www.archive.org The British Library, London

Therefore, it appears that communities in the study area had developed diverse, indigenous water skills to manage available water resources in the late 19th century, but not *suranga*. On the other hand, it might be that *suranga* existed in very small numbers in the study area at this time but were unknown to the outer world. Therefore, attempts were made to construct an environmental history based on critical events to provide inclusive background to agriculture, land types, land tax, because these issues were indirectly related to settlements, and water harvesting and storage for agriculture, so that suitable temporal markers for the birth of the *suranga* system could be traced. The following subsection provides a brief history of the study area constructed from the archival documents (Table 4.2) consulted at various public and private archives, followed by data on population growth, land ownership, agriculture, and irrigation development. In addition, the results collected from oral history interviews (subsection 4.2.2) have been collated to add further evidence for the possible nascent history of *suranga* in a region already imbued with traditional technological responses and adaptations to water scarcity (Freund, 2009; Freund, 2014). Finally, in the absence of a well-documented history of the *suranga* system, attempts are made to identify key events in the history of the study area that led to the introduction and development of the *suranga* system.

4.2.1 A brief history of the study area

The study area was a part of a historical region known as Canara (also known as Kanara), ruled by various empires. The British East India Company ousted the last ruler of Mysore and Canara, Tipu Sultan[17], in the fourth Anglo-Mysore war in 1799 CE (Buchanan, 1807; Bhat, 1998). Canara was annexed to the Madras presidency administered by the East India Company with its capital in Madras (Miley, 1875, pp. 1-3; Madras District Gazetteers, 1938). Thus, Canara was not only a large administrative region in the Madras Presidency, but it was remotely situated on the Western coast of India (Figure 4.3) away from the capital, which was situated on the Eastern coast of India (Bhat, 1998).

[17] Hyder Ali ruled Mysore and Kanara from 1761-1782, then his son Tipu Sultan ruled the Kingdom of Mysore and the region of Kanara from 1782 to 1799.

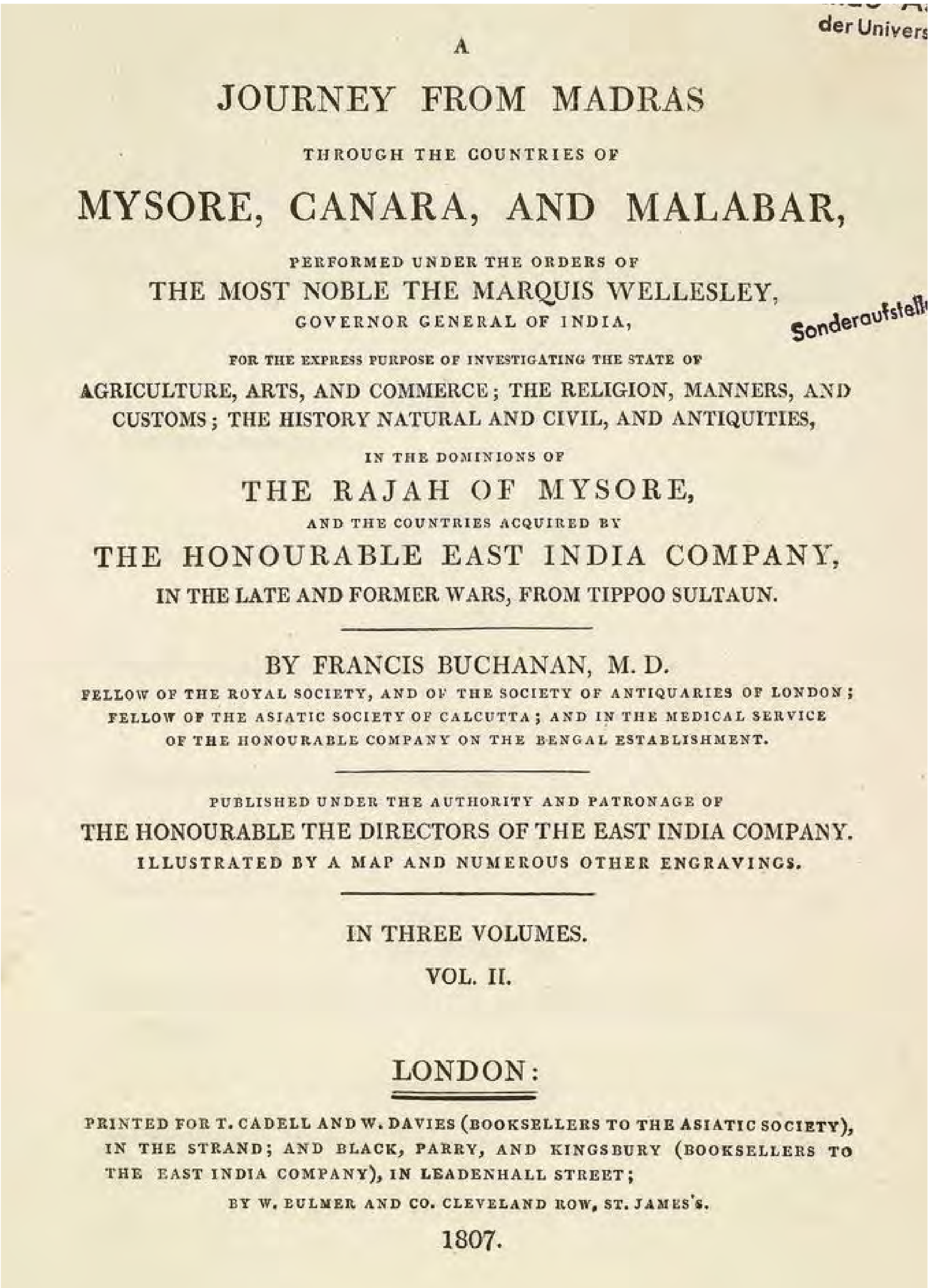
Figure 4.3: A map of India in 1805 CE (Joppen, 1907, p. 21).

Moreover, the region of Canara was a geographically undulating region, with dense tropical moist deciduous forests (Kodandapani & Parks, 2019), many streams and rivers, barren laterite plateaux, steep hill slopes, fertile valleys with gullies and ravines, and flat coastal regions (Miley, 1875, p. 2; Hunter, 1887, pp. 358-363; Rao, 1919; Bhat, 1998). The dense forests in this region were home to wild animals such as leopards, tigers, and panthers (Madras District Gazetteers, 1938, pp. 304-305). No documented information was available to the administrators of the East India Company about Canara because written documents about Canara were rare prior to 1799 CE (Hunter, 1887, p. 356), and if there were any, possibly they were in local languages (Bhat, 1998). Therefore, after acquiring Canara and some other parts of South India in 1799, the British Governor General of India, Lord Wellesley, appointed Francis Buchanan (1762-1829), a surgeon and botanist, to survey the Kingdom of Mysore and neighbouring states, including the regions of Canara, and Malabar in the year 1800 (Buchanan, 1807). This survey seems to be the oldest document in English (Figure 4.4) that provides a detailed description of the region of Canara (Bhat, 1998).

Canara, with difficult geographical access, was a remote frontier that affected its management in the Madras Presidency; therefore, to improve and simplify its management, Canara was bifurcated into North Canara and South Canara[18] districts in 1859 CE (Bhat, 1998; Bhat, 2001). Later, North Canara was permanently ceded to the Bombay Presidency in April 1862, and South Canara remained in the Madras Presidency (Hunter, 1887, p. 357; Miley, 1875, p. 2). The focus of this study was on the historic South Canara district[19] of the Madras Presidency, where *suranga* are now found (Figure 4.5). This district was historically inhabited by diverse communities (Miley, 1875, p. 26) and was the only polyglot district in the Madras Presidency, with *Tulu*, *Malayalam*, and *Kannada* as the main languages, and *Konkani* and *Hindi* spoken by smaller communities (Madras District Gazetteers, 1938, p. 222).

[18] The region of present Dakshin Kannada, and Northern Kasaragod districts.

[19] A district was usually divided into sub-districts (known as taluks), and a sub-district was made of towns and *magane* (similar to a present day panchayat), and a *magane* was made of several villages, and a village had several hamlets (Madras District Gazetteers[19], 1938, pp. 216-217).



A

JOURNEY FROM MADRAS

THROUGH THE COUNTRIES OF

MYSORE, CANARA, AND MALABAR,

PERFORMED UNDER THE ORDERS OF

THE MOST NOBLE THE MARQUIS WELLESLEY,

GOVERNOR GENERAL OF INDIA,

FOR THE EXPRESS PURPOSE OF INVESTIGATING THE STATE OF

AGRICULTURE, ARTS, AND COMMERCE; THE RELIGION, MANNERS, AND CUSTOMS; THE HISTORY NATURAL AND CIVIL, AND ANTIQUITIES,

IN THE DOMINIONS OF

THE RAJAH OF MYSORE,

AND THE COUNTRIES ACQUIRED BY

THE HONOURABLE EAST INDIA COMPANY,

IN THE LATE AND FORMER WARS, FROM TIPPOO SULTAUN.

BY FRANCIS BUCHANAN, M. D.

FELLOW OF THE ROYAL SOCIETY, AND OF THE SOCIETY OF ANTIQUARIES OF LONDON; FELLOW OF THE ASIATIC SOCIETY OF CALCUTTA; AND IN THE MEDICAL SERVICE OF THE HONOURABLE COMPANY ON THE BENGAL ESTABLISHMENT.

PUBLISHED UNDER THE AUTHORITY AND PATRONAGE OF

THE HONOURABLE THE DIRECTORS OF THE EAST INDIA COMPANY.

ILLUSTRATED BY A MAP AND NUMEROUS OTHER ENGRAVINGS.

IN THREE VOLUMES.

VOL. II.

LONDON:

PRINTED FOR T. CADELL AND W. DAVIES (BOOKSELLERS TO THE ASIATIC SOCIETY), IN THE STRAND; AND BLACK, PARRY, AND KINGSBURY (BOOKSELLERS TO THE EAST INDIA COMPANY), IN LEADENHALL STREET;

BY W. BULMER AND CO. CLEVELAND ROW, ST. JAMES'S.

1807.

Figure 4.4: Francis Buchanan's field survey published in 1807 provides a detailed account of life in Canara (Buchanan, 1807)**.**

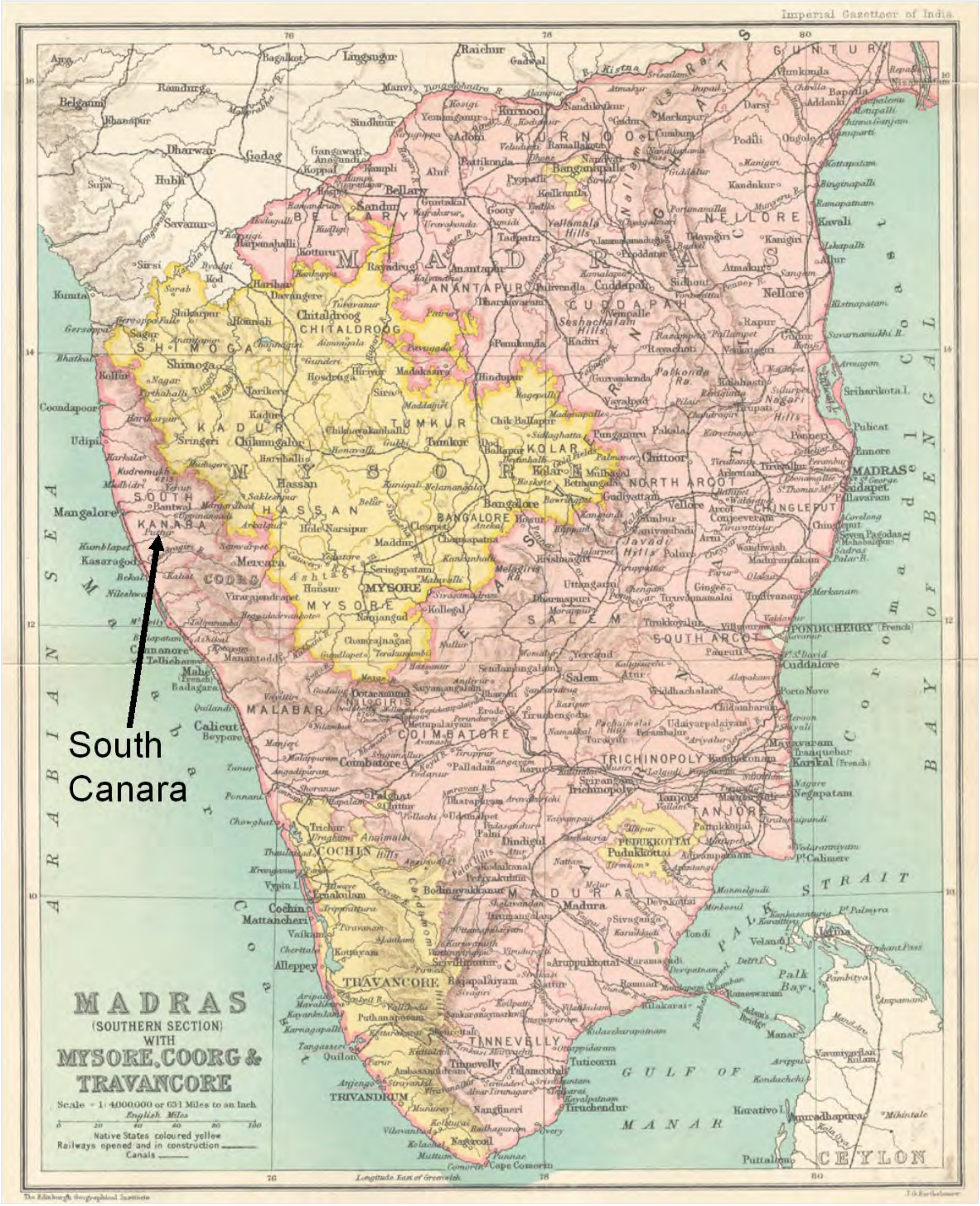


Figure 4.5: Distribution of Madras Presidency and location of South Canara in 1907 CE

(Hunter *et al.*, 1907).

The first official census of South Canara was undertaken in 1871 (Census of 1871, 1874). The adjusted population density trend of South Canara from 1871-2011 has been presented in Figure 4.6, with a best fitting trend line based on the exponential model. It is clear that the population of South Canara increased exponentially since the first census in

1871; however, there was a slight decrease in the population growth of the district between 1891-1931 CE because of the outbreak of an influenza epidemic in 1918 (Madras District Gazetteers, 1938, pp. 216-217). See Appendix C for the corroborated population data for the study area.

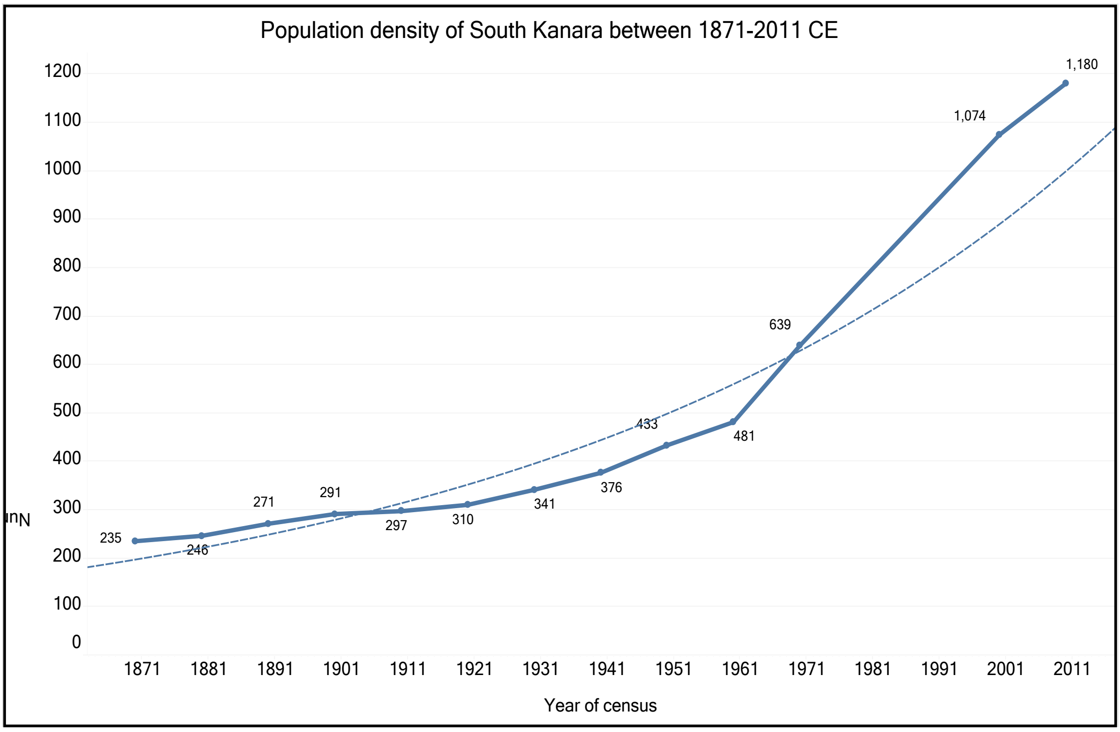


Figure 4.6: Adjusted population density of South Canara between 1871-2011 CE

(Census of 1871, 1874; Census of 1881, 1883; Census of 1891, 1895;

Census of 1901, 1901; Government of India, 2012).

According to the census of 1931, the overall population density in the South Canara district (341 people per square mile) was higher than the average for the entire Madras Presidency (329 people per square mile) (Madras District Gazetteers, 1938, pp. 216-217). This increase can be attributed to the coastal areas, where the population density was the highest in South Canara. For example, the coastal town of Mangalore (838 people per square mile) was the most densely populated in South Canara, whilst the population density was the lowest in the inland forested areas in South Canara (Madras District Gazetteers, 1938, pp. 216-217) where *suranga* are now found. The high population density in flat coastal areas can be linked to trade, employment opportunities and relatively better living standards, in comparison to the limited subsistence agriculture and challenging living conditions in the isolated hilly forests of South Canara (Bhat, 1998). Unlike the clustered dwelling in towns and villages situated in flat areas, homes and estates were often sparsely distributed in the hilly inland villages (Madras District Gazetteers, 1938, pp. 216-217). The census data suggests that the overall number of houses in the South Canara district increased from 189,584 to 244,232 between 1891-1931 (Madras District Gazetteers, 1938, pp. 216-217). The steady population growth in the study area may have resulted in the fragmentation of large joint families in the study area and was followed by fragmentation of land and natural resources. For example, the first settlement survey in Manila village was completed in 1905, with a cadastral map of the village (Figure 4.7). This document was found from the personal archives of a farmer. This map shows individual landholding, and the map was complimented by a settlement booklet containing detailed land records, such as owners' name, land extents, agricultural types of land, respective land revenues, and water resources available on the land. Figure 4.8 is a cadastral map of the Manila village for the year 1997. Comparing both cadastral maps shows that the size of individual landholdings had decreased in 1997 compared to 1905 because of gradual land fragmentations. It also shows that the number of family units in Manila village increased over the 20th century. Traditionally people in South Canara were self-sufficient for their staple food, with rice and sugarcane as the main subsistence crops in the region (Buchanan, 1807, p. 283; Karanth, 1933, p. 12; Bhat, 1998), but the steady population increase may have increased demands for food and water supplies. Moreover, the nuclear families initially relied on shared water resources inherited from the original joint family, but gradually families developed their own water resources either by using traditional knowledge or by employing the latest technological developments such as borewells. Therefore, it is likely that the food security issues may have pushed people to prospect marginal upland areas where water sources were limited.

Figure 4.7: A copy of the first cadastral map of Manila village in 1905 CE, showing large land pockets (Source: Murva Mahabal Bhat, personal archive).

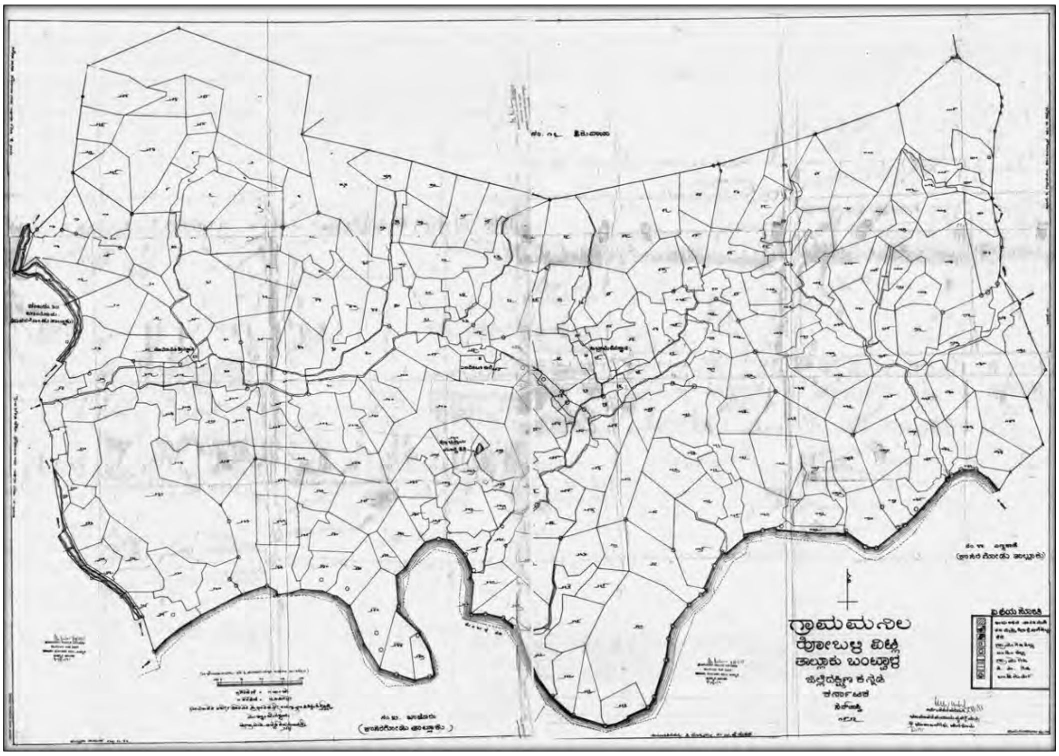


Figure 4.8: A cadastral map of Manila village in 1997 CE, showing small land pockets caused by land fragmentation (Source: Manila Govind Bhat, personal archive).

Like the other districts in the Madras presidency until the late 19th century (Rao, 1919), South Canara district has predominately been a region with many people employed in agriculture and with jobs related to agriculture (Hunter, 1887, pp. 360-361; Madras District Gazetteers, 1938, pp. 270-271). Over generations, the farmers in South Canara, unlike other districts, adapted their agriculture and crop rotation to the hilly geography, soil, and seasonal water availability (Hunter, 1887, pp. 361-363; Bhat, 1998). Historically, the lowlands, situated on sandy plains along the seashore and the banks of the rivers, or the narrow valleys with well water, were the main cultivated areas, and the forested hillslopes were used for grass and wood for fuel supplies (Hunter, 1887, p. 346). However, the cultivable lands were not cultivated up to their full extent or were often abandoned as a wasteland with forest growth because of the harsh climate and labour shortage, and endemic malaria in this forested region (Hunter, 1887, pp. 347-355; Thimmaiah & Aziz, 1983). Thus, with so few settled people in the forested uplands, there would have been little incentive to build a *suranga* in this area.

The main staple crops of the region were rice, sugarcane (*Saccharum officinarum*), millet (*Pennisetum glaucum*), and maize among food grains; gingelly (*Sesamum indicum L.*) amongst oilseeds; and chillies, tobacco, gram (*Cicer arietinum*), plantains, and betel leaf (*Piper betle*) amongst garden crops (Miley, 1875, pp. 46-47; Karanth, 1933; Bhat, 1998). The plantations of coconut, areca nut (*Areca catechu)*, jackfruit (*Artocarpus heterophyllus*), mango, cashew, pepper vines, and tamarind were also common (Miley, 1875, pp. 1, 46-47; Madras District Gazetteers, 1938, p. 306), and small numbers of rubber plantation (Karanth, 1933). In addition, vegetables such as yams, chillies, and seasonal vegetables were grown for food requirements (Hunter, 1887, p. 355). However, rice has been the staple diet and the most popular crop in South Canara (Table 4.3) (Madras District Gazetteers, 1938, p. 211; Kumar & Krishna, 2015).

Table 4.3: Average annual crop distribution 1924-1928 CE in the Madras Presidency (Madras District Gazetteers, 1938, p. 210).

Crop	The average annual cultivated area in ha, (1924-1928 CE)	%
Rice	234511.49	81.72
Coconuts	18814.26	6.56
Horse gram	9200.13	3.21
Areca nut	6914.87	2.41
Black gram	4608.16	1.61
Green gram	3188.52	1.11
Millet	2628.44	0.92
Pepper	2443.49	0.85
Gingelly	1107.22	0.39
Plantain	1054.61	0.37
Castor Seeds	719.94	0.25
Tobacco	589.22	0.21
Betel leaf	407.52	0.14
Turmeric	382.43	0.13
Ginger	180.49	0.06
Hemp	146.09	0.05
Cotton	79.72	0.03
Coffee	8.90	0.00

The paddy fields were in high demand because wealthy ryots invested in paddy fields, while poor farmers and tenants needed paddy fields for their family subsistence (Miley, 1875, p. 44). The best paddy fields were often located at the flat fertile valleys (Figure 4.9) with laterite loam soil and supported by seasonal streams (Hunter, 1887, p. 361). The dry crops were usually cultivated on wetlands after the paddy crop (Madras District Gazetteers, 1938, pp. 28-30). A paddy crop was usually followed by a pulse crop that was succeeded by gingelly if the season was favourable (Department of Agriculture, Madras, 1925). The other staple diet, millet, was usually grown on hillslopes or drylands and was mainly used by poor communities (Hunter, 1887, p. 347).

Figure 4.9: A view of paddy fields and plantations situated on flatlands in Puttur town in the study area (Karanth, 1933)**.**

Coconut was the second most popular product after rice. The popularity of coconut plantations was because of the varied use of coconut tree, leaves and fruits (Miley, 1875, pp. 46-47; Bhat, 1998). Coconut trees were often planted on the boundaries of the paddy field (Madras District Gazetteers, 1938, p. 212). Areca nut was the third most popular cultivation after rice and coconut. South Canara had suitable soil and climate for areca nut plantations. Areca nut palms were irrigated by constructing seasonal dams on the rivers and artificial diversion water channels (Madras District Gazetteers, 1938, p. 213). Areca nut plantations were usually found in the nooks and corners of the valleys (Figure 4.10), where paddy cultivation was not possible, but water and shade were available for the plantation to survive (Hunter, 1887, p. 362). A surge was noticed in coconut and areca nut plantations by 1938 (Madras District Gazetteers, 1938, p. 299), and this is reflected in the current structure of agriculture (Shannikodi, 2013; Kumar & Krishna, 2015), as presented in Chapter 7.

Figure 4.10: A view of a typical areca nut plantation in a valley in the study area
(Karanth, 1933).

There was very little knowledge of the land revenue history of South Canara when the British East India Company acquired South Canara in the fourth Anglo-Mysore war in 1799 CE (Hunter, 1887, p. 356; Bhat, 1998). It is essential to understand this history because it may provide a glimpse into where *suranga* were found. There was inequality in the collection of this revenue in the absence of any set/written rules of land revenue and lack of comprehensive land settlement records, and these revenues varied between 10% - 60% of the total value of the produce (Madras District Gazetteers, 1938, p. 27). Moreover, a comprehensive land record was needed in the Madras Presidency to apply the *ryotwari*[20] revenue system across the Madras Presidency. Therefore, the first cadastral

[20] The *ryotwari* agricultural revenue system was developed by Sir Thomas Munro and Captain Read in 1820 CE, but in the absence of comprehensive land settlement records, it could only be applied to a small area in the Madras Presidency.

survey of the Madras Presidency was initiated in 1858 by the survey department, with the primary objective for the survey being the demarcation of properties at the village level and to produce field maps and land registers with supplementary information about nature, area, assessment, and ownership of each property (Boag, 1933, p. 45; Bhat, 1998). Gradually, most of the region in the Madras Presidency was incorporated under the *ryotwari* revenue system; however, it could not be applied in South Canara to solve land disputes because of the absence of a comprehensive land survey in South Canara (Miley, 1875, pp. 44-47; Boag, 1933).

Finally, a land survey in South Canara was started in 1889, and the settlement operations began in 1894 (Hunter, 1887, p. 368), but could not be completed until 1903 CE because of technical and administrative delays (Madras District Gazetteers, 1938, p. 27, pp. 206-210). Thus, South Canara was the last district in the Madras Presidency to be settled (Madras District Gazetteers, 1938, p. 27), demonstrating that the region of South Canara at the turn of the 20th century was sparsely populated and less than one-fifth of the total land was cultivated by 1903-04 (Hunter, 1887, p. 362). Challenging geography, dense hilly forests, torrential seasonal rainfall, and the inaccessibility of South Canara may have been the reasons for the delayed start of comprehensive land surveys and settlements in South Canara. So, it seems logical to assume that there would have been little demand to build new water harvesting structures like *suranga* before this point.

Farmers could also apply for *dharkast* (contract) on wastelands near to their properties, that could eventually be converted into the cultivable farm (Miley, 1875, p. 40) and land prospecting in the form of encroachment onto dry land/wasteland by the farmers was common in the district (Hunter, 1887, p. 363; Bhat, 1998). The cultivated area steadily increased between the settlement records in 1903 and resettlement in 1934-35 (Madras District Gazetteers, 1938, p. 299), but still, there was further scope for extension of cultivable land in 1938 (Table 4.4). Just over half of the government land was considered uncultivable because it was mainly forest, wasteland, roads, streams, rivers, and villages. Significant initial investments were usually required to convert drylands to cultivable land, and most of the population in the area was small ryots.

Table 4.4: Government land proportions in 1938 CE in South Canara

(Madras District Gazetteers, 1938, p. 298).

The total Government land in hectares	**Land type**	**%**
1,041,486.42	Forest land, wasteland, not cultivable	51.65%
	Cultivated land	22.24%
	Available for extension of cultivation	26.11%

The low taxes on converted land motivated peasants to increase the cultivated area, but this needed to be underpinned by developing new water resources. Dug well were commonly made in the valleys because water could be found easily at shallow depths (Karunanidhi *et al.*, 2021b), but terraced fields, such as situated at high elevation, could be used only for single crops during the monsoon season because of water scarcity for irrigation. Therefore, in the past, farmers mainly used to grow rainfed crops.

Slash and burn agriculture, also known as *kumari, bewar, jhum,* and shifting agriculture, was also popular in the highland forests of South Canara (Hunter, 1887, p. 348; Fisher, 2018, p. 27). In *kumari* agriculture, paddy and tuber crops were usually grown in forested regions after clearing and burning the brushwood and trees (Madras District Gazetteers, 1938, p. 159; Viswanath *et al.*, 2018), and some of these forests were government lands (Miley, 1875, pp. 46-47). *Kumari* cultivation was mainly practised for subsistence food by tribal (locally known as *Kudubies*) and poor ryots living in the forests (Madras District Gazetteers, 1938, p. 302). These communities would move from place to place in the process of shifting agriculture (Fisher, 2018, p. 27). *Kumari* cultivation was practised in 21 villages in Kasaragod taluk (Madras District Gazetteers, 1938, p. 189), which is part of the study area. *Kumari* cultivation was initially discouraged and later prohibited by the government by implementing Forest Acts first in 1860 (Hunter, 1887, p. 364; Fisher, 2018, p. 29) and later entirely in 1920 (Madras District Gazetteers, 1938, p. 302) because slash and burn cultivation was said to be unhygienic, and damaging to the environment (Miley, 1875, pp. 46-47; Fisher, 2018, p. 29). As a result, the *kumari* cultivators gradually started to undertake settled cultivation or work as labourers in other farms (Madras District Gazetteers, 1938, p. 302). Perhaps that is why there seems to be no indication of any tension between the foragers (slash and burn) and the new permanent farmers recorded. During the resettlement in 1934-35, the forested *kumari* lands were permanently resettled as dry, wet, or garden land (Madras District Gazetteers, 1938, p. 189). The land tax rates were lower for interior land areas because of complex living conditions in these densely forested lands (Madras District Gazetteers, 1938, pp. 28-30). So, this represents a peopling process in the study area, thereby creating a demand for irrigation water.

State irrigation under the Madras presidency was divided into two types, the first for the construction of canals that were mainly used for large scale irrigation and navigation (Agarwal & Narain, 1997), while the latter was for the maintenance of smaller tanks and river channels that were overseen by the local government (Boag, 1933). The Godavari, the Krishna, and the Cauvery deltas were examples of grand irrigation systems in the Madras Presidency. It appears that various irrigation improvement plans and agricultural loans were in place in most of the districts of the Madras Presidency (Boag, 1933), but strangely there was no government irrigation works/plans, such as a largescale water project or a dam (Bhat, 1998). Largescale water projects or dams were not practical in this region, because of the challenging geography, with steep hilly terrain and the dense forest of the Western Ghats, laden with abundant, torrential monsoon rain made this area geographically more complex and less attractive for the administrators (Hunter, 1887, pp. 355-363; Madras District Gazetteers, 1938, p. 295, 301). Therefore, the government did not significantly invest and administer agriculture and land in South Canara (Hunter, 1908). Therefore, the locals initially relied on seasonal water resources and gradually may have developed the *suranga* system to increase water availability for subsistence agriculture. This section provided a brief history of the study area, and now the following section focuses on finding the age and origin of the *suranga* system within this history.

4.2.2 The age and origin of *suranga*

The results collected from archival methods provided a historical context to agricultural and land management in the study area and based on the presumption of silence, which is a rarely used epistemological approach that argues if something is so significant or ubiquitous and visible in the present-day environment, it would be worthy of being officially recorded or enumerated in historical documentation (see Elvin & Crook, 2003; Crook & Elvin, 2013), which provides the starting point for the building of *suranga*. In the study area, traditionally, water from streams and rivers had to be manually lifted with the help of indigenous water lifting structures, such as *pycottah* (Miley, 1875, p. 25) and *kaidambe* (Buchanan, 1807) (Figures 4.11 and 4.12), which is like the ancient water lifting shaduf found in India and in other parts of the world (Yannopoulos *et al.*, 2015). Wells were a primary water source in towns (Miley, 1875, pp. 8-9), and a minimal number of borewells were reported in Mangalore town constructed by the local government to provide drinking water in the town by 1938 (Madras District Gazetteers, 1938, p. 295). Two field surveys undertaken by CWRDM in 1992 and 2002 CE to explore the distribution of *suranga* appear to be the first official studies, and they aimed to explore the distribution and physical characteristics of the *suranga* systems in a small area (Prasad *et al.*, 1991; Nazimuddin & Kokkal, 2002). They did not, however, examine the origin and development history of *suranga*.

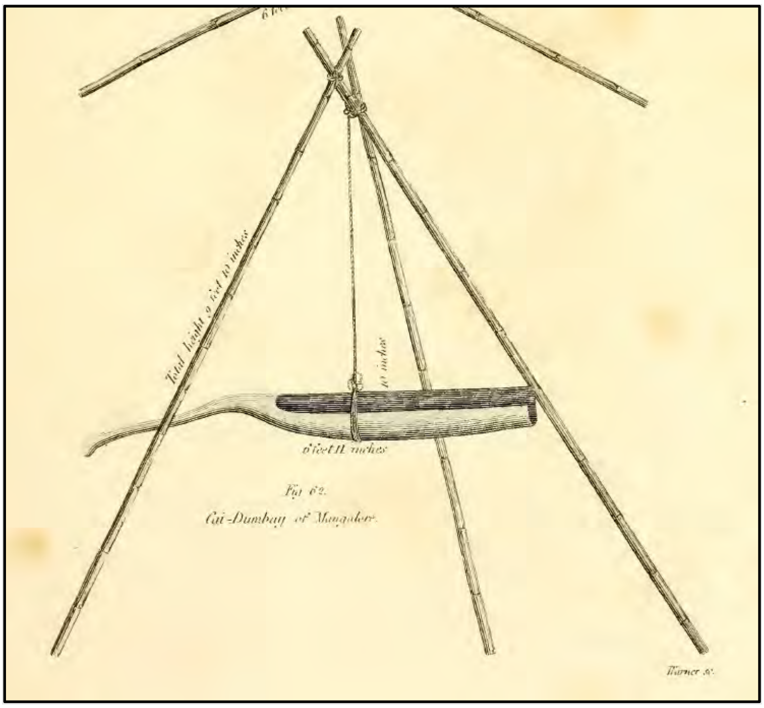


Figure 4.11: A traditional water lifting method known as *kaidambe* from South Canara (Buchanan, 1807).

Figure 4.12: Paddy and sugarcane fields with a *kaidambe* in the picture in the study area (Karanth, 1933).

To overcome the *lacuna* in official information on *suranga*, an alternative data collection strategy was used from the social sciences to find the history of *suranga*. Using oral history or testimony, farmers provided accounts and estimates about their *suranga* (R43; R83; R69; R93; R104; R133; R135; R163)[21]. Though it is still difficult to say with confidence about the exact age of the *suranga* system in the study area, oral history suggests that the oldest *suranga* in the study area were constructed in the early 20th century (R58; R98). Based on a farm owners' account, the oldest *suranga* would have been made in Bayar village in the 1920s, and the oldest *suranga* in Manila village was made sometime in the 1930s (R127). However, some farmers who bought a farmstead/farm did not have exact information about the history of *suranga* in their property because *suranga* were made by the previous owner (R116; R152; R156; R157).

In another example, a detailed map of one of the oldest farmsteads in the Manila village from the study area in 1896 CE has been shown in Figure 4.13. This document is written in old Kannada, which was challenging to understand. Still, this map seems to be an agreement set by a district court proceeding to support a water issue because it mentions Plaintiff and Defendant. Before the 1960s, there were no water pumps in those days (Bahinipati & Viswanathan, 2019), so farmers relied on water through channels from large shared/private tanks. A detailed description of all water resources available in and around the farmstead, including various water tanks, a large shared water tank (area 1.6 ha), springs, various water channels, seasonal water streams, use of wooden water pipes, and stone lined water channels have been provided in the map. Furthermore, the location of the house, cowshed, stone walls, laterite stone boulders, farm boundary, paddy fields, barren land, grassland, coconut and areca nut plantations, palm trees, jackfruit trees, tamarind trees, and remains of large trees have been mentioned. There is no mention of *suranga* or any similar structure on this map, suggesting there were no *suranga* within the property in 1896 CE; however, during the field survey, five perennial *suranga* were

[21] The numbers such as R43; R83; R104 are references to the in-depth qualitative interviews.

found in the same farmstead, but according to the current owner, these five *suranga* were constructed between 1940-1970 CE.

Figure 4.13: A map of a farmstead from the study area from 1896 CE

(Source: Murva Mahabal Bhat, personal archive).

Furthermore, most of the respondents did not know the exact age of their *suranga;* therefore, they were asked about the approximate year of construction of their oldest and the latest *suranga*. Thus, Table 4.5 is presented as four broad periods of *suranga* construction pre-1900 CE, between 1900-1950 CE, between 1951-2000 CE, and post 2000 CE. The first *suranga* of 91.6% of families were made in the 20th century, and only 5% of the first *suranga* of any family was made post-2000 CE. A total of 84.3% of the families reported that their latest *suranga* were constructed in the 20th century.

Table 4.5: Periods of *suranga* construction in the case study area.

	Pre-1900 CE	1900-1950 CE	1951-2000 CE	Post-2000 CE	No information
The first *suranga* constructed in a household	0	19.7%	71.9%	5.0%	3.4%
The last *suranga* Constructed in a household	0	3.9%	80.3%	12.4%	3.4%

The main conclusion that emerged from the survey and in-depth interviews were that none of the *suranga* in the study area had been made before 1900 CE, but the excavation of *suranga* seems to be started in this region post-1900 CE, and the rate of construction of *suranga* was the highest in the second half of the 20th century. Similar results were obtained in surveys undertaken by CWRDM (Prasad *et al.*, 1991; Nazimuddin & Kokkal, 2002).

A small number of local people believed that *suranga* might have been brought into this region by a migrating community of *kharad* Brahmins from Maharashtra because *suranga* are widely used by the families of this community (R65). In the survey, people with the surname '*Bhat'* constituted 40.9% of the respondents, and Naiks were 22.3%. These two were the dominant castes using *suranga* systems. Bhats are *kharad* brahmins, and Naiks are allegedly the lower caste community, and both communities migrated to the study area from Konkan, Maharashtra. According to a local scholar of *kharad* history, this migration took place approximately 400 years ago (Halemane, 2007), but *suranga* do not seem to be that old (R37).

Moreover, there is no similar *suranga* reported at the place of origin for *kharad* Brahmins in Maharashtra. The primary occupation of this community was initially religious teaching, but it is assumed that gradually they started undertaking agriculture after settling in this area (R37), perhaps to achieve food security for the growing population. Therefore, there is no evidence to support the idea that *suranga* were brought to this region by the *kharad* Brahmin community. However, some respondents also believed that *suranga* might have been made as a hideout by the local people living in the hilly forest area to keep away from the associates of the tyrant Muslim rulers, especially Hyder Ali and his son Tipu Sultan, who ruled between 1763-1799 CE (R22; R55).

There is no concrete evidence available to link both the ideas suggested above with *suranga* history because none of the *suranga* in the study area was found to be constructed before 1900 CE. Moreover, the study region was a remote, densely forested frontier with a small number of aboriginal communities during the reign of the rulers mentioned above. Therefore there was no practical requirement to excavate *suranga* for agricultural reasons. The only possible use could have been as a hideout. The communities might have migrated into these frontiers either to avoid persecution during the reign of tyrant rulers or to prospect the frontiers; however, this is not sufficient evidence to support the idea of *suranga* construction for shelter refuge.

In contrast, there is a widely held view held by Indian academics that the *qanat* water system technology (see chapter 2) of the Middle East may have been diffused into the western coast of India through trade. There is evidence for this technology transfer in other parts of India (Raghuwanshi, 2006; Wahurwagh & Dongre, 2015; Mishra, 2017), as mentioned in section 1.2. Through conjecture and misplaced ideas of structural similarity, this leads to the most popularly held myth based creation theory that *suranga* may have been introduced to this region by the sailors from the Middle Eastern countries who visited and settled following trade (Prasad *et al.*, 1991; Nazimuddin & Kokkal, 2002). However, there is no correspondence between the relatively recent history of *suranga* and the medieval period when Arab traders, that reached their peak in the 9th century, and especially when these traders caused significant influences on the language and socioeconomics of the indigenous Muslim communities inhabiting the western coast in India (Flecker, 2001; Ilias, 2007).

Furthermore, there is no supporting terminology or nomenclature for various technical and operational aspects of the *suranga* systems usually found in other old water harvesting systems, such as the *qanat* system (English, 1968; Stiros, 2006; Lightfoot, 2012; Mahan *et al.*, 2019). Some farmers believed that the first *suranga* in the area was made for drinking water by digging a seasonal spring or a seasonal stream, inspired by two famous sacred, thermal springs *Bendre Thirtha* near *Puttur* and *Panekal* near *Uppinangady* (Chandrashekar *et al.*, 2020) and natural water-bearing sacred caves which may have been formed because of long term subsurface weathering and gully erosion (Kumar *et al.*, 2020, pp. 8-10) such as on the *Possadigumpe* hill of Bayar village $_{(R53, R58)}$. There are several other natural caves in the hills in this region, such as *Jogipade* in Manila village, a cave in *Ananthapura* Lake Temple, and caves of *Kadri Manjunatha* Temple in Mangalore $_{(R40)}$. The *Possadigumpe* cave has a significant water source inside it (Figure 4.14), and this cave is assumed to be holy and auspicious by locals and usually linked with mythology, but the origin and age of this eroded cave is unknown $_{(R55)}$, but very likely formed by soil piping erosion, which is common in the study area (Sarath *et al.*, 2020).

Figure 4.14: The entrance of the *Possadigumpe* cave in Bayar village.

There is no historical evidence of syphoning techniques being used in this region, which is the only way water could be used from these large cave sources. Thus, there seems little foundation for these claims either. Of more probability, it seems likely that farmers, as they first pioneered these lands searching for water in a place of scarcity, would have focused their attention on identifying existing natural spring locations where freshwater supplies could be found. During the dry season, these sources are most likely to have slowly dried up or lessened in flow, such that this prompted at least one farmer to dig further into the hill to see if more water could be abstracted from a known source. With success and by word of mouth, this idea slowly spreads throughout the nascent community, and a small jump is made to try the same techniques on slope faces of laterite that seem to have high water content. Again, successful retrieval of water from these gallery filtration systems further enhances a successful reputation, and the *suranga* system starts to flourish.

4.3 Chapter summary

This chapter answered research question 1, which identified the origin and development history of *suranga* in the study area. Oral history and analysis of archival documents were used to collect data. The results suggest that the study area, a remote frontier of the large Madras Presidency, was a densely forested area with undulating terrain and a relatively sparsely distributed population over fertile valleys. The increasing population in the late 19th century and food demands may have forced farmers to achieve food security by either growing more crops or cultivating new areas, and both needed regular water supply for irrigation. This water availability based on monsoon rains was seasonal but resulted in water scarcity in dry summers. Therefore, over the centuries, the communities may have developed indigenous methods for water management in the study area to combat seasonal water scarcities such as dug well and seasonal check dams. However, the *suranga* became the latest adaptation in the early 20th century to capturing and storing seasonally scarce water resources. Based on oral testimony and the field survey, one of the oldest *suranga* was constructed in the early 20th century in the Bayar village of Kasaragod district, yet the actual origin of *suranga* could not be traced. However, the results suggest that the inspiration for constructing a *suranga* may likely have been germinated from the natural watering caves, or by digging the receding seasonal springs might have been the origin of *suranga* in the study area. The next chapter presents the data collection methods and results obtained about the spatial distribution, design principles, construction and maintenance of the *suranga* system in the study area.

Chapter 5 – Spatial distribution and design principles

Chapter 4 provided the context to the origin and development history of *suranga* to understand the reasons for their development and origin. It then becomes vital to understand if the *suranga* system provides a potential or partial solution to providing clean water supplies to marginalised groups in the study area where water is scarce. It is only possible to appraise the potential success of the system by fully understanding the spatial distribution, design principles, and structural classification of *suranga*. Therefore, this chapter provides the answers to research questions two and three below.

> **Research Question 2:** What is the spatial distribution of the *suranga* system in the study area?
> **Research Question 3:** What are the design principles, governance and management systems underpinning *suranga* use in the study area?

Section 5.1 provides a description of the survey method used to explore the spatial distribution (section 5.2) and physical characteristics of the *suranga* system, which includes site selection techniques for a new *suranga*, excavation process, design principles (section 5.3), structural classification (section 5.4), and the associated construction and maintenance costs (section 5.5). Section 5.6 reports flora and fauna found inside the *suranga* during the survey. These results increased understanding of the key technical adaptations that allowed *suranga* to function successfully over approximately the past 100 years. A summary of this chapter has been presented in section 5.7.

5.1 *Suranga* survey

The literature review indicated an absence of a comprehensive database of *suranga* and *suranga* users. Therefore, during the initial stage of this study, it was planned to compile a complete database of *suranga* users by surveying the whole population in the study area. However, after a couple of weeks of fieldwork, the constraints of undertaking a comprehensive data collection survey were realised. Undulating topography, monsoon climate, dispersed dwellings, inaccessible families living in remote locations, difficult travel, the limited availability of local guides to support the fieldwork, and the duration of the fieldwork were the main factors in restricting the size of the survey sample.

Fortunately, the research was reported to a national and regional audience by an Indian English newspaper (The Telegraph, 2012) and the Kannada news channel ETV with an audience of around 1 million viewers. To raise local awareness about this study in the region and to increase the catchment area and the population of the survey, it was possible through personal links to the Indian water journalist, Shree Padre, to get news on data collection activities published in various local newspapers, such as *Vijayavani*[22], *Vijay Karnataka*[23], and *Udayavani*[24], where the readers were requested to provide any information related to *suranga* by contacting the host in the study area (Figure 5.1). Despite the limited distribution of local newspapers into the towns, a small number of people (five people) provided additional information about *suranga* in their area by contacting the local guide over the phone. The main success of this technique was finding three *suranga* in the Shimoga district of Karnataka state. Increased publicity of the research also increased awareness and acceptance of the research by the communities in the study area.

[22] https://www.vijayavani.net

[23] https://vijaykarnataka.com

[24] https://www.udayavani.com

ದಕ್ಷಿಣ ಕನ್ನಡ - ಕಾಸರಗೋಡು ಲೋಕಲ್ ಸೋಮವಾರ 29 ಅಕ್ಟೋಬರ್ 2012 5

‘ಸುರಂಗ ನೀರು’ ಅಧ್ಯಯನಕ್ಕೆ ಬಂದ ವಿದೇಶಿಗರು

Figure 5.1: A news article covering this study in a Kannada daily newspaper, *Vijayavani*, on 29 Oct 2012.

During data collection, various social events and religious gatherings were attended along with the local host so that contact could be made with people and to develop a rapport with the locals, which later indirectly helped the survey and in-depth interviews and enabled gradual embedment into the community. Moreover, local schools, colleges, banks, cooperative and religious meetings were visited to become acquainted with the wider groups, and some of the survey interviews were done during these meetings. Help was also sought from eminent and famous individuals, such as local political and religious leaders, from the study area to develop further contacts and find respondents in the study area.

An attempt was made to learn the local dialects so that it was possible to communicate with the farmers and workers in the absence of a local guide. It helped in reinforcing a keenness and researcher’s respect for local customs and language, and in return, gained support during the fieldwork. In this way, sometimes it was possible to unearth *suranga* information that even local guides were unaware of. In the consecutive field trips, farmers and workers were provided with their photos taken during the first meeting, which helped increase cooperation and help from them. Regular field trips to the region also built confidence among the locals. Furthermore, using public transport for travelling between villages was also helpful in meeting new respondents for the survey and increasing the contacts in the study area. The only form of public transport in the study area was government and private buses, which connected villages and towns, and was used by a sizeable portion of the population because access to personal vehicles is not common. Thus, the use of public transport provided opportunities to interact with new acquaintances. As a result, local farmers came forward to offer information and an invitation to interview them in many cases.

Gradually, over time inclusion into the community occurred and was acknowledged by the type of questions asked by the local people. For example, locals asked questions about identity and personal background information during the first field trip. However, over time these questions transformed and were gradually replaced by questions related to the arrival and duration of stay, this indicated acceptance into the community. Thus, a nonprobability snowball sampling strategy was the best way to move forward in a community where networking was crucial for collecting data, as described in the next section.

5.1.1 Field measurement methods

The physical survey of the *suranga* involved measuring dimensions and recording various physical characteristics of *suranga*. The following structural properties, which were initially observed by the CWRDM survey (Prasad *et al.*, 1991) and Tripathi (2009), were recorded for *suranga* to ascertain the design principles of the system (Table 5.1).

Table 5.1: Structural properties of a *suranga.*

Design feature	Method of data collection
Length (m)	Pacing
Width (m)	Tape measure
Height (m)	Tape measure
Location (Elevated/ Inside a well)	Visual
Single or branched channels	Visual and count
Number and types of water sources	Count
Number and location of ponding structures	Visual and count
Perennial/seasonal/dry	Visual and question
Convergence: Open channel or piped	Visual
Number of collapsed sections and their locations	Visual and question
Number of airshafts and their locations	Visual, count, question

All *suranga* had external features recorded, noting location, airshafts, and water availability. In most cases, it was not always possible to use a tape measure inside a *suranga*; thus, the pacing was used to estimate the distance from the entrance to the end of a *suranga*. This distance was then calibrated with a standard tape measure. An internal survey of each *suranga* was not possible because of access and safety risks caused by low heights, short widths, darkness, and various dangerous snakes found inside *suranga*. Therefore, the decision to enter any *suranga* was based on the host's advice, local guides, owners of the *suranga*, personal observations and risk assessment (see Appendix D). Moreover, some *suranga* were inaccessible because of their location. For example, *suranga* in an open well or a dug well could not be accessed because they were mostly submerged in water. Thus, in *suranga* that could have been unsafe to enter or were not accessible, the details were orally confirmed with the owners during the *suranga* survey (see Appendix E).

The results for this chapter are presented in the following sections.

5.2 Spatial distribution of *suranga*

In context to the vast area of India, the distribution of *suranga* is mainly restricted to hilly regions in DK and Kasaragod districts (R54, R161). Manila Village was the centre of this study, with families interviewed, supplemented with data from families in the neighbouring villages, with 700 *suranga* surveyed in fourteen villages (Table 5.2) that are shown in Figure 5.2. These numbers are only the surveyed *suranga* in this study. The actual number of total *suranga* is likely to be higher.

Table 5.2: Summary of *suranga* surveyed in the study area.

Village name	State	Number of *suranga*
Manila	Karnataka	266
Enmakaje	Kerala	187
Kepu	Karnataka	49
Peruvai	Karnataka	47
Bayar	Kerala	41
Padre	Kerala	32
Kanyana	Karnataka	19
Priyol	Goa	14
Paddvanuru	Karnataka	13
Alike	Karnataka	10
Karvapadi	Karnataka	9
Puttur	Karnataka	5
Maire	Kerala	5
Hiremane	Karnataka/Shimoga	3
Total *suranga*		**700**

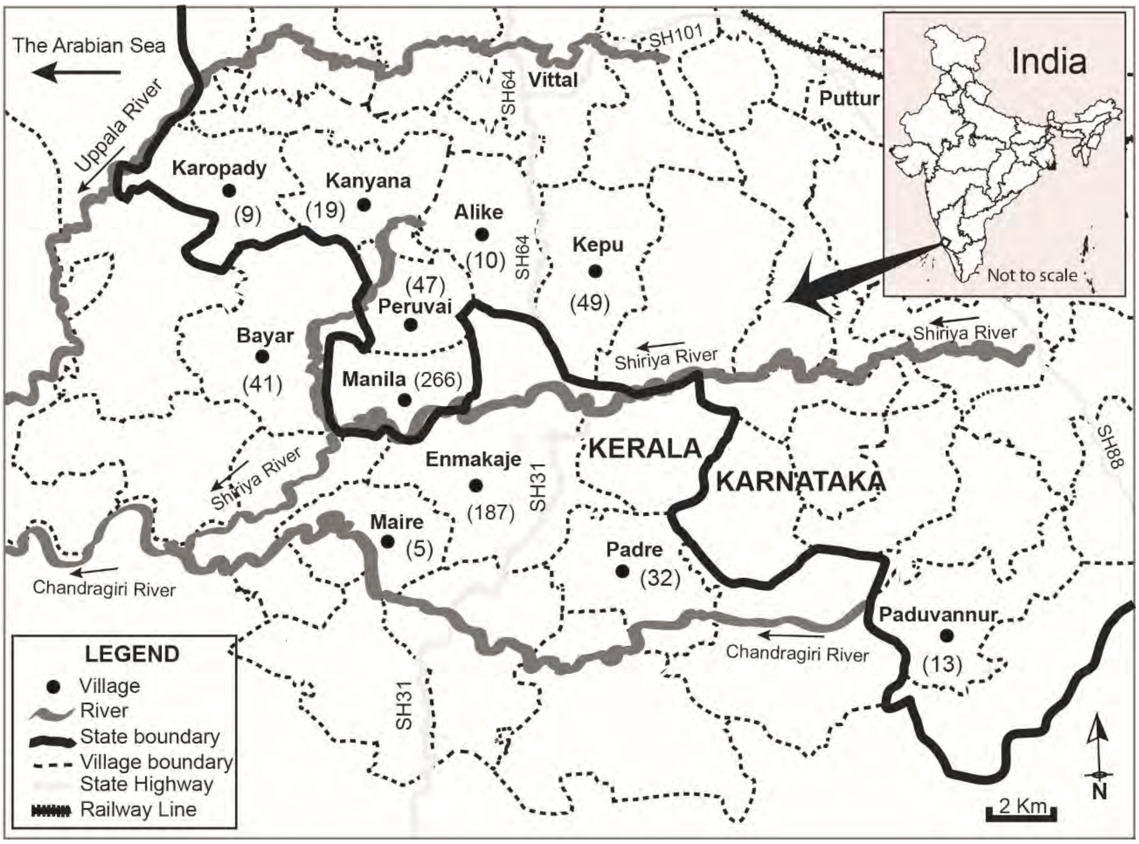


Figure 5.2: A map of the core study area with the number of *suranga* surveyed.

During field interviews, it was found that the technique of *suranga* construction spread out of the study area on two occasions (R48; R60; R62). First, the knowledge of *suranga* was transferred from *Bayar* village in Kasaragod district to the water scarce villages in the Ponda district of Goa after an arranged marriage. In this case, a *suranga* worker was called to make a *suranga* in the Ponda district in Goa, which is approximately 400 kilometres north from the study area, and later the *suranga* worker was contracted to construct further *suranga* for neighbouring families (R55). Thus, fifteen *suranga* were found in Priyol village in the North Goa district of Goa state (R60; R62). In the second example, a tourist from Shimoga district was impressed when he saw the reliability and quality of water supplies in *suranga* found in Kasaragod district, and this person later constructed a *suranga* in his home in Hiremane village in the Shimoga district of Karnataka state, which is approximately 240 kilometres north of the study area (R48). The owner led the *suranga* excavation with hired local labourers (R7). *Suranga* were also reported in the Wayanad district and Kannur district of Kerala by a *suranga* worker who constructed these (R51). However, they were not included in this survey because the *suranga* worker could not remember their exact locations. Nevertheless, in this study, the majority of *suranga* were found on the western slopes of the foothills of the Western Ghats in India, and these *suranga* are known to have been excavated by workers either from DK or Kasaragod districts (R51), which suggest that the *suranga* are mainly found in a small geographical region in and around the study area.

5.3 Physical characteristics of *suranga*

Suranga are known by different names in local languages and dialects, and the other names are *surangam*, *jal-thurangam*, *thurangam*, *thorapu* and *mala* (Basak *et al.*, 1997; Halemane, 2007). These names often mean a tunnel, and *jal-thurangam* means a water tunnel. The varied nomenclature of *suranga* can be ascribed to the multilingual nature of communities and the cultural diversity of the area. The dimensions of a tunnel are often optimised to just over the size of the *suranga* worker assigned to excavating the tunnel (R44) (Figure 5.3). Thus, the heights of *suranga* excavated were mostly between 1.5 metres to up to 2 metres, and the width of tunnels were found to be between 0.4 – 1.0 metre. The height and width of a *suranga* may increase over time because of soil collapse inside a *suranga*. The average length of *suranga* was found to be 33.08 metres long, with the shortest *suranga* found in Manila village in DK district at three metres long, and the longest *suranga* in a school in *Maire* village in Kasaragod district at ~295 metres long.

Figure 5.3: Inside view of a typical *suranga* tunnel, during excavation of a *suranga*.

Before constructing any new water resource, including *suranga*, people usually seek help from local water diviners for site selection (R38; R100). The water diviner is invited to visit the farmstead by the farm owner. Although the water divining task is often undertaken voluntarily, as a goodwill gesture, a water diviner is often paid in cash or kind for their time and travel costs. The task of a water diviner is to suggest the spot within a farmstead with the most significant water availability and suggest the most appropriate traditional water harvesting method to be used from a selection of *suranga*, well, and dug well (R38). If the water diviner thinks there is insufficient groundwater available, people may choose to construct a borewell (R55; R173). Nowadays, some of the traditional *suranga* water diviners also divine suitable locations for sinking a borewell (R55; R173), however, the hydrologists trained at research organisations and working for government departments are also available to help in locating suitable sites for borewell sinking.

Water diviners only suggest a location for constructing a *suranga* or a well; they usually do not have any experience of constructing a *suranga* or a well (R106). Water diviners are mostly self-trained and have their own methods of water divining, and usually, their methods are kept a secret by the diviners (R53). Seeking advice from a water diviner is not a mandatory process. For example, some experienced *suranga* workers also claimed to have water divining skills developed by learning the basic principles of water movement through observations while working inside a *suranga* (R51; R52). Besides this, farmers decide on a site for *suranga* construction by externally observing the topography and water movement during the rainy season (R109). However, there were examples when people did not seek advice from a water diviner either because ownership of a small land parcel limited choice (R85), or they already had a basic understanding of water movement from their previous personal experiences of constructing a dug well, or a *suranga* (R60; R108; R109; R165). Some amateur *suranga* workers sought advice from water diviners before starting excavations (R124), whilst others selected the location themselves (R121).

During the survey and interviews, broadly, two types of water diviners were observed. The first type of water diviner uses their knowledge about the physical characteristics of a hill, such as the natural slope, geology, catchment orientation, and soil, rock, and vegetation types to find a water rich area, and other times they may just follow the natural surface water movement during the rainy season (R38). For example, a hillslope is often taken as a sign of subsurface water availability (R73; R128). Water diviners also often search for traces of seasonal springs and locate hydrophilic plants, vegetation and trees that primarily grow in water rich areas. Examples of such plants are *Nekare* (*Melastoma malabathricum*) shown in Figure 5.4, *Uppaylge* (*Heliotropium subulatum*), *Goli* (*Ficus tinctoria*), *Basari* (*Ficus lacor*), *Dhoopada Mara* (*Vateria indica*), *Pala* (*Alstonia scholaris*), and naturally occurring bamboo shrubs (R68; R69; R152). The humidity of soil further helps narrow down the most suitable spot for excavation, which is often interpreted by the white mottled appearance and clayey texture of the soil (R79). Termite hills are another water indicator because these are often associated with a shallow water table (Padre, 2002; Halemane, 2007). Observations and experience mostly underpin these water divining techniques. Thus, the success of these water divining methods can vary according to the logic and experience of a water diviner.

Figure 5.4: According to locals, *Melastoma malabathricum* grows in water rich spots.

The second type of water diviners are people who claim to have some mystical powers. These water diviners often use an object for the water survey, such as a coconut, twig, metal y-fork, gold chain, or gold watch (R111). These diviners walk through the field with the object in their hands, and wherever they sense a strange movement of the object in their hands, or if the object falls from their hands, they suggest a subsurface water source (R128). These water diviners usually did not openly discuss their techniques when asked during the interviews (R121).

> *"I decided the location for this suranga myself… I am planning to make a borewell. I have decided on the location for this myself"*. [When asked about their water finding technique, the water diviner just laughed but did not say anything] *(R121)*.

Thus, the second system of divining has been reported elsewhere (Vogt & Golde, 1958; Dillinger, 2017) and seems less objective than the first, and as such, the first method seems to be more commonly used.

Once a suitable location for a *suranga* is decided, specialist workers are hired. These workers are skilled in lowlight, underground excavation in claustrophobic conditions (R163). *Suranga* workers often learn excavation skills by assisting an experienced *suranga* worker as an apprentice (R51; R71; R166) or merely observing a *suranga* being constructed (R73). In addition, some of the *suranga* workers learnt excavation skills at an early age by helping their families build a *suranga* (R143; R145). Figure 5.5 shows a *suranga* worker during excavation.

Figure 5.5: A *suranga* worker during the excavation of a *suranga*.

Occasionally, a *suranga* owner may choose to work as an assistant in their *suranga* along with the expert *suranga* worker to minimise the cost (R51, R71; R153), or the owner may choose to excavate their *suranga* themselves because of financial difficulties (R101). These amateur *suranga* workers learn *suranga* construction work by observing others (R64; R79; R88; R100; R118). Forty two labourer families in the survey excavated their own *suranga* because they did not have enough funds to employ expert *suranga* workers (R118; R142). Several poor daily wage labourers, who could not afford to skip their job to make a *suranga* at home, excavated their *suranga* themselves part-time and mainly in the evenings, and they were helped by their family members (R44; R77; R88; R109; R121). The families who did not have a male member in the family to help the primary worker were supported by the women of the house, who supported the digger by removing soils from the *suranga* (R99; R109). However, women are not usually directly involved in *suranga* excavation or decision making processes related to *suranga* construction (R178). In a small number of cases, untrained farmers also excavated *suranga* purely out of personal interest in the technique (R101). In these cases, a minimum of one *suranga* per family was often excavated by the owner and subsequent *suranga* were excavated by professional *suranga* workers (R90).

Any new development work, including excavating a *suranga*, usually starts on an auspicious day and time suggested by a local religious person based on the regional almanac. The essential manual tools used in any construction settings are used for *suranga* excavations: a chisel, hoe, spade, sledgehammer, pickaxe, head pan, candle, and oil lamps (R38). Some of these tools are shown in Figure 5.6 and 5.7 from a *suranga* worker's collection. A maximum of two workers can work inside a *suranga* at any time: the chief worker excavates the tunnel at one end, and the helper removes the rubble from the tunnel to the other end (R51; R151) (Figure 5.8).

Figure 5.6: Tools used for *suranga* excavation.

Figure 5.7: Pickaxes of different sizes used for digging inside a *suranga*.

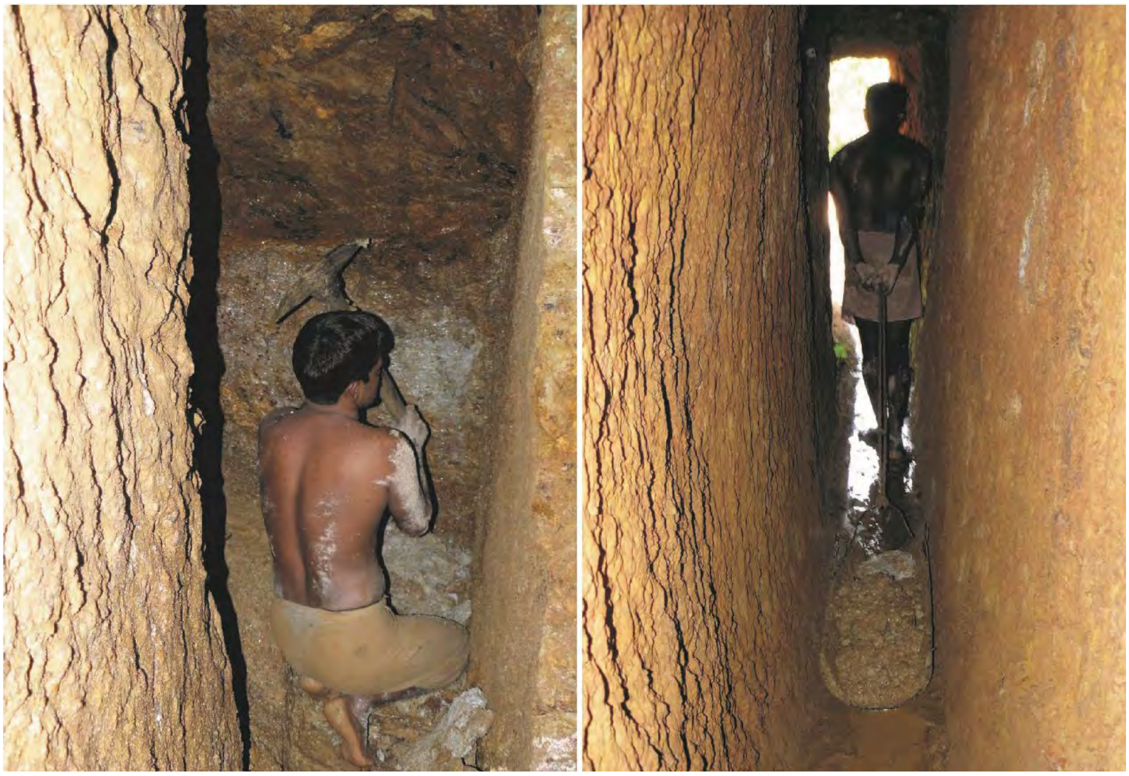


Figure 5.8: Excavation inside a *suranga* and removal of debris (Source: Shree Padre).

Historically, large leaves of Fishtail Palm (*Caryota urens),* locally known as *Bynemara* trees, were used to remove excavated soil inside a *suranga*, but these soon wore out. Head pans have also been commonly used for lifting excavated soil from inside a *suranga.* In the late 1980s, an experienced water diviner from Manila village, rather than use the *Bynemara* leaves, adapted the design of the soil carrier and constructed a wooden sledge like structure using the trunk of the Fishtail palm. This idea soon caught on, and gradually wooden sledges like this have started to replace the use of a head pan inside a *suranga.* The use of wooden sledge to remove excavated soil was commonly practised in Manila village (Figure 5.9). The *Bynemara* tree is not of much economic value to the farmers. The sledge is filled with rubble and is pulled out of the *suranga* by the workers (Figure 5.10). The sledge technique is relatively easy, less wearing and more practical than removing soil by manually lifting with the head pan in a *suranga* with a low ceiling (R53). Soil lifting in a head pan can be potentially unsafe compared to the sledge pulling method because of the health risk associated with the bend and lift associated with carrying heavyweights, especially in a constrained tunnel. Moreover, if excavated soil is cleared by manual lifting, the tunnel height also needs to be high enough to accommodate the use of the head pan. The excavated soil is usually dumped at a lower level from the entrance of the *suranga*, which is later used to construct the berm for a pond that will store *suranga* water or landscaping of a lower terraced field.

Figure 5.9: A farmer constructing a wooden sledge to be used for *suranga* construction.

Figure 5.10: The excavated soil from a *suranga* being removed on a wooden sledge.

The time taken to finish a *suranga* depends on the length, the soil characteristics of an area, and the excavation pace. If the soil is hard, the excavation can be as slow as two feet of the tunnel (0.61m) in a full day's work (R68). For example, a *suranga* worker claimed that the longest *suranga* he excavated was 224 *kolu*[25] (204.8 m), and it took approximately eight months to complete (R50). *Suranga* constructed on a part-time basis can take between six months up to one year to complete (R76; R122), which is significantly longer than a *suranga* made by a professional, full-time worker.

There is no standard design for *suranga*; thus, they are constructed in a range of shapes and sizes. The design of a *suranga* is primarily guided by the type of soil and rocks, ease of excavation, and subsurface water source availability. *Suranga* can be straight, serpentine, or an intricate design made of the main tunnel and several branches. However, a straight tunnel is the most preferred design because a straight tunnel is relatively easy to excavate and undertake regular maintenance and rescue from it in the event of collapse (R100). On the other hand, a serpentine or zigzag *suranga* is made only when excavation in a straight line becomes difficult because of blockage caused by a hard impermeable rock, then diversion from the straight path is sought to bypass the hard rock. If a water source has not been found and the *suranga* starts to collapse during excavation because of soft soil layers, then debris is removed carefully, and the *suranga* worker reassesses the risk before further excavation is carried out (R109). If further excavation is not recommended and there is the risk of collapse, two options arise: either the *suranga* is abandoned because of the risk of accident and the possible entrapment of the *suranga* worker(s) (R55; R68; R76; R79); or the collapsing end is abandoned, but a new branch is excavated in the main tunnel (R153). Collapse can occur if the water flow inside a *suranga* is high enough to destabilise it (R59; R161), causing soil piping which is common during the rainy season, creating underground cavities and channels in the study area (Sarath *et al.*, 2020). Thus, a *suranga* with water dripping from a ceiling is also susceptible to collapse because of the high moisture and saturated soil layers above (R100). In a *suranga* prone to collapse during excavation, passing points are made in the main tunnel, which can be used either for shelter during an accident or for clearing debris from the main tunnel. Though a

[25] *Kolu* is the local unit of length measurement, 1 *kolu = 0.91 metre*

straight *suranga* is the priority if no water source is found by digging straight for significant distances, then the *suranga* expert may decide to excavate branches at the proximal end of the main tunnel, at an angle between 0-90 degrees to the main tunnel as a form of bifurcation as shown in Figure 5.11 (R80; R100). However, if the water is found after a short length, then branches are not required. Therefore, branches and diversions in the main tunnel are a sign of an adaptive response to find water inside a *suranga* when no water source is found, or the path is blocked by hard rock, and any further excavation is impossible (R85; R93; R122; R149; R155). Moreover, the amount of water harvested from a *suranga* can be augmented by making branches inside so that more water sources can be tapped (R72; R73; R151) (Figure 5.12). In local parlance, these branches are known as *kai*, which means fingers (R124). Branches from the main tunnel can be further divided into sub-branches. The excavation of a *suranga* aims to find a sufficient supply of water while exposing a family to minimal risk and cost. In the survey, 70% of *suranga* were found to be without branches, and 30% had branches.

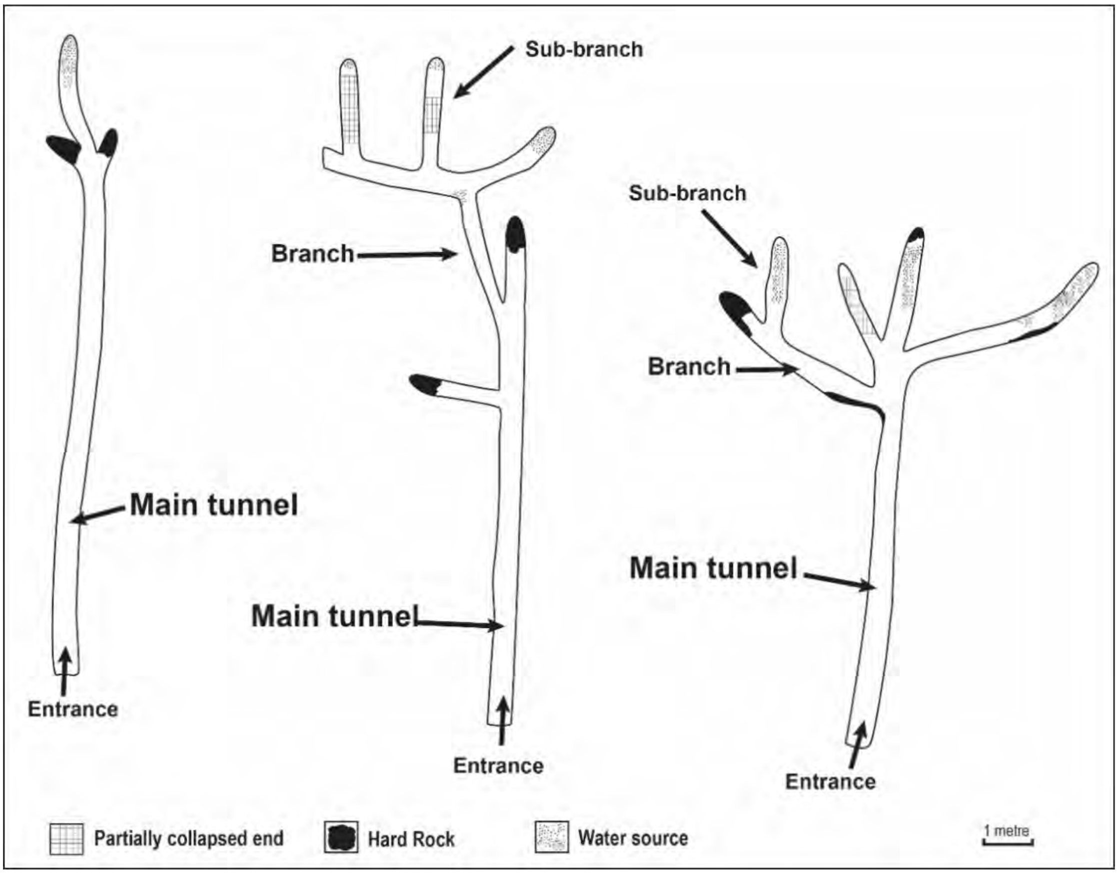


Figure 5.11: Internal structures of three different observed *suranga*.

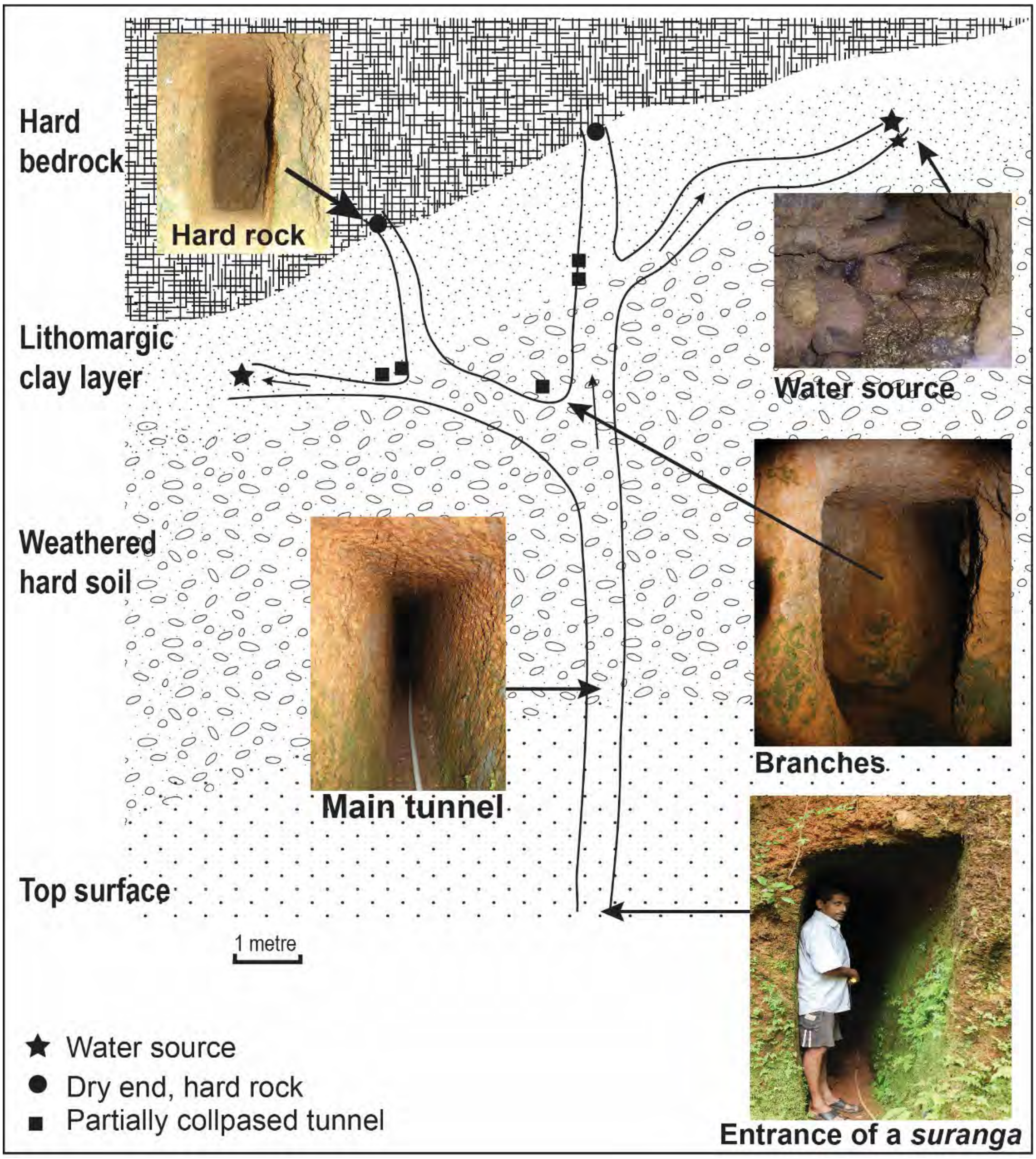


Figure 5.12: Design of a complex *suranga* with several water sources.

Light travels in a straight line; thus, a serpentine *suranga* is darker than a straight one, so more lighting is needed at various points in the *suranga*. A small mirror placed outside the tunnel is often used to reflect sunlight into the *suranga* to provide working light inside the tunnel (Figure 5.13). Furthermore, sunlight reflected from a mirror can provide a guide to regularly check if the tunnel is being excavated in a straight line. However, the mirror lightning technique does not work for a serpentine *suranga*. Therefore, candles or oil lamps are used for lighting inside these *suranga* during the excavation process (R149). However, oil lamps and candles may decrease oxygen availability inside the *suranga*, which can present a health risk (R44). Thus, sunlight reflected through a mirror provides a slightly better alternative than using an oil lamp or candle because this adaptation is safer, brighter, and costs less.

Figure 5.13: A worker using a mirror to cast light inside a *suranga*.

Electric lights cannot be used inside *suranga* for safety reasons because the interior can be highly humid and wet during the excavation. Moreover, it can be expensive for families to provide a power supply for lighting because *suranga* are not always excavated near to an electricity source, such as a dwelling. Battery operated lighting is theoretically possible but can be costly because batteries do not last a full day and can be exhausted in a few hours, especially as the excavation process may last months. Therefore, using electric or battery operated lights is impractical and make the construction costs high (R55); however, small battery operated torches are used for inspection purposes.

Some experienced *suranga* workers claimed that they could predict a potential *suranga* collapse by closely observing soil types and soil layers (R79). For example, the excavation of a *suranga* usually involves cutting through at a right angle to soil layers; if the overall direction of the tunnel is parallel to the soil layers, then a *suranga* may collapse (Tripathi, 2009). According to farmers, collapse can also be predicted by the presence of dampness in soil layers; however, a minimal number of serious accidents during the construction and maintenance phase have ever been reported inside a *suranga* (R55; R73; R100). A *suranga* worker told a story of another worker killed while trying to remove a stone (R73), and in another incident, three people were allegedly suffocated to death while hunting a wild boar inside a *suranga* (Doddamani, 2007). There have been at least two recent separate incidents where people were stuck and died inside the *suranga* during hunting (The Hindu, 2018). In another recent example, a man died trying to restore a collapsed *suranga* *(*The News Minute, 2020).

Though no workers reported severe oxygen shortage while working inside a *suranga*, they do take regular breaks to come out in the fresh air during excavation to reduce the risk of suffocation. A genuine sense of oxygen depletion was experienced when accompanying a large inspection team into a long, dark, serpentine *suranga*. Therefore, if a single worker is excavating and clearing rubble, they get more fresh air than a group.

> *"I never had an accident inside a suranga because I always used to observe soil types and soil layers inside a suranga before and during the excavation. A landslide inside a suranga can always be predicted with careful observation. I never had oxygen problems [suffocation] working inside a suranga" (R73).*

Occasional soil collapse inside a completed *suranga* may block the water supply (R103); however, sometimes this is temporary, and after time it can continue to provide a water supply (R56) depending on the amount of soil deposited in the collapse. Traditionally, in these cases, stone boulders were placed in a random order in the *suranga* so that even if the access was blocked because of collapse, then water could still flow out through the spaces between the stone boulders (R161). In an atypical example, a *suranga* worker tried to put a stone lining on the ceiling of the *suranga* to stop the collapse. However, he was unsuccessful because it did not stop the problem (R153). Some *suranga* workers also tried to minimise the height of the *suranga* by digging in a sitting position to minimise disturbances to soil layers caused by excavation (R149).

Once a reliable water source was found inside a *suranga,* excavation is stopped. Traditionally, water used to flow out through the tunnel and then it was transported through wooden pipes made of areca nut trunk (locally known as *dumbe,* see Figure 5.14). The current practice is to construct a small bund/dam at the water source inside the *suranga*, and water from this small reservoir is conveyed outside through an underground Polyvinyl chloride (PVC) pipe running through the channel of the tunnel (R101; R159) (Figure 5.15). This design has minimised the water loss through seepage inside the *suranga*, and the water supply remains intact even during the soil collapse inside the tunnel. However, regular cleaning of the pipe, which attracts root systems, is required to maintain the water supply (R173). In one example, a *suranga* was blocked because of a massive landslide caused by a road constructed on the upper side of a *suranga*, but the *suranga* still yields water for drinking and household supply through the pipe (R20). In another example, the entrance of the *suranga* was partially blocked with a concrete wall, and a pipe was connected to the wall to draw water from the *suranga* (R147).

Figure 5.14: A traditional wooden pipe (*dumbe*) made of an areca nut tree.

Figure 5.15: Water from a *suranga* being transported with a pipe.

The entrance to *suranga* used for drinking water is usually covered with a net curtain (Figure 5.16), whilst occasionally either a metal gate (Figure 5.17) or broad leaves are used to avoid the ingress of dust and stop wild animals and bats from entering the *suranga*. This practice reduces the risk of water contamination (R87; R147); however, it was not found to be followed strictly by all *suranga* users. In one atypical example, a *suranga* worker hung an electric wire at the entrance of his drinking water *suranga* to scare away dogs, goats and cows and prevent water pollution, although the wire was not connected to the electric supply.

Figure 5.16: A drinking water *suranga* covered with a net for safety.

Figure 5.17: A drinking water *suranga* covered with a metal gate.

Water from *suranga* is usually collected into earthen ponds just outside a *suranga* (see Figures 5.18 and 5.19), and the water from these ponds is transferred to the plantations through a further network of pipes. Traditionally, the storage capacity and irrigation efficiency of the ponds were increased by usually connecting ponds in a cascading series within the terraced landscape in a farmstead (Figure 5.20). The ponds work as headwaters for the lower fields and the main house $_{(R140)}$ with overflow from a higher pond diverted under gravity to the lower ponds through a piped network $_{(R38)}$ from which irrigation takes place (Suseelan, 2008). A schematic diagram of a typical farmstead based on *suranga* is shown in Figure 5.21, where water from various *suranga* is collected in ponds situated at a gradually decreasing height of a hillslope. These ponds are used as overhead tanks to irrigate crops on terraced farms (see quote below) (Figure 5.22).

> *"Our house is situated at a higher level, and below the house, there are areca nut plantations. There is a hill on the back of the house, where there is a suranga. The water flows through plastic pipes first into the house, and excess water is collected in a tank, and this water is used to irrigate fields situated at a lower level. So, no water pumping is needed as water flows free because of gravity"* $_{(R38)}$.

However, nowadays, a growing practice used by most farmers is to lift water from smaller ponds, dug wells or any other water resources situated at lowers levels to a large open, concrete tank constructed at the highest level within a farmstead by using electric water pumps. These large tanks are often lined with tailored plastic sheets to avoid water loss through seepage (Figure 5.22).

Figure 5.18: Earthen pond to collect *suranga* water.

Figure 5.19: Earthen pond to collect the *suranga* water through a pipe.

Figure 5.20: A pond situated at the highest elevation within a farmstead.

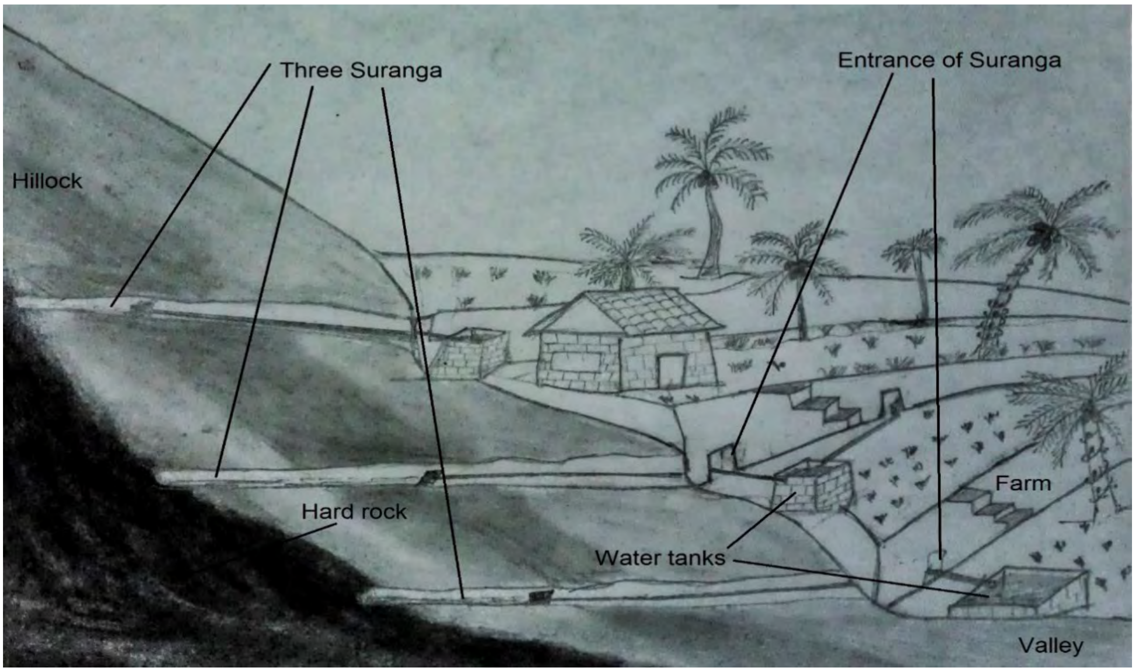


Figure 5.21: Schematic diagram of a farmstead with *suranga* systems.

Figure 5.22: An overhead water tank under construction on a hilltop.

Extending a *suranga* may increase the water supply inside a *suranga* (R143; R152; R153), but not always (R178). According to the locals, afforestation, rainwater conservation and constructing groundwater water recharge pits at upper levels of hills can also increase water availability inside a *suranga* (R151). Some farmers made trenches and pits on hilltops and hill slopes to encourage the collection of water (R128), as shown in Figure 5.23. The local government has funded these initiatives under the National Rural Employment Guarantee Act 2005[26].

> *"Water recharging pits that collect rainwater or runoff made at a higher level of hills can increase the overall yield of suranga. I have made such pits and yield in my suranga have increased" (R149).*

Figure 5.23: Water recharge pits on a hillslope.

[26] National Rural Employment Guarantee Act 2005 commonly known as NREGA, later renamed as Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) is an Indian social security measure. MGNREGA guarantees minimum of 100 days wage employment, in rural areas, to every household whose adult members volunteer to undertake unskilled works.

The majority of *suranga* (63%) provide a perennial and reliable water supply for farmers in the survey (Figure 5.24). Water in perennial *suranga* may decrease in summer, but the water is still enough to meet drinking and household needs, and sometimes there may be excess water for irrigation in the summer (R53; R60; R72; R96; R109).

> *"The water in the suranga at my home starts to decrease in April-May, but when collected efficiently, it is still enough for drinking requirements"* *(R38)*.

Seasonal *suranga* constitute 19% of the total *suranga*. These usually dry up during the summer season (R122; R153) and may re-emerge with the start of rain (R60). The term seasonal supply embraces various supply circumstances because some seasonal *suranga* supply water only during and immediately after the monsoon period. However, several other seasonal *suranga* can provide water into the late summer season. Seasonal *suranga* are still helpful to farmers because water from seasonal *suranga* can be used for household and irrigation. If the number of perennial and seasonal *suranga* are added together, then the percentage of a *suranga* with water increases to 82%. The last type of *suranga* were dry *suranga*, and they did not produce water and were abandoned. A total of 18% of *suranga* were found to be dry in the survey.

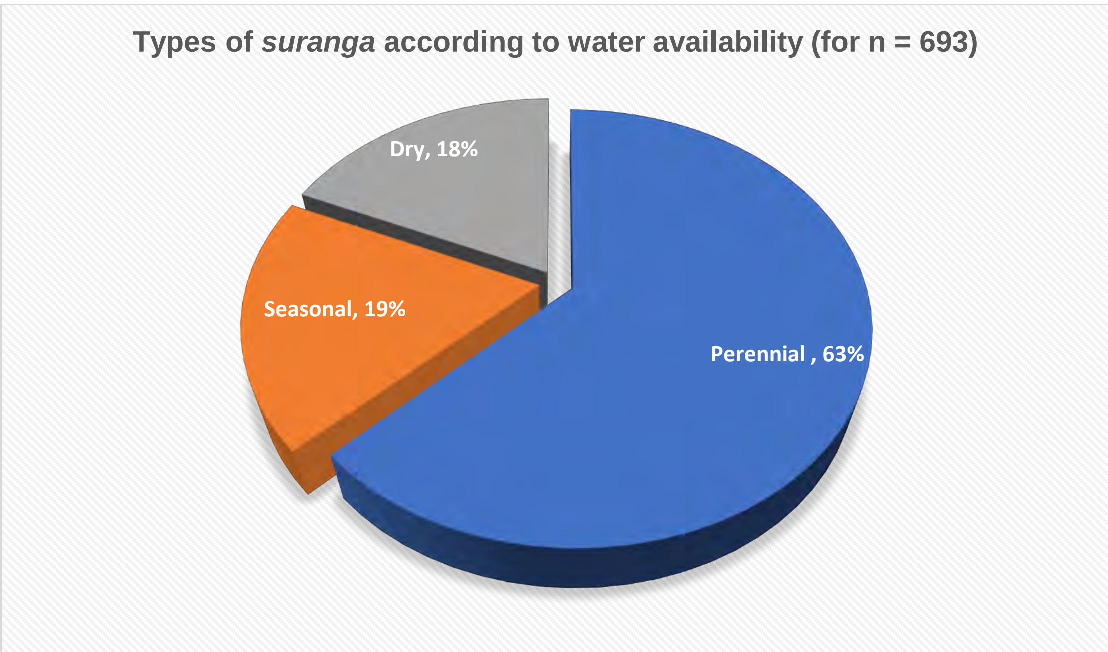


Figure 5.24: Types of *suranga* according to water availability.

During the rainy season, some dry *suranga* may produce water but is of no use because there is no water shortage (R173). Sometimes a dry *suranga* is used as a storage unit (Figure 5.25), and in an atypical case, a dry *suranga* was used as a cesspit by a farmer. Nevertheless, dry *suranga*, which are usually abandoned, can still provide a vital niche ecosystem for flora and fauna.

Figure 5.25: A dry *suranga* being used for storage.

There are several reasons for a *suranga* to be dry. Firstly, a water source may never have been found inside a *suranga* because of wrong site selection (R85). Secondly, the soil layers may not be strong enough to hold the tunnel so that the *suranga* may collapse during the excavation phase; hence the search for water must be stopped immediately as the risk of tunnelling further becomes too high. In such a case, sometimes a water source is found, but regular collapsing of a *suranga* obstructs the water channel and can cause a hindrance to access water. Then water cannot be supplied, and for safety reasons, a *suranga* is abandoned. Thirdly, the occurrence of hard rock layers too hard to be excavated can be another reason for a dry *suranga* (R141).

5.4 Structural classification

Based on structural patterns, *suranga* can be classified into two main types: the first and the most common type of *suranga* are excavated into the hillslopes[27] and referred to as elevated *suranga* in this study; the second type of *suranga* are excavated inside a dug well or a concrete circular well to augment supply in these. The elevated *suranga* were the most common type found in the case study region. Out of 700 *suranga*, 84% were elevated and excavated into a hill, and 16% were dug inside a well or a dug well. Elevated *suranga* account for the longer *suranga* (100 m+), while those inside a dug well are typically shorter (1-20 m). The *suranga* found inside circular wells are the most compact in dimensions with limited space and the challenge of removing rubble from inside them because the space is too small for a person to enter (R76; R91; R114). Therefore, elevated *suranga* are the most popular form of *suranga* found in the study area, and these characterise the irrigation system typology.

5.4.1 Elevated *suranga*

Elevated *suranga* (see Figures 5.26 and 5.27) are found both near to the family home (drinking water and domestic use) or distributed throughout the terraced units found at different altitudes (irrigation). Water for drinking and household requirements from an elevated *suranga* is conveyed directly from the *suranga* to a concrete tank or a PVC tank next to the house through pipes, so that family members do not have to go long distances to fetch drinking water and other household requirements (R148) (see Figures 5.28 and 5.29). Usually, *suranga* for drinking and household requirements is constructed near the house so that water can be collected straight into a vessel with the help of PVC pipes (R117) (Figure 5.30).

[27] Elevated *suranga* and hillslope *suranga* both words have been used interchangeably in this study.

Figure 5.26: Entrances of two separate elevated *suranga*

(Left picture source: Shree Padre).

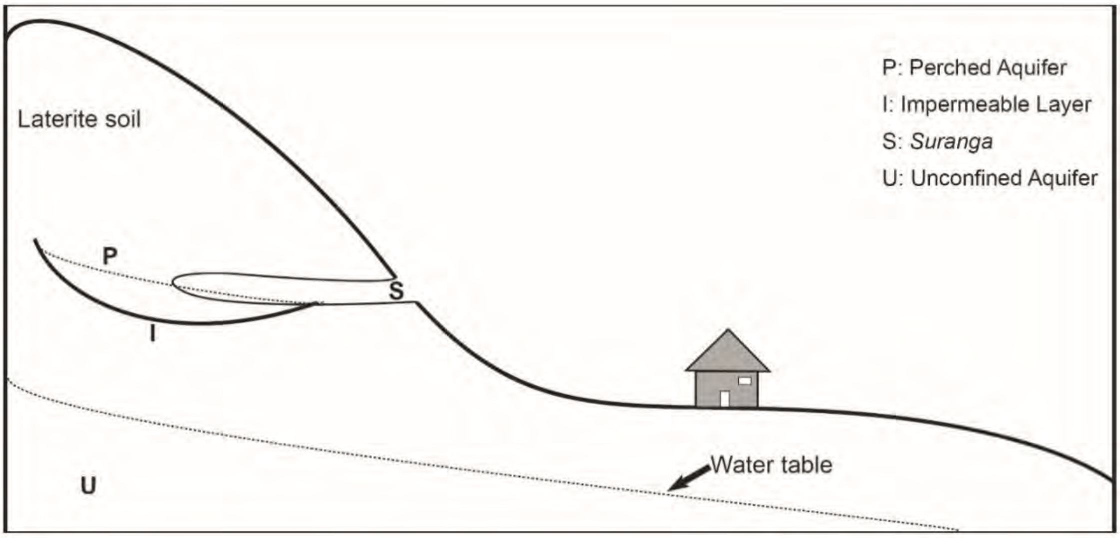


Figure 5.27: Schematic diagram of an elevated *suranga*, not to scale.

Figure 5.28: Drinking water supply with a pipe from an elevated *suranga*.

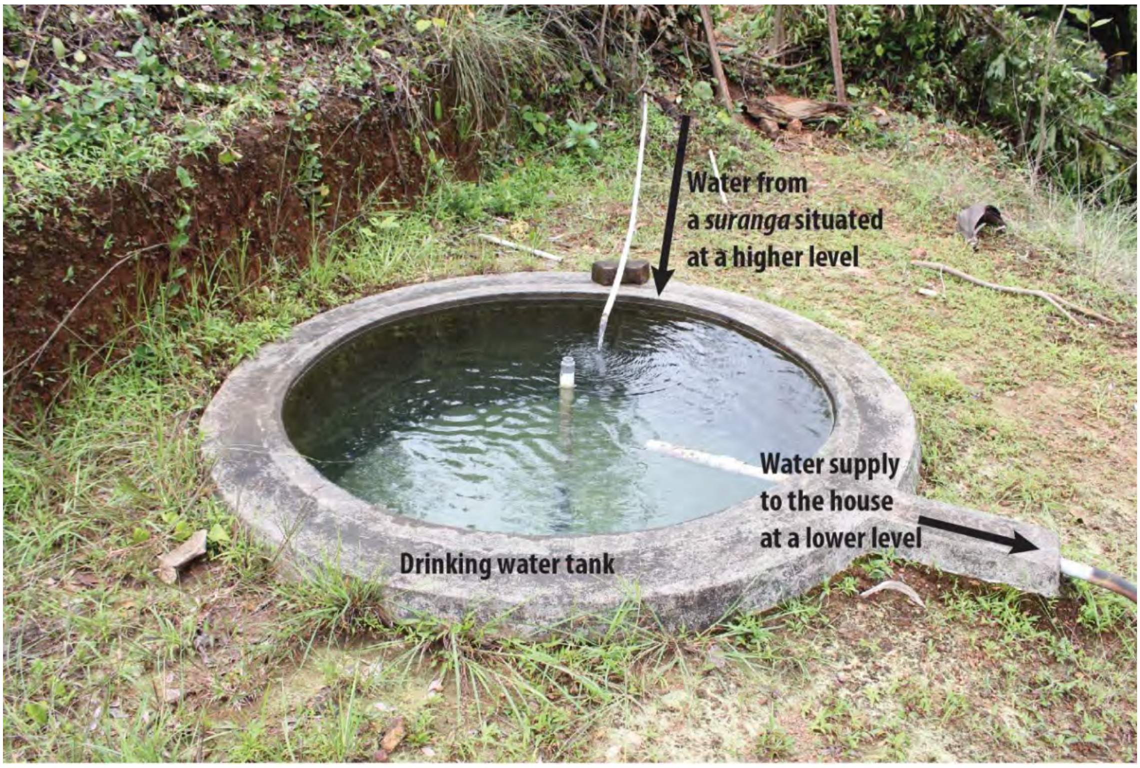


Figure 5.29: A typical drinking water supply system.

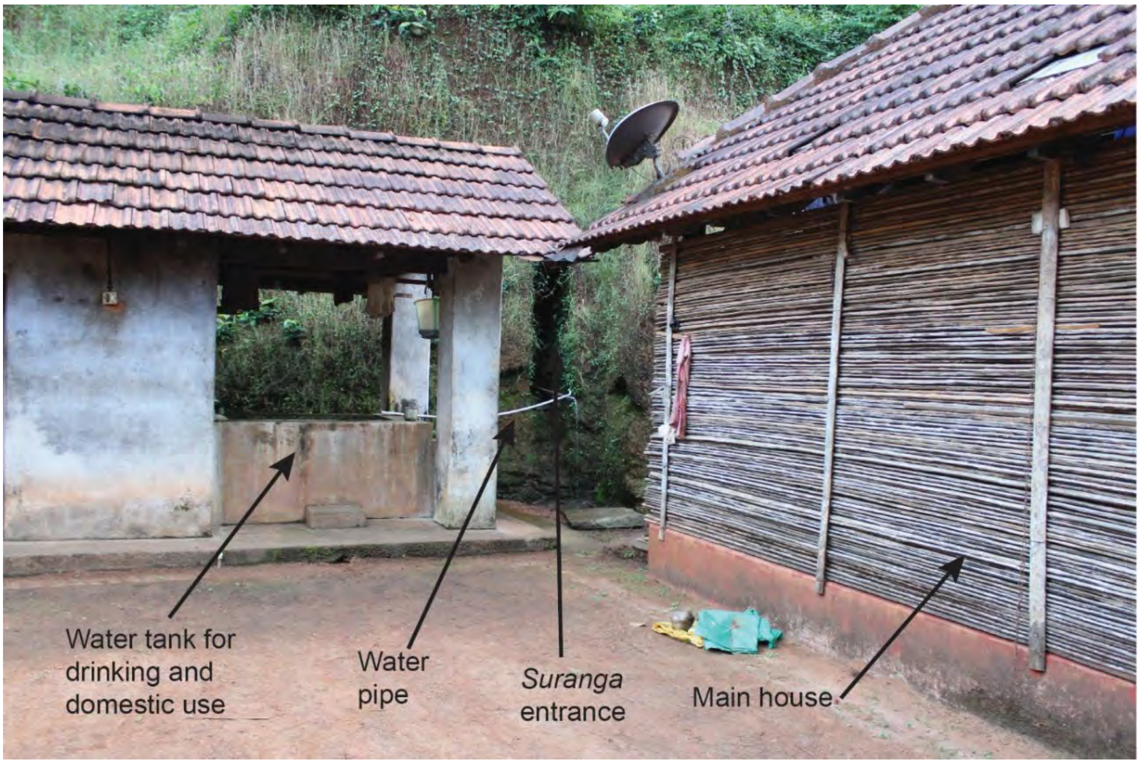


Figure 5.30: An elevated *suranga* in the backyard of a house.

Elevated *suranga* found throughout the farmstead away from the main home are usually located in places, like separate terraced units, from where water can easily be distributed to crops via ponds (*kere*) and irrigation networks attached to spray and drip irrigation.

5.4.2 *Suranga* in a dug well

A *suranga* 'in a well' is excavated inside a circular well (Figure 5.31) or inside a rectangular or irregularly shaped dug well[28], and sometimes these dug well have steps to access the water body. A schematic diagram of a *suranga* inside a well is shown in Figure 5.32. The primary rationale for making *suranga* in a dug well/well is to increase the existing water supply of the dug well/well by finding additional water sources inside the well (R76; R92; R97). Water from these types of *suranga* are stored in the same well, and it is

[28] The terms well, dug well, and open well are used interchangeably in this study, and both mean irregular shape and sized well used for harvesting water. On the other hand, circular wells have usually concrete or laterite rings to support the well.

either manually lifted or lifted using an electric pump (Figure 5.33). A *suranga* inside a dug well provides additional water storage and a groundwater recharge unit during the rainy season. However, the *suranga* inside a well are usually submerged because of the high water level during the rainy season (Figure 5.34). Therefore, *suranga* inside a well are excavated during the dry season when water availability in the well/dug well is minimal (R151).

Figure 5.31: A *suranga* inside a circular well.

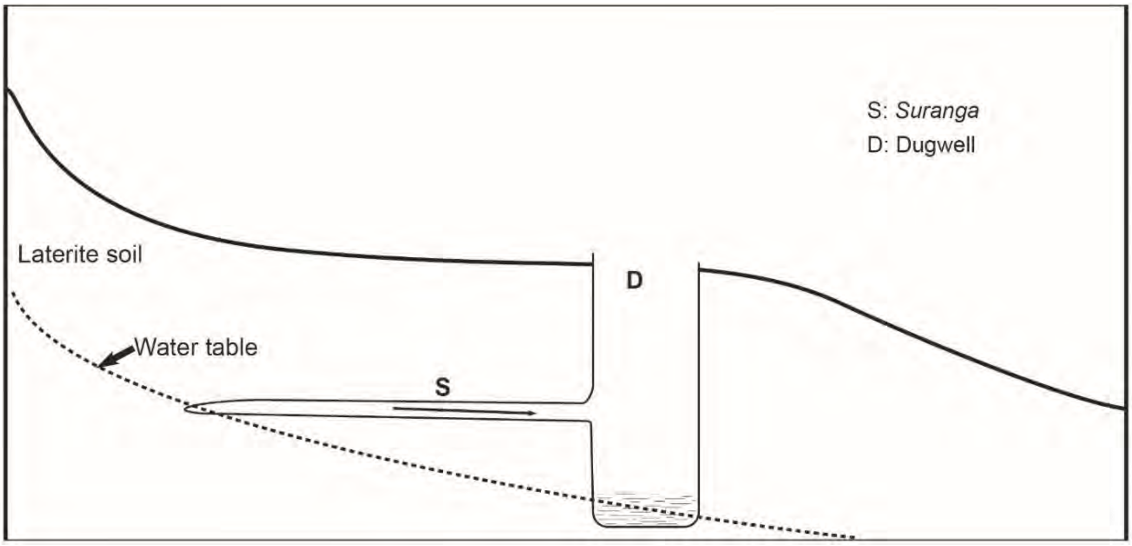


Figure 5.32: Schematic diagram of a *suranga* in a well.

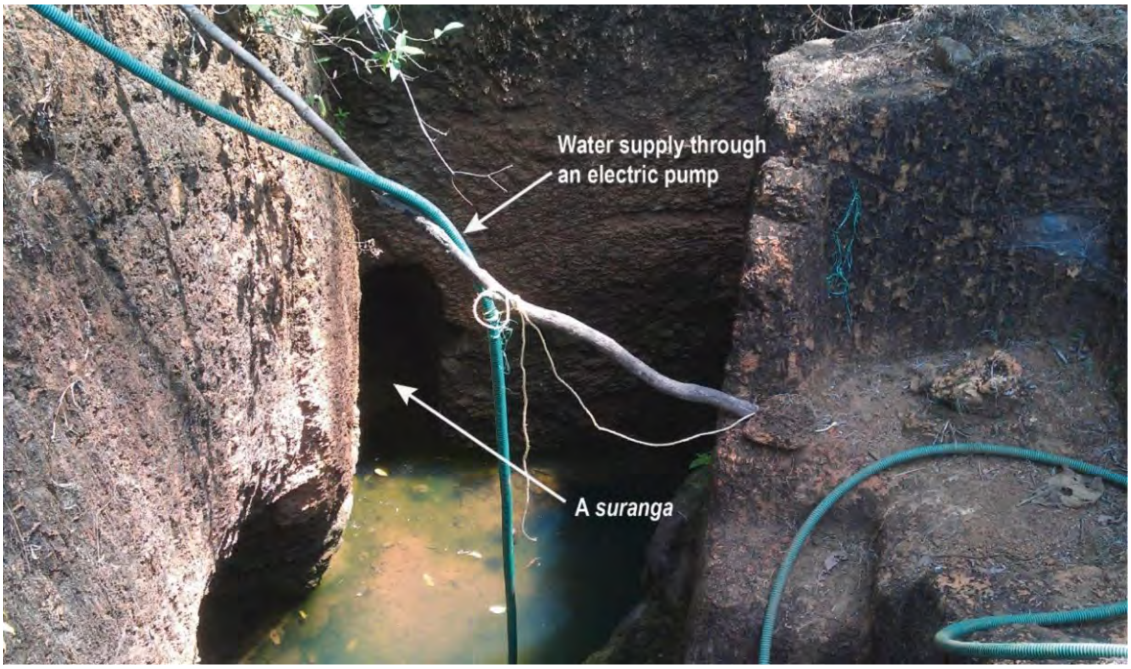


Figure 5.33: A *suranga* inside a stepped dug well.

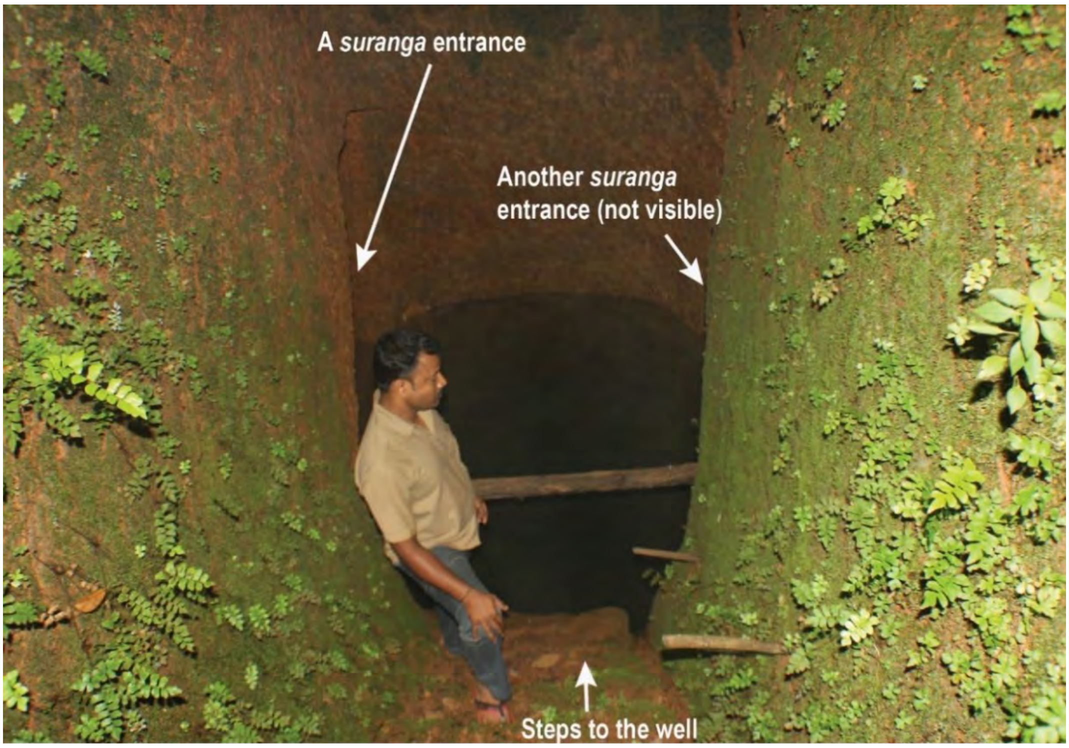


Figure 5.34: Two submerged *suranga* inside a stepped well

In some cases, airshafts are not made intentionally but are made through improvisation. For example, when a big rock has blocked further excavation, it is removed, and a dug well is excavated from the top of the hill connected to the *suranga* and another *suranga* made inside the dug well where water was found (R120). Such *suranga* inside a dug well with access to a dug well through another *suranga* (R56) may appear like an airshaft, but technically these are just *suranga* located inside a dug well (R120). For example, in Figure 5.35, a dug well (D) collects water from five individual *suranga* (S1, S2, S3, S4, and S5) via an access *suranga* (A) (R96; R139).

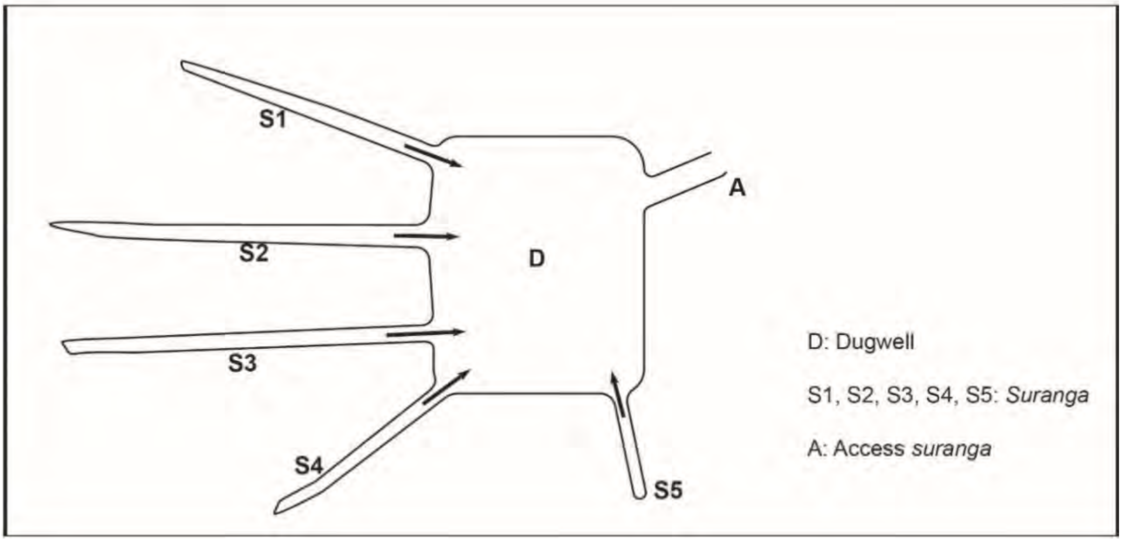


Figure 5.35: A schematic diagram of an aerial view of a dug well with five *suranga* in Manila village.

In some cases, the dug well works as a water collection body, while in other instances, the dug well is merely used as a method for access into a *suranga* made at lower levels from the dug well. Occasionally, a *suranga* is used to connect two separate *suranga*, two wells; or provide access to a well (R50).

5.4.3 *Suranga* with vertical airshafts

In the study area, only eight *suranga* had vertical airshafts constructed throughout the *suranga* conveyance channel (R43; R116) (see Figures 5.36 and 5.37). Airshafts are generally made in long tunnels, and they serve two primary purposes. Firstly, they are used to lift the rubble from the *suranga* during the construction and maintenance processes (Figure 5.38). Secondly, they serve as dug well at regular intervals (Figure 5.39). Moreover, airshafts also regulate oxygen supply inside the deep *suranga* and can be used as an emergency exit during an accident (Figure 5.40).

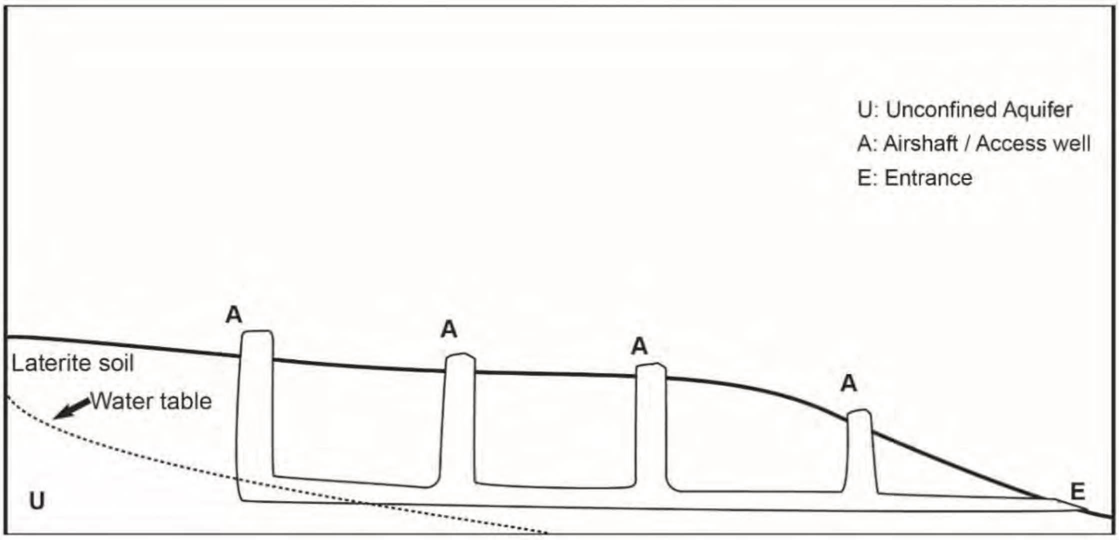


Figure 5.36: Schematic diagram of a *suranga* with airshafts.

However, airshafts do not seem to be an essential characteristic of *suranga* in the case study area because 93% of *suranga* did not have airshafts. Only eight *suranga* had vertical airshafts, and out of the eight, only two *suranga* were found to be more than 100 metres long. These were situated on a flat plateau area, which had airshafts constructed along the *suranga,* also used as separate lifting dug well systems by farmers to complement the conveyance system that flowed horizontally below. Thus, the hilly terrain does not often allow constructing such long *suranga,* as the quote below illustrates.

> *"...sometimes we see some special suranga such as Sheni suranga… airshafts are needed only if suranga is extended beyond a length, if you can find a good water source before a certain length is reached, then you do not need an airshaft inside the suranga…however, this (Sheni) suranga could not have been excavated without airshafts (because this suranga is 200+ metres longs)…in the past, the labourers were not so expensive (as today) so such a long suranga could be made…"(R44).*

Figure 5.37: An outside view of an airshaft, which opens into a working *suranga*.

Figure 5.38: Looking down an airshaft in a dry *suranga*.

Figure 5.39: Looking down an airshaft with a submerged *suranga.*

Figure 5.40: View from inside a *suranga* through an airshaft.

In the remaining six *suranga* with airshafts, these were in *suranga* with a semi-natural opening created by weathering of the laterite by rain or caused by soil collapse inside a *suranga*. Thus, the construction of airshafts in hilly terrain is impractical because, during the torrential monsoonal rain, airshafts can get flooded and collapse into the *suranga*, which can destabilise the whole *suranga*. Furthermore, airshafts can increase the overall cost, which decreases the economic efficiency for the subsistence users. Thus, *suranga* with vertical airshaft were not common in the study region. Therefore, airshafts are a rare or exceptional feature of *suranga* in the study area.

5.4.4 Semi-natural *suranga*

Occasionally, a *suranga* may interlink with underground cavities and caverns caused by soil piping erosion or subsurface erosion underneath the weathered surface and soil often caused by longterm erosion of clay layers by subsurface water flow (Sarath *et al.*, 2020). The clay deposits are formed in the subsurface of laterites because of the long-term chemical weathering of rocks over thousands of years. In this type of *suranga, the* water source is at a lower height from the outer surface, so people often gain access to these by using a ladder and by using syphoning techniques/or pumps to convey the water outside. Several *suranga* used in *Possadigumpe* hill have been constructed within the last 10-20 years to abstract water in this way (Figure 5.41).

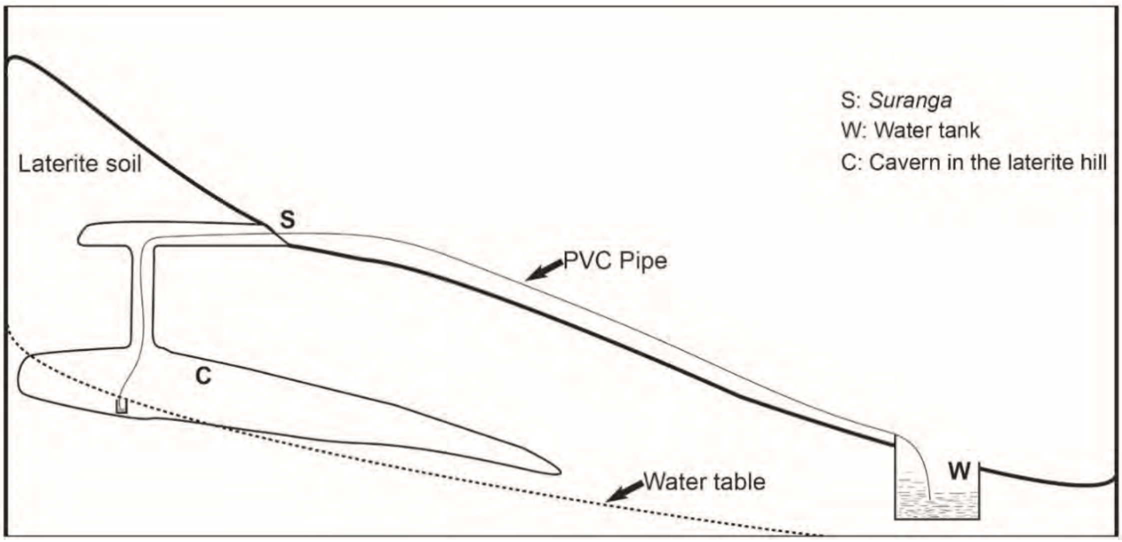


Figure 5.41: Schematic diagram of a semi-natural *suranga* with syphon system.

From the entrance, these *suranga* do not appear any different from any other type of *suranga* but usually require a ladder to descend to a lower level (Figure 5.42).

Figure 5.42: A farmer preparing to enter a semi-natural *suranga* with a bamboo stem used as a ladder.

Suranga within natural caverns can produce a good supply of water, for example, as found in two *suranga* in *Gumpe* hamlet on the *Possadigumpe* hill, one of the highest hills in the study area. However, high water levels can cause internal flooding and soil piping during the wet season, which in turn can lead to collapses in both the natural cave system and excavated access tunnels (Figure 5.43).

Figure 5.43: Inside view of a natural cavity caused by soil piping.

This hybrid mixing of natural and excavated tunnels was only occasionally seen in the study area. In some examples, such as on *Possadigumpe* hill, there was a deliberate attempt to access known underground sources of water, and in others, the cave system has been serendipitously tapped into at the proximal end of a long *suranga*. Now that the different construction techniques have been discussed and a typology established, it is essential to understand the economic cost of excavating and maintaining a *suranga*.

5.5. Construction and maintenance costs

Suranga workers charge for their labour in accordance with the length of the *suranga*, and the excavation charges gradually increase because manual excavation becomes more complex and slower in longer tunnels (R51). Therefore, the number of days to complete the *suranga* are irrelevant in such a case. Some *suranga* workers, however, charge daily wages (R100). In this case, the cost of a *suranga* depends on the number of days taken to finish the *suranga*, as the examples below illustrate.

> *"I charge 300 Rupees per 2.5 feet, and if we get hard rock, then I charge 1000 Rs per feet. I do not charge by the day. Approximately 2.5 feet/day can be excavated for the first 25 feet. Though* [at the start] *it may earn me the same amount of wages per day as a normal farm worker, but I get work security until suranga is completed, and the wages increase if the suranga get longer"* (R79).

> *"…suranga was made eight years ago, and it cost approximately 50000 Rs (350 Rs/Kolu was the rate till the half-length of the suranga) because dug well water was not enough, so a suranga was built" (R129).*

> *"I charge 500 Rs/day for the suranga excavation. A normal labourer usually gets 250 Rs/day" (R100).*

> *"Suranga worker rates: In 2012 it was 300 Rs/per day, and in 1998 rates were the same for a normal labourer and a suranga worker" (R6).*

Overall, there were no set standard rates for *suranga* workers. However, an often used informal agreement is that *suranga* workers usually charge more than a typical farmworker or a labourer because of the challenging aspect of the work. The cost of construction of a *suranga* inside a well is the highest, followed by *suranga* inside a dug well, and then an elevated *suranga*, because a minimum of three workers are needed to make a *suranga* in a well, in comparison to a minimum of one worker required for a hillslope *suranga*. Constructing a *suranga* inside a well is relatively difficult because wells, mainly circular with the concrete ring, are deeper and less spacious than a dug well.

Dug wells are usually at shallow depths and square, rectangular, or irregularly shaped and sized, so a dug well is a relatively spacious type of a well, making the excavation of a *suranga* inside a dug well easier and less costly than inside a well (R130). A minimum of two professional workers would be needed to construct a dug well, but a single person can excavate a hillslope (elevated) *suranga* (R100; R136). The low income families may not have suitable land to make a *suranga*, but low income families can apply for grants under the Karnataka state government's *Ganga Kalyan Yojna* to fund a borewell, or a dug well (R109). *Suranga* costs can be high if made by expert workers, but still cheaper than a dug well (R109) and far cheaper than a borewell (R39), which influence the decision to dig a *suranga* (R100; R136). However, it is difficult to compare the costs of various traditional water harvesting structures because of the flexible design, lengths, and depths. Table 5.3 provides a crude comparison of the relative types of cost associated with constructing the four main water harvesting structures in the study area.

Table 5.3: Relative costs of construction and usage of water resources in the study area.

Suranga	**Dug well**	**Concrete well**	**Borewell**
Initial excavation cost	Initial excavation cost	Initial excavation cost	Initial excavation cost
PVC pipe network		Concrete rings or laterite stone linings	The inner casing of the borewell
Storage pond construction cost	Electric or fuel pump cost	Electric or fuel pump cost	Electric submersible pump cost
--	Electricity/fuel cost	Electricity/fuel cost	Electricity cost
Annual maintenance	Annual cleaning	Annual cleaning	--
--	Maintenance of the pump	Maintenance of the pump	Maintenance of the pump
Approximate initial cost **20,000-50,000 INR**	Approximate initial cost **40,000-60,000 INR**	Approximate initial cost **40,000-80,000 INR**	Approximate initial cost **60,000-120,000 INR**

Local government grants and loans from banks are available for the construction of a dug well or a borewell under the broad category of agriculture development. However, loans or grants are usually not provided for constructing a *suranga* because a *suranga* is not a government recognised water resource. Thus, construction costs are borne by the owners (R69; R170). However, an atypical opportunity seems to have emerged recently under the Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA)[29]. The low income families can apply for labouring wages from the local government to undertake manual development work on their farms. Although *suranga* are not officially included in this list, families may still seek financial support from the local government if they construct a *suranga* by claiming wages under the MNREGA scheme (R46).

> *"There is no permission required for making a suranga, but people should observe health and safety. However, people can claim a day wage, which is approximately 155 INR/day, and 3 INR/day for renting tools, for working in their own farm under MGNREGA scheme by the central government" (R46).*

There is no need for irrigation during the rainy seasons. Therefore, *suranga* and other water harvesting sources are often ignored during the rainy season, except for the drinking water sources. *Suranga* yield can decrease significantly over time because of blockages, water loss, and vegetation growth in the water channel or inside a conveyance pipe. Thus, *suranga* and other water resources may need regular maintenance. Furthermore, during the wet season, the soil becomes saturated and may induce soil collapse in several places inside the *suranga*. During the monsoon season, water absorbed by tree roots on the top surface can emerge from the ceilings of the *suranga* that can also cause collapse (Figure 5.44).

---

[29] The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) guarantees hundred days per year of wage-employment in rural areas to adult members for voluntary manual work (www.nrega.nic.in).

Figure 5.44: Roots emerging from the ceiling of a *suranga*.

If a *suranga* has suffered a largescale collapse and there is a risk of further collapse, no maintenance is done, and any water still available from the *suranga* is used; otherwise, the *suranga* is abandoned (R55). Structurally stable *suranga* may not need regular maintenance, and it is enough to maintain them annually or once every two years (R109) or unless water flow has decreased significantly (R105; R126). The entrance and the tunnel may regularly get blocked because of dense vegetation growth during the rainy season. Once the monsoon is over and dry weather results in water sources diminishing and irrigation water requirements increasing, then owners start maintenance work on their *suranga* and other water resources (Figure 5.45). Chances of soil collapse inside a *suranga* are higher during the season of rainfall and high humidity. Therefore, to minimise the risk of collapse and any accidents, maintenance inside a *suranga* is done only during the dry seasons, which is between October-May (R44). During the summer, people also undertake maintenance of ponds and wells because water availability in these water structures in summer is at a minimum, which makes maintenance and cleaning easier.

Figure 5.45: A worker coming out from a *suranga* after completing maintenance.

Seepage is problematic inside a *suranga* and in earthen ponds because of structural issues and the damage caused by crabs and vegetation growth. Seepage problems inside the *suranga* caused by crabs are avoided nowadays using PVC pipes to transfer water from a *suranga*; however, crabs can still damage the earthen ponds. The maintenance of a *suranga* involves removing the build-up of rubble and clearing any vegetation growth, plugging any holes in the water channel and pond; thus, maintenance costs of the *suranga* system are relatively low (R68; R135). *Suranga* workers are usually responsible for annual maintenance. They receive daily wages from the farmers, but sometimes owners or ordinary labourers can undertake the maintenance (R60). If more than one family uses a *suranga*, then all the stakeholders bear the cost of the annual maintenance in proportion to their water abstraction roster (R84).

5.6 Flora and fauna in *suranga*

Access can be difficult and hazardous in partially or fully collapsed *suranga* (Figure 5.46), and during the monsoon season, entrances of tunnels were found to be covered with dense vegetation growth that can attract poisonous snakes, as shown in Figure 5.47. According to a local snake expert, sometimes a Python (*Python molurus*), Indian Cobra (*Naja naja*), King Cobra (*Ophiophagus hannah*) and other species of snakes may enter a *suranga* in search of food and water, but the snakes usually do not live inside a *suranga*. Furthermore, Indian Boar (*Sus scrofa cristatus*), porcupine (*Hystrix indica*), and a variety of turtles, frogs, crabs (*Gubernatoriana alcocki*), lizards, cockroaches, crickets, spiders, and mosquitoes are commonly found inside *suranga* (R68; R128; R148).

Figure 5.46: Two structurally unsafe *suranga*.

Figure 5.47: Two typical *suranga* covered with dense vegetation during monsoon.

Bats were also commonly found inside *suranga* (Table 5.4) because the dark and highly humid conditions are favourable habitats for them (R36; R49). Large deposits of guano were noticed during the fieldworks in dark *suranga* that were inhabited by bats. The typical bats found in *suranga* are leaf nosed bats, with two species identified by a bat expert as *Hipposideros apeoris* and *Hipposideros ater*, which have an average wingspan of 250 mm (Srinivasulu *et al.*, 2015) (Figure 5.48). These were found inside three separate *suranga* in Manila village.

Table 5.4: Flora and fauna commonly found inside *suranga* in the study area.

Flora and fauna (scientific name)
Variety of lichens and moulds
Leaf nosed bats, two species (*Hipposideros apeoris; Hipposideros ater*) Indian fruits bat (*Pteropus mediusi*) usually found in natural caves
Small crab (*Gubernatoriana alcocki)*
A variety of insects, including spiders, cockroaches, crickets, mosquitoes, and centipedes
Indian boar (*Sus scrofa cristatus*), Porcupine (*Hystrix indica*),
Rat snakes (*Ptyas mucosa*) King Cobra (*Ophiophagus hannah*) Pit viper (*Trimeresurus gramineus*) Indian cobra (*Naja naja*) Python (*Python molurus*)

Figure 5.48: A *Hipposideros* bat from a *suranga*.

The insectivorous bats (*Hipposideros apeoris* and *Hipposideros ater*) roosting inside *suranga* are smaller than the greater Indian fruits bat (*Pteropus giganteus*), also known as the Indian flying fox that is found in the study area. *Hipposideros* species predate on various insects, including mosquitoes (Srinivasulu *et al.*, 2015) which may help to reduce the number of mosquitoes breeding in ponds and tanks in the area. These mosquitoes can be vectors for malaria, dengue, chikungunya, and Japanese encephalitis in India, and so it is important to control their numbers to avoid endemic diseases amongst the human population (Shivakumar *et al.*, 2015).

5.7 Chapter summary

This chapter answered research questions 2 and 3 about the spatial distribution and design principles of the *suranga* system. A survey was undertaken to find the distribution of the *suranga* system and various structural characteristics. A total of 700 *suranga* were found in fourteen villages in the study area; however, the exact number of total *suranga* in the study area and neighbouring villages should be far higher. This chapter focused on the various technical aspects of the *suranga* system, including water divining, tunnel excavation process, structural classification, construction, and maintenance costs of the *suranga* system. The results suggest that *suranga* are based on simple, replicable, and low cost tunnel designs. Flexible structural adaptations used during the excavation process allow mitigation against environmental challenges, structural stability, maximise yielding water capacity. Gravitational conveyance from tunnel systems based on gallery filtration allows free flowing water diverted through a network of pipes and small ponds. Moreover, natural filtration from soil layers leads to good water quality for drinking and domestic usage. The next chapter focused on finding the hydrological characteristics of the *suranga* system to explore the source, quantity, and quality of water from *suranga*.

Chapter 6 – Hydrogeological and hydrological characteristics of *suranga*

When you drink the water, remember the spring.

Chinese Proverb

This chapter presents the results from a geohydrological and hydrological survey of *suranga* to better understand water supplies in the system. It starts by examining the hydrogeology of the study area (section 6.1). The radiocarbon dating method was used (see section 6.2) to supply results about several groundwater sources to explore the origin and provenance of groundwaters in the catchment area of *suranga*. These results are then used to refute the existing paradigm of groundwater movement (section 6.3) linked to *suranga* and justify an argument presented for a new hypothesis of *suranga* geohydrology (section 6.4). Next, a seasonal measure of the operational levels of water in *suranga* is presented as annual discharge data, and conveyance and distribution are discussed (section 6.5). The final part (section 6.6) of the chapter presents the results from the water quality test of various water samples, and these are linked to their suitability for drinking and household uses based on WHO standards. The chapters conclude with a summary of this chapter in section 6.7. Thus, the combined results from this chapter answer research question 4.

> **Research Question 4:** What are the key geohydrological and hydrological characteristics of *suranga*?

6.1 Hydrogeology of the study area

To understand the hydrology of *suranga,* it was first necessary to understand water sources in *suranga*. As *suranga* are underground tunnels, it was clear that water was harvested from groundwaters. Thus, it became necessary to examine the hydrogeology of the study area. *Suranga* are found in a predominantly lateritic region of the foothills of the Western Ghats in Southern India. Laterites are highly weathered pedogenic surface deposits, mainly found in tropics and subtropics. Laterites are rich in iron and aluminium oxides in varying proportions and with clay, quartz, and other minerals but low in alkalies (McFarlane, 1976; Bonsor *et al.*, 2013; Sarath *et al.*, 2020). The laterites with higher iron and aluminium contents are harder than the laterites with higher clay contents, and the proportion of materials is governed by the type of parent rock and the degree of weathering. The laterites are formed by prolonged: intensive chemical weathering of igneous and metamorphic rocks from water in the subsurface; and physical weathering because of rain and wind on the surface (Ollier, 1988; Fan *et al.*, 1994; Ollier & Galloway, 1990). Depending on iron oxide and clay concertation, the colour of laterites ranges from red to yellowish-brown. For example, reddish-brown laterite becomes harder on exposure to air because of the high content of iron that is oxidised on exposure to air, while yellowish laterite is soft because of the higher clay content. In this study, the terms 'laterites', 'laterite profile'', and 'weathered profile' have been used interchangeably to refer to the predominant soils in the study area. A detailed discussion on the geohydrology of laterite soil profiles in the study area has been provided in Appendix F. The laterite soils in the study area were formed by the weathering of gneisses, charnockites, and granites rocks (CGWB, 2013; Sarath *et al.*, 2020; Sarath *et al.*, 2021). The colour of laterites in the study area is predominantly reddish brown because of the high iron and aluminium content, but yellowish, clay rich laterite is also present (Figure 6.1).

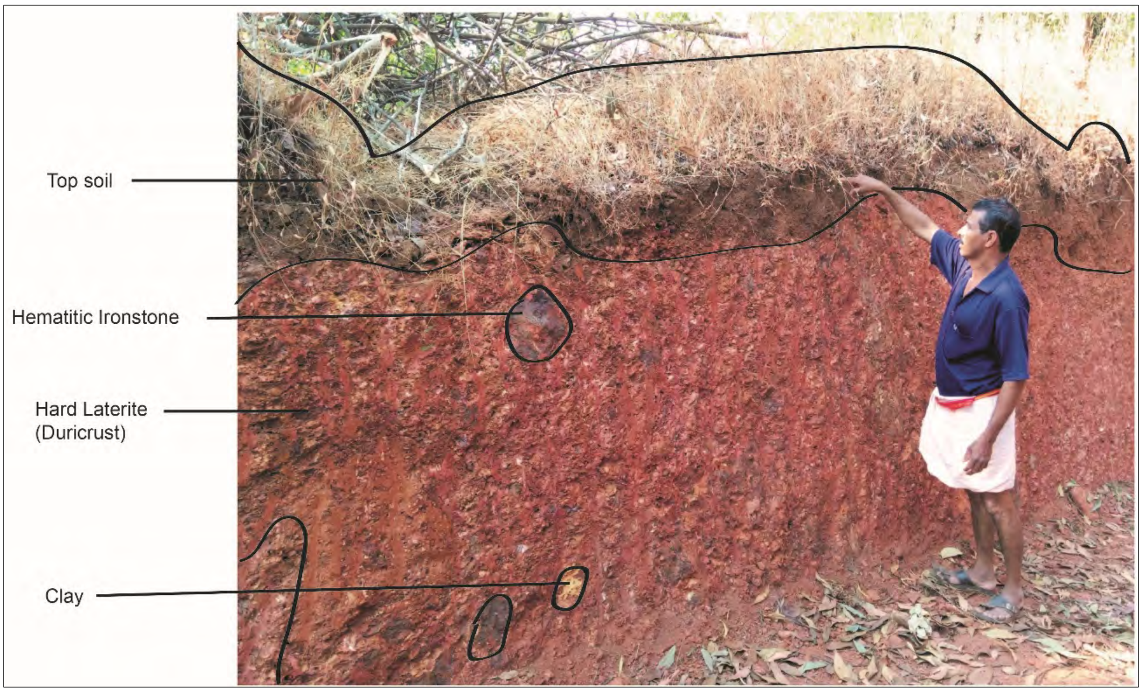


Figure 6.1: Top two layers in a laterite profile in Manila village.

Soft, reddish-brown, sandy soil with or without organic humus is the top layer of these laterite profiles. Under this laterite topsoil, the most weathered layer of hard laterite rich in iron and aluminium is found, scientifically known as ferricrete or bauxite, depending upon the percentage of iron or aluminium (Sarath *et al.*, 2020). In the absence of the topsoil layer, a hard laterite layer is exposed to air, and it becomes the hardest laterite known as duricrust (Langsholt, 1992). The hilltops usually have exposed ferricrete layers (Sarath *et al.*, 2020). For example, in places such as *Possadigumpe* hill, a dark brown ferricrete layer is exposed because the top surface has eroded and accumulated in the valleys because of heavy rain and winds (Figure 6.2). A hard, dark brown ferricrete layer is also visible in Figure 6.3.

Figure 6.2: The exposed ferricrete patches on the *Possadigumpe* hill in the study area.

Figure 6.3: A *suranga* with exposed, black, permeable, hard ferricrete layer.

Just below the duricrust, there is often a yellow and reddish iron and aluminium oxides zone known as mottled clay (Sarath *et al.*, 2020). The laterite found in the mottled clay zone is sometimes called wormhole laterite or vermicular laterite (Figure 6.4), as clay is infused in small cavities in these layers (CGWB, 2013; Sarath *et al.*, 2020). This layer is soft and rich in iron oxides and hardens when exposed to air; thus, soft laterite bricks are cut from this layer, and these bricks harden on exposure to air (Eggleton & Taylor, 1999). This layer was firstly named laterite by Buchanan in 1808, as '*Later*' means brick in Latin because he was impressed by the self-hardening property of these soft soil bricks, which have been extensively used as a primary source of building material in south India (Buchanan 1807; Schellmann, 2017).

Figure 6.4: Laterite block cut from the mottled clay zone.

The clay from the duricrust and mottled clay region gradually leaches over a long time because of the chemical weathering of gneiss, charnockite, and granite in the upper laterite (Ollier, 1988; Ollier & Galloway, 1990; Sarath *et al.*, 2020). It leaves vesicular texture in upper zones and creates clay pans at the deeper depths in a laterite profile. A clay pan, often found in the pallid zone, is made of residual clay layers composed of kaolinitic clay and quartz sand formed of leeched components (mainly Silica) (Ollier & Galloway, 1990; Flores-Román *et al.*, 1996; Schellmann, 2017). The clay pans create a highly impermeable barrier to the infiltrating water, and a nonlinear decreasing trend has been observed in horizontal hydraulic conductivity with the depth, which implies water infiltrates rapidly in upper laterite layers during rainfall. However, the infiltration rate significantly decreases as it reaches the mottled zone (Figure 6.5).

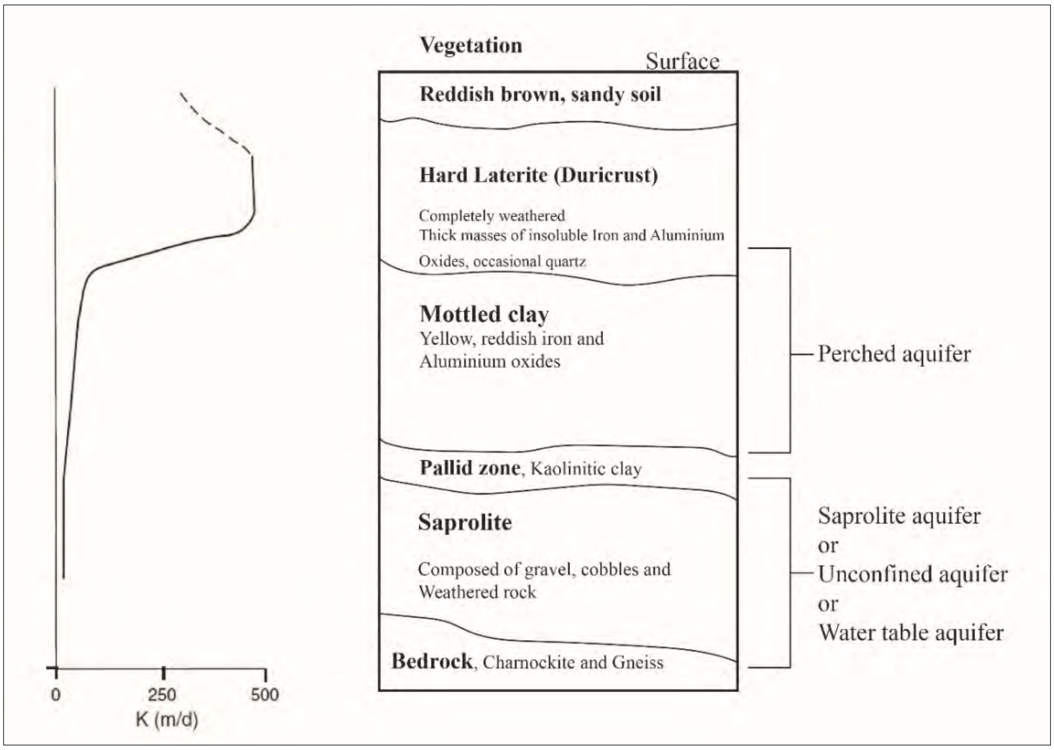


Figure 6.5: Variation in hydraulic conductivity in a laterite lithological profile

(Adopted from Langsholt, 1992; Devaraju & Khanadali, 1993; Flores-Román *et al.*, 1996; Cable Rains *et al.*, 2006; Bonsor *et al.*, 2013; Sarath *et al.*, 2020).

Thus, infiltrated rainfall water often gets perched between the vesicular duricrust and Pallid zone, forming perched aquifers situated at shallow depths (Ollier & Galloway, 1990; Flores-Román *et al.*, 1996; Schellmann, 2017; Sarath *et al.*, 2020). A partially less weathered zone, known as saprolite, is often found below the clay layers, made of gravel cobbles and the parent bedrock. The saprolite layer is in graduation from highly weathered laterite to bedrock. The deep aquifers are often found in saprolite and bedrock layers. It was thought that the existence of perched aquifers in the catchment area where *suranga* are found might represent most groundwater sources for these systems. Several groundwater samples were collected to date their origin as a proxy measure of provenance to further explore this emergent hypothesis. The section on groundwater assessment now follows.

6.2 Groundwater assessment

Groundwater[30] assessment aimed to understand the groundwater provenance according to residence time at various depth in the subsurface. The traditional methods of groundwater assessment, such as slug and pumping tests (Hiscock & Bense, 2014), could not be used because of the restricted time available in the field, limited human resources, remote locations and undulating terrain, and these methods were costly and required regular monitoring for extended periods. Therefore, the initial groundwater assessment was done by undertaking an alternative route of radiocarbon dating of groundwater water samples. The radiocarbon ages of various groundwaters collected from various depths were compared with rainfall data and *suranga* discharge data. This comparison allowed an understanding of the provenance and age of the groundwater in the study area. This was done to develop a hypothesis to explore the formation of shallow depth aquifers in the soil profiles in the study area. In addition, the hydrogeological data, such as *suranga* discharge rates and precipitation data, were used to understand the subsurface movement of water in laterite profiles in the case study area.

Therefore, groundwater water samples from various water sources found at different elevations on a hillslope in Manila village were collected (Figure 6.6). The idea was to compare various water resources from a single catchment to understand the broader hydrogeology based on their elevation from mean sea level and their residence time. Furthermore, an additional sample was collected from an atypical natural laterite cavern caused by tunnelling erosion that forms underground cavities and channels (Sarath *et al.*, 2020), situated in a different catchment at *Gumpe* hamlet in Bayar village. The reason for collecting groundwater from this cave system on *Possadigumpe* hill was to explore the

---

[30] In this study, the term groundwater is used to denote infilatrated water availiable in subsurface.

source of waters that characterised several *suranga* that all had relatively higher discharges than other *suranga*. All samples with their elevation from mean sea level and location have been shown in Table 6.1.

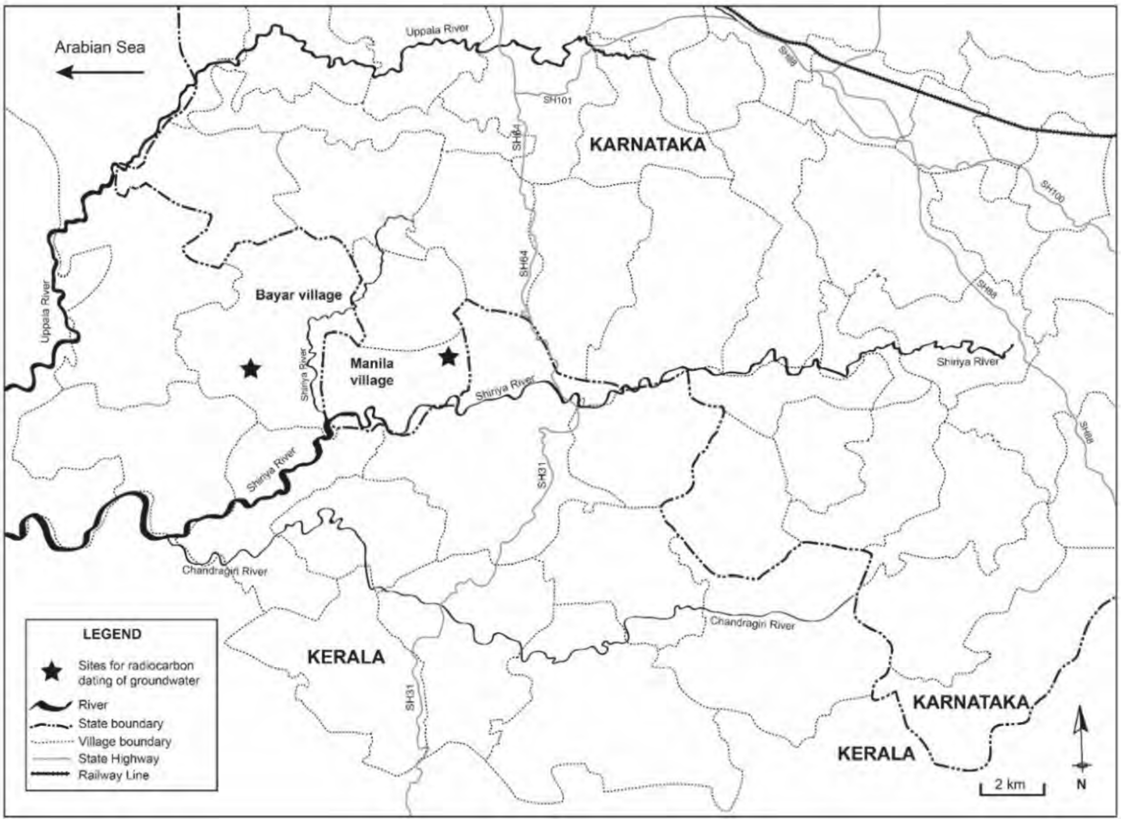


Figure 6.6: Sample sites for radiocarbon dating of various subsurface waters.

Table 6.1: Location of water samples for radiocarbon dating.

Type	Height above mean sea level (metres)	Location, Hamlet, Village
Natural laterite cavern	180	Hilltop, Gumpe, Bayar
Dug well	180	Hillslope, Manimoole, Manila
Suranga	150	Hillslope, Manimoole, Manila
Community borewell (drinking water supply)	132	Hillslope, Manimoole, Manila
Suranga	120	Hillslope, Manimoole, Manila
Dug well-*suranga* system	105	Hillslope, Manimoole, Manila
Private borewell	111	Valley, Manimoole, Manila
Private borewell	71	Valley, Nayarmoole, Manila

These groundwater water samples collected in one litre plastic sample bottles were exported to the BETA Analytic[31] laboratory based in the USA for carbon dating using ^{14}C Accelerator mass spectrometry (AMS) to determine their approximate residence time.

6.2.1 Radiocarbon dating results

The results in the form of residence time in years of the water samples, with the elevation of the water source and approximate depth of the water level from mean sea level, have been presented in Table 6.2. The height of the water source was calculated with the help of a Garmin GPS unit, while the approximate depth of the water level was calculated from information provided by the dug well and borewell owners and users.

Table 6.2: Radiocarbon dating results of various subsurface water samples.

Water source	Height above mean sea level (metres)	Approximate depth of water level from mean sea level (metres)	Radiocarbon age/ Residence time
Natural laterite cavern	180	180	Post-1950
Dug well	180	150	Post-1950
Suranga	150	150	1150 ± 22.5 BP
Suranga	120	120	1830 ± 30 BP
Dug well-*suranga* system	105	100	1150 ± 26.9 BP
Borewell	111	35	5460 ± 21.1 BP
Borewell (community)	132	26	8030 ± 40 BP
Borewell	71	-34	8440 ± 21.9 BP

[31] www.radiocarbon.com

The adjusted residence time of seven groundwater samples has been plotted against the approximate height[32] of the water level of seven samples from the mean sea level in Figure 6.7. It suggests a negative association between the residence time of groundwater samples and approximately the depth of the water level from the mean sea level, which means residence time is high for the deeper groundwater samples.

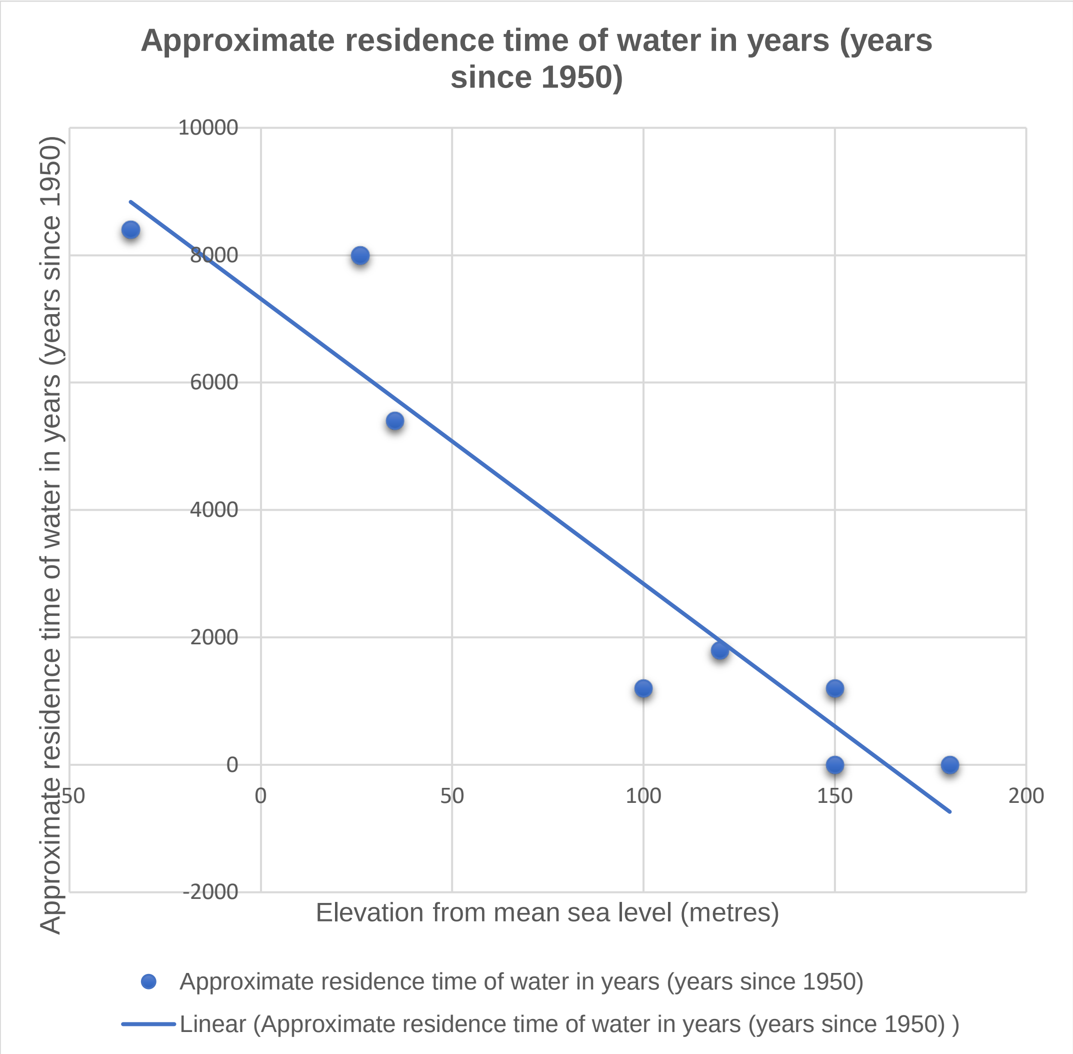


Figure 6.7: Adjusted residence time of various water samples collected from multiple elevations.

[32] Approximate height of water level (from mean sea level) for bore/dug well samples were calculated by deducting the depth of borewell/dug well from the surface elevation. For samples from *suranga* and spring elevation of the source was same as the elevation of water level inside it.

Further to this, borewell and *suranga* in the study did not extract water from the same or directly connected aquifer. For example, borewell extract water from much older crystalline aquifers that are either very slowly recharged or confined. *Suranga* were most likely to extract water from shallow depth aquifers or perched aquifers found within the laterites. For example, a *suranga* situated on a hilltop at 180 metres from mean sea level as part of a natural cave system, and an open well situated on a hillslope were extracting water from the shallowest perched aquifers, which in theory are more vulnerable to changes in seasonal weather patterns because of the fast recharge rates. Thus, it appears that like dug wells that harvest water from shallow aquifers (Karunanidhi *et al.*, 2021b), the *suranga* in the study area abstract water from small scale aquifers formed at shallow depths in laterite profiles. These discrete perched aquifers exhausted by *suranga* and dug well users are recharged during the seasonal rainfall by rapidly infiltrating rainwater because of their shallow depths.

6.3 Reframing the hypothesis of *suranga* hydrology

Among nearly all previous studies, it is assumed that *suranga* abstract water from the groundwater table in the phreatic zone in a laterite hill (Basak *et al.*, 1997, p. 222; CGWB, 2013). According to this idea, highly permeable laterite profiles facilitate quick groundwater recharge during the rainy monsoon season, which results in the increased water table in the subsurface, and *suranga* harvest water from this water table. Basak *et al.* (1997, p. 222) initially used this idea (Figure 6.8), which was based on one of the initial field studies on *suranga* (Prasad *et al.*, 1991).

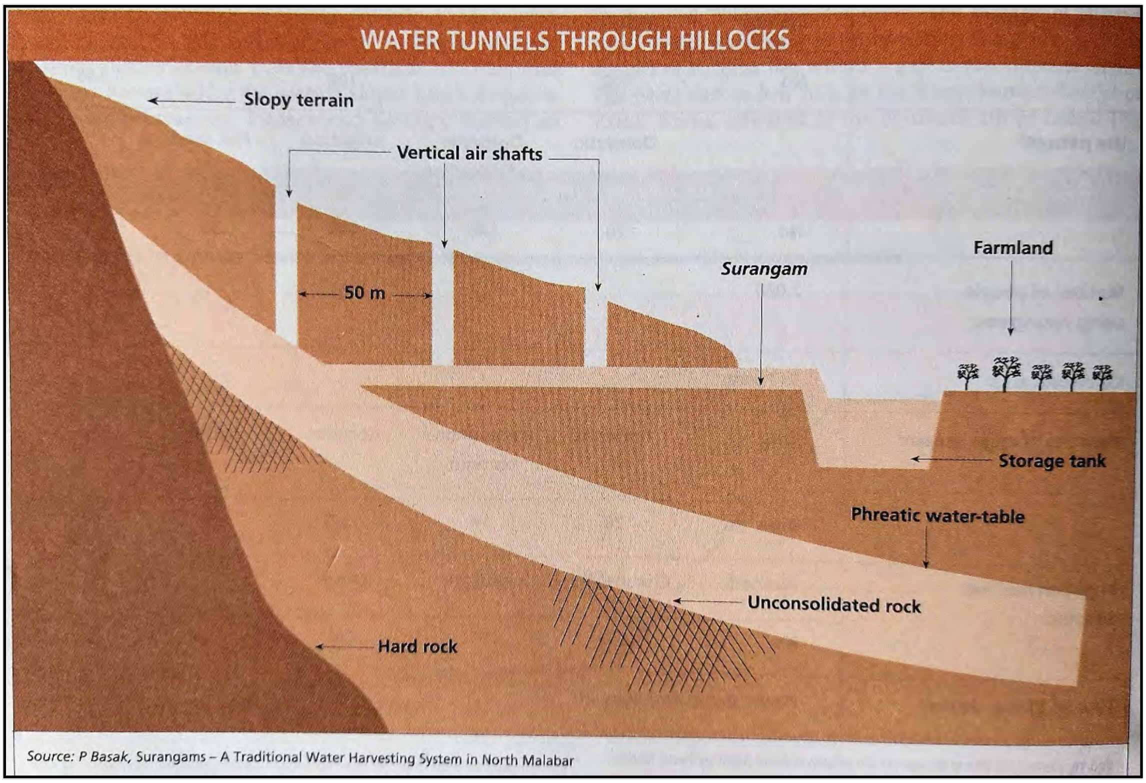


Figure 6.8: A schematic diagram of *suranga* hydrology

(Source: Basak et al., 1997, p. 222).

Water levels in *suranga* seem to be contingent on rainfall, and the prevailing published hypothesis based on the work of Basak *et al.* (1997) supplied an easy explanation for this seasonal variation in *suranga* discharge. If the above explanation was correct, then groundwater should be available consistently underneath the hillslope, and the users should be able to make water yielding *suranga* anywhere on a hill slope. However, on many instances during the survey, *suranga* situated on a hilltop were found to be perennial, while *suranga* positioned at lower levels on the same hillslope were either seasonal or completely dry. In the study area, the subsurface waters have preferential pathways, depending on geology, gradient, and substrate. Therefore, it is erroneous to assume that subsurface water flows in all possible directions within a hillslope, as shown in Figure 6.8. A real life example of two families living on the opposite sides of a hill in Manila village is given to support this hypothesis. The first family had 23 water yielding *suranga*; in contrast, a second family living on the other side of the hill had five *suranga* that never produced water $_{(R93)}$. A second point to reinforce, the view that groundwater does not flow uniformly in all directions under a hillslope in the study area, is that if a borewell is constructed in a water catchment according to the existing hydrological explanation of *suranga* (as shown in Figure 6.8), this should reduce water discharge in a *suranga* situated in the same catchment. However, several real life cases disprove this point, as *suranga* discharge was not necessarily affected by the presence of a borewell constructed in the same watershed. Thus, there was a need to provide an alternative hypothesis that could explain *suranga* geohydrology, which is discussed in the next section.

6.4 A new hypothesis for *suranga* geohydrology

The central proposition is that there are various groundwaters situated at different depths in a weathered profile. For example, the dispersed, perched aquifers situated at shallow depths, porous weathered soil profiles with vesicular zones (Saha & Agrawal, 2005) are the primary water source in *suranga*, dug wells, springs, and seasonal streams located at the higher elevations. However, *suranga* and dug wells located in the lower hills and valleys may harvest water from either a perched aquifer or saprolite unconfined aquifers, constituting a local water table (Figure 6.9).

The borewells often abstract water from deep unconfined, and confined aquifers (Patel *et al.*, 2020; Karunanidhi *et al.*, 2021b). The deep *suranga* and deep dug well may react slowly to seasonal precipitation because they draw water from saprolite aquifers located between the shallow perched aquifers and the deepest bedrock (Flores-Román *et al.*, 1996). Saprolite aquifers only get recharged once the perched layers nearer to the surface get saturated because of continuous precipitation and infiltration. During the southwest monsoonal rainfall, approximately two-thirds of the precipitation is infiltrated through the porous laterite profiles (Langsholt, 1992) and is deposited on perched and shallow aquifers. Once perched aquifers are saturated, water starts moving laterally and may emerge as natural springs or seasonal streams in the valleys (Flores-Román *et al.*, 1996). This subsurface water flow is also often harvested in *suranga,* and shallow dug wells. Thus, there seems to be a yearly process of recharge and discharge of these perched aquifers. Though deep perched aquifers or saprolite aquifers may continuously recharge over hundreds of years, and the deepest confined aquifers may recharge over thousands of years. Thus, *suranga* and shallow dug wells, underpinned by perched aquifers in laterite hills, are at the topmost position of the watershed in the case study area, followed by the springs, seasonal streams, and the west flowing rivers ultimately discharging into the Arabian Sea.

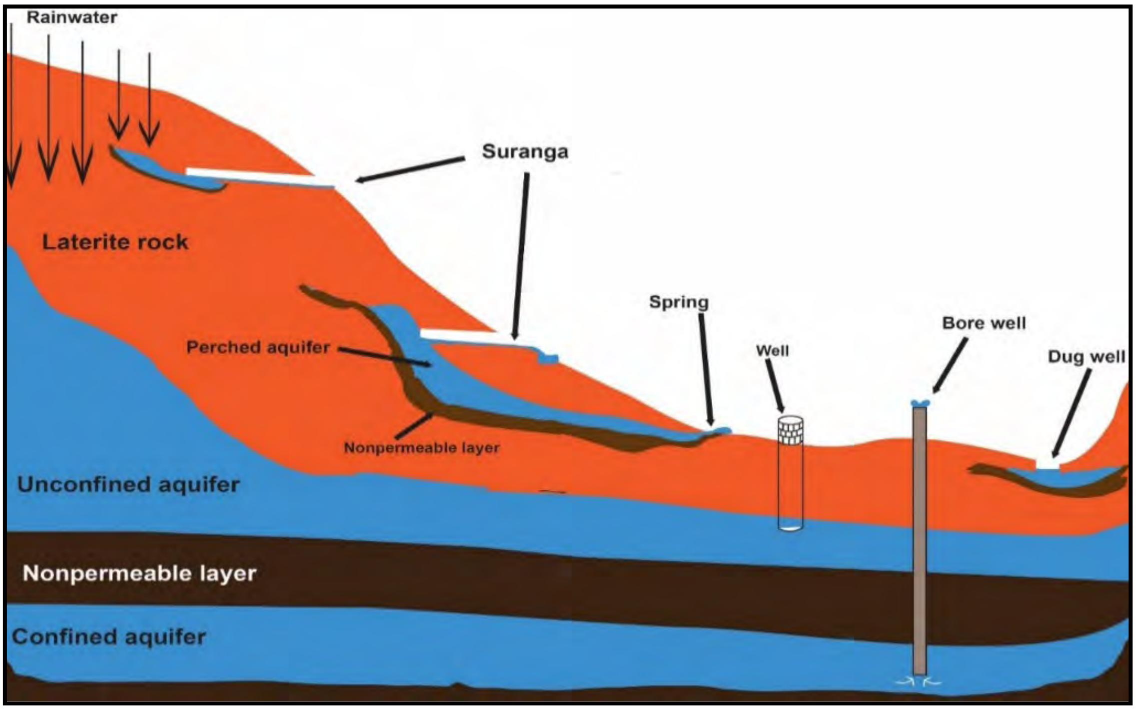


Figure 6.9: Water availability in a theoretical laterite profile.

It seems that the perched aquifers, often formed at shallow depths in weathered soil profiles, maybe the primary source of water in *suranga*. The water availability in these perched aquifers is directly dependent on precipitation and recharge of the groundwater. These perched aquifers are easily recharged during the monsoonal rain. Therefore, discharge in *suranga* is the highest during the monsoon and post-monsoon season. Moving on, it becomes essential to know just how much the water is supplied from *suranga* over an agricultural calendar year. The following section introduces these data and attempts to address this question.

6.5 Water supply in *suranga*

It is essential to understand how much water is available to farmers over an agricultural year from *suranga* because it allows for a better understanding of their vulnerability and resilience to pressure from competing sources and climate change. To estimate the water yielding capacity of *suranga* and seasonal variation in *suranga water* availability, point measures of water discharge rates from five different *suranga* were recorded from a micro catchment. The *suranga* discharge rates were compared with local rainfall data to explore any association between these two. The rainfall data were extracted from the Indian meteorological department[33] and district office website[34], which receives from the local metrological station at Mangalore.

The sampling strategy for the selection of *suranga* for discharge measurements was purposive and convenience based. The sites were selected because of the potential for long term monitoring of these supplies, made possible by the researcher's familiarity with the catchment and good rapport with the site owner. The location of five *suranga* numbered 1-5 selected for discharge measurement are shown in a diagram in Figure 6.10. These were situated at various altitudes on the *Sunambada* hillslope in Manila village. The approximate elevations shown in Figure 6.10 are mean heights above sea level. Coconut and areca nut plantations densely populate the area (as seen in Figure 6.11), but only vital features related to water resources have been shown in the diagram below.

[33] www.imd.gov.in

[34] www.dk.nic.in

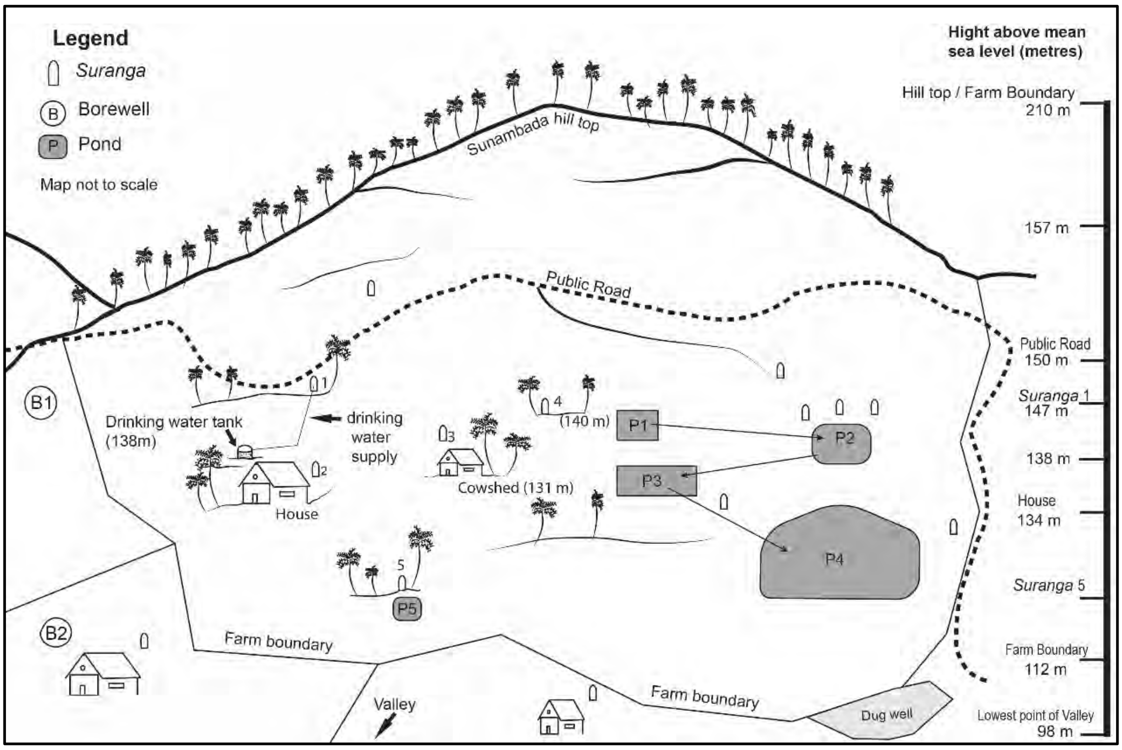


Figure 6.10: Schematic map of a hillslope farmstead used for water discharge measurements from *suranga.*

Figure 6.11: A view of the hillslope farmstead used for water discharge measurements.

Stream discharge is often measured using volumetric gauging, float gauging, current metering, dilution gauging, and slope area methods based on the flow volume (Jones, 1997; Hiscock & Bense, 2014). However, a basic volumetric gauging method was used for discharge measurement because the flow in *suranga* was often too low to use any other standard velocity measurement method. Nowadays, water from the source inside a *suranga* is usually transported out with the help of PVC pipes. This made the measurement of spot discharge easy and minimised any errors caused by any water losses in transportation. Therefore, the discharge from a *suranga* was measured at the discharge point just at the entrance to a *suranga* or at the discharge point into a pond. The discharge measurements provided the total output from a *suranga*, but it ignored any water lost to seepage and infiltration near the water source inside a *suranga*.

The time taken to fill a calibrated 500ml bottle with water from a *suranga* was recorded with the help of a stopwatch. Three consecutive readings (T_1, T_2, *and* T_3) were taken for each sample, and an average of these three readings (T_{avg}) was calculated. The instantaneous discharge was calculated from equation 2 (Stone, 1999). The formulas for calculating average water time taken (equation 1) and discharge in litre/hour are provided (equation 2) below, assuming water discharge remains constant.

$$T_{\text{avg}} = \frac{(T_1+T_2+T_3)}{3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$Discharge\ in\ \frac{litre}{hour} = \left(\frac{0.5}{Tavg}\right) \times 60\ \times 60 \ldots\ldots\ldots \text{(2)}$$

Litres per hour were converted into m^3/day when presenting these data. Initially, discharge measurements were taken during the field trips in December 2012, May 2013, and January 2014, but later, it was realised that it did not provide enough longitudinal data. Therefore, help was sought from a local engineering student, who was briefed to follow the same measurement system used in the initial surveys. This student undertook bi-monthly measurements between January 2014 and January 2015.

6.5.1 *Suranga* discharge results

The water discharge data in cubic metre per day (m^3/day) of five separate *suranga* situated in a single water catchment area have been presented in Table 6.3, and it shows that the water discharge rates from all five *suranga* were lowest in June and maximum in September between January 2014- January 2015. Overall, the *suranga* discharge varied between 1.1 m^3/day - 26.2 m^3/day in five different *suranga* over a year in this study. Local rainfall data was recorded at its highest between July-August 2014 (Table 6.4).

Table: 6.3: *Suranga* water discharge in cubic metre per day between Jan 2014-Jan 2015.

	Water discharge in cubic metre per day								
	Jan-2014	Apr-2014	May-2014	Jun-2014	Jul-2014	Aug-2014	Sep-2014	Nov-2014	Jan-2015
Suranga No. 1	2.1	1.3	1.2	1.1	8.7	8.4	15.8	5.4	3.7
Suranga No. 2	2.9	1.7	1.5	1.2	11.6	10.9	19.7	4.4	4.0
Suranga No. 3	7.1	5.5	5.0	4.6	24.7	22.7	25.4	5.7	8.3
Suranga No. 4	3.3	2.8	2.8	2.6	5.1	4.8	6.7	4.2	3.6
Suranga No. 5	7.5	5.3	5.0	4.4	21.9	24.3	26.2	9.6	6.0

Table 6.4: Rainfall data in DK district between Jan 2014-Jan 2015
(Indian Meteorological Department).

Date	Rainfall (mm)
30/01/2014	0
14/04/2014	10.1
11/05/2014	140.6
15/06/2014	549.0
15/07/2014	1070.7
24/08/2014	1041.7
15/09/2014	388.4
15/11/2014	44.8
15/01/2015	0

According to *suranga* users, rainwater is the prime source of water in *suranga* because discharge fluctuates with seasonal rainfall (R73; R92; R49), as supported by the field data. To further illustrate this point, discharge rates and the rainfall data have been compared in a dual-axis chart (Figure 6.12), which indicates that discharge from these five *suranga* increased immediately after the monsoon season and continued increasing until September 2014, thereafter gradually decreasing. A similar increase in the water level of shallow dug wells has been noticed soon after rainfall (R135). Thus, rainfall infiltration seems to be the primary source of water recharge in aquifers and is in line with the results of Saha & Agrawal (2005), who have found that the groundwater level in shallow aquifers rises between July and August and reach their maximum in September.

According to a *suranga* worker, discharge from their *suranga* seem to have reduced over time (R51). Deforestation on the hillslopes is also the cause of decreasing water availability in *suranga* and other traditional water resources, but some farmers also believe that the decreasing groundwater is caused by the increasing use of borewells in the area (R53; R103; R111; R112; R149). However, some farmers believe that borewell do not directly reduce *suranga* water supplies because they did not observe changes in *suranga* water supply after a borewell was made in the neighbouring property (R105; R108). Therefore, it seems that some borewells reduced *suranga* and dug wells supplies, whilst others did not.

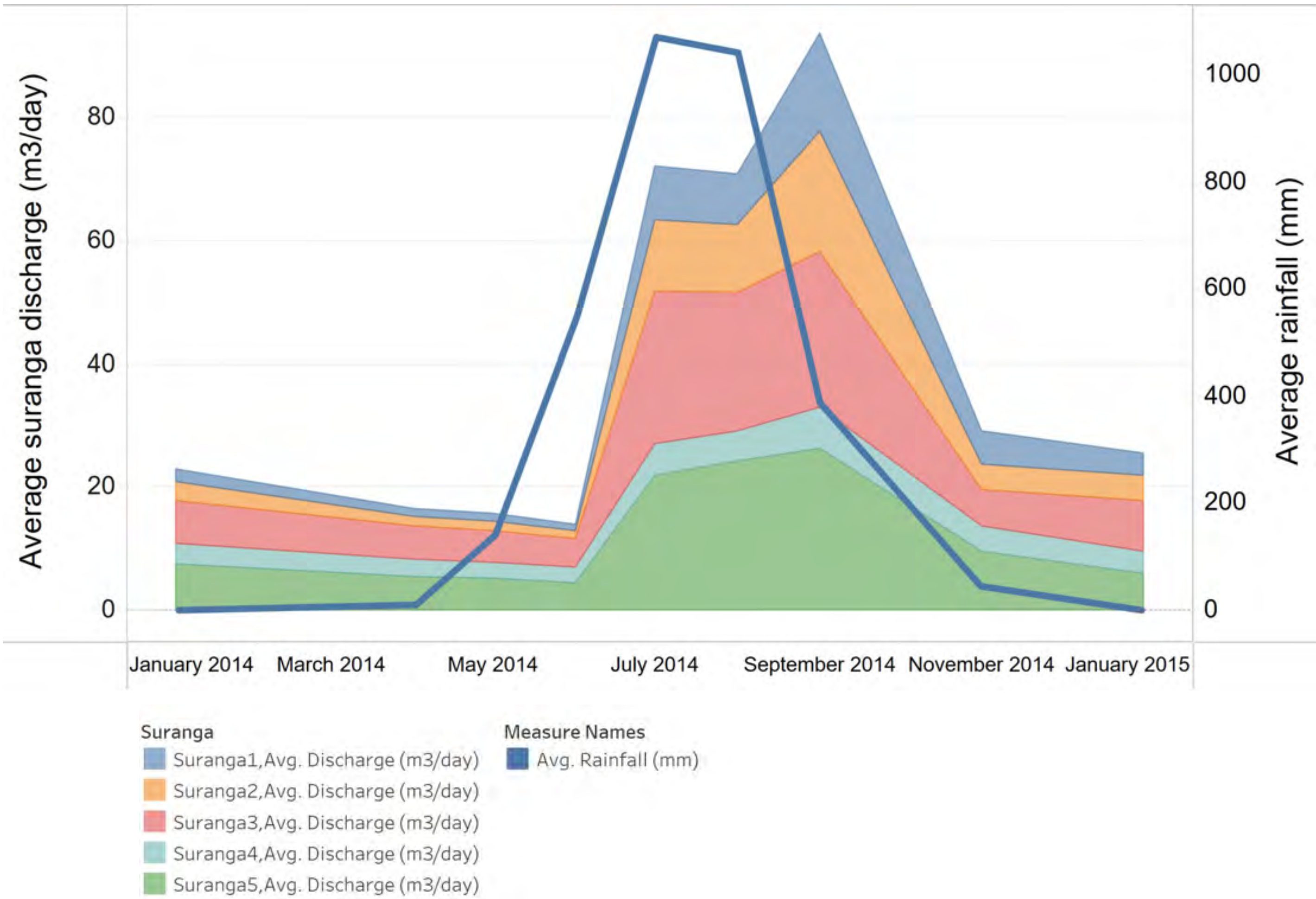


Figure 6.12: Average annual rainfall and water discharge from five different *suranga* between January 2014-January 2015.

Having ascertained how much water is harvested by *suranga* in a year, it is essential to understand what measures are taken to store water on the farm unit during times of plenty that can be used during the dry season and topped up by *suranga* over this period. It was typical for medium to large farm units to have multiple storage ponds, thus creating a more extensive water budget that protects farmers from the vagaries and uncertainties around water supply during times of short term drought, recurring every 4-5 years in the study area (Chakraborty & Shukla, 2020, p. 6). The number of storage ponds one farm unit had depended on the scale and topography of a site alongside the choice of crops grown and their irrigation requirements.

The capacity of earthen ponds and tanks categorised into three main categories according to their size, location, users are presented in Table 6.5. Deeper ponds are expensive and difficult to excavate and are uncommon in Manila and the broader study area. These ponds often collect water from *suranga*, streams, springs, and rainfall and were usually plastered with clay to minimise water loss through seepage. In addition, the excavated soil is used for creating berm around the ponds to raise the wall and to increase water capacity.

Table 6.5: The water storage ponds and tanks in the study area.

	Location	**Material**	**Use**	**Example dimensions (metre)**	**Capacity (*Cubic metre)***
Small ponds	Terraced fields, raised surface	Soil, clay, stones, concrete (for drinking)	Drinking, Domestic water	3x3x2	18
Small-medium ponds	Raised surface and often dug into the ground	Stone and soil and clay	For irrigation, but also used for domestic water requirements	10x10x4	400
Large tanks	Hilltops mainly dug into the ground	Often dugout and use of plastic sheet linings, occasionally made of stone and concrete	For irrigation	40x40x20	32000

Nowadays, the availability of excavators has allowed well off farmers to save time and resources by investing in large tanks with high capacity water. These tanks often serve as large overhead tanks situated at the highest elevations within a farmstead. The large open tanks collect direct precipitation and surface runoff. During the monsoon season, the average high rainfall of 3789.9 mm in the study area (CGWB, 2012) is sufficient to fill these large tanks, but water from well, *suranga* and other sources are also stored in these tanks. These ponds and tanks also serve the purpose of water recharge, thus increasing water availability downstream. Historically, however, medium size, and small cascading ponds situated in the terraced fields, manually excavated with local materials, were the most common in the study area. Medium sized water tanks can be made by cutting into a sloping plane, using the natural topography, and building a retaining wall on the outer side to hold water in. Smaller ponds are preferred for storing drinking water from *suranga*, and they are often made from concrete to minimise water loss through seepage. In addition, the small ponds allow a regular flow of water so that water does not become stagnant. These techniques are designed to maintain the quality of the water in these storage ponds and tanks. This is important because India ranks low in the world water quality index, with up to 70% of water resources contaminated, and every year around 0.2 million people die because of using contaminated water (Niti Aayog, 2018, pp. 27-30).

As the dry season approaches and water availability decreases, farmers, who do not have borewells, use water efficient irrigation techniques. By using water efficient distribution techniques, such as drip, fogger (Figure 6.13), and sprinkler, farmers can not only increase the duration of irrigation days in dry weather, but water can be distributed in a water efficient way to each plant, and they can survive the dry summers until the onset of another monsoon. The natural pressure gradients created by steep sloped fields allow for small spray irrigation networks or the use of foggers. The types of micro sprinkler used to supply water usually in the range of 35-360 l/h at a pressure of 1-4 Kpa, foggers deliver 20-30 l/h, whereas drip irrigation delivers water at ~8 l/h to crops. At the opposite end of the spectrum, large hoses are sometimes used for a short period to irrigate tree crops.

Figure 6.13: Water-efficient drips and foggers are used by farmers in the study area to improve water efficiency.

The frequency or scheduling of irrigation on the farm of the local host varied from once a week to once every two weeks using spray irrigation and foggers, which depended on water availability, but since 2005 daily use of drip irrigation has been used. Of interest is also the timing of when these techniques were first used. For example, on the farm, areca nut plantation irrigation started in 1955, but coconut plantations did not start being irrigated until 1980. Some farmers have laid bespoke underground networks of pipes to transport water from one source to another storage place at a lower level on their terraced farms. Thus, *suranga*, ponds, and dug well at different altitude of a hill are connected through cascading networks used to provide water for drip, fogger and sprinkler systems for distribution. Gate valves are used in these networks to divert water according to the requirements. For example, if there is excess water in a pond at the highest level, the water is diverted to another pond within the farm by gravity through the piped network. Presently, the federal and state governments provide subsidies up to 90% of the total cost to install micro irrigation systems for farming under the *Krishi Bhagya scheme* and *Pradhana Mantri Krishi Sinchayi Yojana* (Niti Aayog, 2018, p. 118; Government of

Karnataka, 2021). As a result, farmers with borewells have also adopted water efficient irrigation methods. As a result, Karnataka micro irrigation systems cover 35% of the total irrigated area, the second highest uptake rate in India (Niti Aayog, 2018, p. 159).

Suranga water is widely used for drinking and domestic usage, therefore, it was essential to understand the quality of these water sources to assess the potential health impacts for farmers reliant on *suranga* sources for domestic and irrigation water supplies because many *suranga* users do not have access to the national water supply grid. Therefore, the penultimate section of this chapter now addresses this point.

6.6 Water quality analysis

Pure water is the world's first and foremost medicine.

Unknown

Water quality tests were done to examine the potability of water from *suranga* and other drinking water sources. According to the Bureau of Indian Standards (2012), the water used for human consumption for drinking and cooking purposes from any water source is termed drinking water. Water samples were collected from four different water sources (*suranga*, dug well, pond, and borewell) to evaluate the variability of drinking water quality from different sources during the post-monsoon (Nov 2012), the pre-monsoon (May 2013), and the dry summer seasons (Jan 2014). This temporal strategy was used because the quality of water in India is often variable during the pre-monsoon and post-monsoon seasons (Mukherjee & Singh, 2018; Kurwadkar, 2019; Singh *et al.*, 2019; Subba Rao *et al.*, 2019; Kurwadkar *et al.*, 2020; Lone *et al.*, 2020; Karunanidhi *et al.*, 2021a). The sampling strategy for selecting *suranga*, dug well, pond and borewell for water quality analysis was purposive and access based. The water samples were collected from different water resources situated at various altitudes (Table 6.6) in a single catchment as shown previously in Figure 6.10 and Figure 6.11, which allowed a comparative analysis of the results according to the types and the height of the water source from mean sea level.

Table 6.6: Water samples for the water quality analysis.

Water source	Height above mean sea level (metres)	Location on Figure 6.10
A borewell	149 m	B1
A *suranga*	147 m	*Suranga* no 1
A pond	125 m	Pond 2
A dug well	110 m	Dug well

Transporting water quality testing instruments from the University of Hertfordshire to the case study site was neither practical nor cost effective. Furthermore, to export water samples to the University of Hertfordshire laboratory from the field was potentially prone to error introduced by the need to use fixing agents and the prolonged duration between the sample collection and potential analysis. Moreover, this process was not cost effective because of transportation costs. Another option considered was portable water potability kits produced by local manufacturers, but these low cost kits do not provide precise quantitative data. Finally, it was decided to get the water samples analysed at a certified laboratory situated in the nearest city of Mangalore. On three separate occasions, the water samples of two litres were collected in plastic sample bottles and transferred the same day for physical, chemical, and microbiological analysis in a NABL[35] India certified laboratory named Mangalore Biotech Laboratory[36]. This laboratory was also approved by the Karnataka State Pollution Control Board with Certificate No. PCB/668(39)/COC/2011/5161. Samples were coded before sending to the laboratory to ensure confidentially and avoid bias during the tests. The Indian Standards guided the selection of the basic parameters for analysis of water samples for drinking water, IS 10500 (2012), and the availability of analysis facilities at the testing Laboratory (Table 6.7). The spectrophotometer method was used in the laboratory using the test protocol IS 3025 of the Bureau of Indian Standards. The water quality results were compared to

[35] National Accreditation Board for Testing and Calibration Laboratories

[36] www.mangalorebiotech.com

India's acceptable drinking water limits to the Bureau of Indian Standards (2012) to investigate if *suranga* water has any quality issues.

Table 6.7: Drinking water permissible limits in India
(Bureau of Indian Standards, 2012).

	Parameters	The acceptable limit in India[37] (Test protocol: IS 3025) Min.—Max.
Physical and chemical parameters	Odour	Agreeable
	Colour	5-15
	Taste	Agreeable
	pH	6.5 – 8.5
	TDS mg/l	500 -- 2000
	Turbidity NTU	1 - 5 NTU
	Total Alkalinity (as $CaCO_3$) mg/L	200 - 600mg/l
	Conductivity mS	<15 mS
	Aluminium mg/L	0.03 – 0.2 mg/l
	Iron content mg/L	0.3 mg/l
	Fluoride mg/L	1.0 – 1.5 mg/l
Microbiological parameters	Total Coliform count MPN/100ml	0 per 100ml water
	Faecal Coliform count MPN/100ml	0 per 100ml water

6.6.1 Water quality results

Suranga are widely used for drinking, household activities, and irrigation in the study area (R38; R64; R87; R92; R127; R146; R151; R173). For some families, *suranga* is the only water source for household and irrigation (R68; R109; R114; R166). It was found from the social survey that 88.4% of families use *suranga* preferentially for their drinking and daily household activities, and any excess water is collected in ponds for irrigation (R50). In some cases, people constructed *suranga* specifically to get better quality water than well or borewell

[37] Indian Standard (IS) 10500 (2012) uniform drinking water quality monitoring protocol.

water. The families relying on seasonal *suranga* may occasionally use drinking water from other sources during a dry summer if their *suranga* dries up, but still, *suranga* water is the most popular choice for drinking water (R116). The water from a dug well, and a *suranga* may taste similar because they come from a similar groundwater source, but *suranga* water is preferred because it is naturally filtered through soil layers, and it is free flowing, unlike other standing water sources such as a dug well or pond water (R34; R116; R129; R170). In just one case, *suranga* water had a strange metallic taste and muddy yellow colour; therefore, it was not used for drinking and household supplies (R86).

The results of physical and bacterial tests of thirteen water sample have been summarised in Table 6.8. The characteristic values above or below the permissible range based on Indian drinking water standards IS 10500:1992 have been highlighted as red. No significant issues with water samples were observed in water potability tests. However, the *suranga* water samples from four different *suranga* were found to be the most suitable for drinking except for one *suranga* with low pH of 5.1. However, low pH values or pH values near the lower range were common in nearly all water samples, attributed to the iron rich, weathered soil (Figure 6.14).

Table 6.8: Water quality analysis of water samples from various sources in three different seasons.

	Total coliform count (MPN/100ml)	Faecal coliform count (MPN/100ml)	pH	Iron content (mg/L)	Conductivity (mS)	Total Alkalinity (mg/L)	Turbidity (NTU)	Fluorides (mg/L)	Aluminium (mg/L)
Borewell_S1	23	0	6.6	3.00	0.20	109.00	31.00	0.07	< 0.1
Borewell_S2	0	0	6.3	2.00	0.90	95	8.50	<0.10	< 0.1
Borewell_S3	0	0	7.0	0.14	0.10	10	0.90	<0.10	< 0.1
*Suranga*_S1	0	0	5.1	0.15	0.00	31	1.00	0.05	< 0.1
*Suranga*_S2	0	0	6.6	0.07	0.10	12	0.50	<0.10	< 0.1
*Suranga*_S3	0	0	6.8	0.58	0.10	17	8.80	<0.10	0.12
*Suranga*_S4	0	0	7.3	0.16	0.50	85	0.90	<0.10	< 0.1
Pond_S1	0	0	6.2	0.13	0.10	37	4.40	0.1	< 0.1
Pond_S2	23	23	6.0	0.30	0.10	23	1.20	<0.10	< 0.1
Pond_S3	0	0	6.2	0.23	0.10	15	6.20	<0.10	< 0.1
Dug well_S1	0	0	5.9	0.08	0.00	26	5.00	0.1	< 0.1
Dug well_S2	0	0	6.5	0.14	0.60	17	14.50	<0.10	< 0.1
Dug well_S3	0	0	5.9	0.14	0.20	24	0.70	<0.10	< 0.1

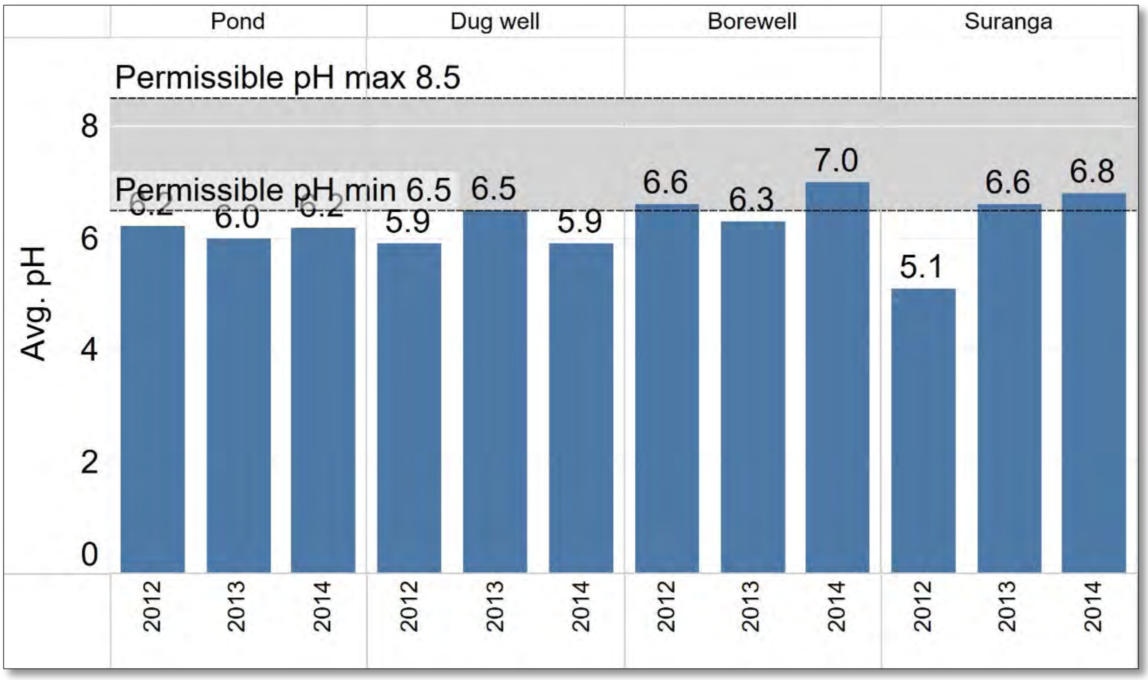


Figure 6.14: pH value variation of all the water samples.

Iron content beyond the permissible range was observed in two borewell samples (3.0 mg/l and 2.0 mg/l), which can alter the taste of borewell water compared to the taste of other water sources with low iron content. It may be the reason that locals prefer to use *suranga* water for drinking and household purposes. Turbidity was found to be above the permissible limit in a borewell (31 NTU) and a dug well (14.50 NTU) sample. The water quality of a borewell and pond samples were found to have bacterial contamination on a single occasion. In the borewell sample, the total coliform count was found to be 23 MPN/100ml. A sample from a pond, situated at the bottom of a water catchment area, collecting water from several *suranga* and seasonal streams, was 23 MPN/100ml faecal coliform count. In the study area, families typically use boiled water for drinking to offset any bacteriological contamination issues in the water (Clasen *et al.*, 2008; Juran & MacDonald, 2014; McGuinness *et al.*, 2020). Thus, in summary, the above water quality results for potability indirectly support local attitudes towards drinking water that led to preferential use of water from *suranga* for drinking and household chores compared to other available water sources, such as borewells.

6.7 Chapter summary

This chapter answered research question no 4, which was about finding the key geohydrological and hydrological characteristics of the *suranga* system, using a measure of discharge from several *suranga* over a year, and radiocarbon dating of various groundwater samples to explore the provenance of groundwaters in the catchment area of *suranga*. In general, the age of various groundwaters was found to be positively associated with the depth of the water sources, which means the water samples from the deepest borewells were found to be the oldest in their provenance. This helped develop a hypothesis that suggests *suranga* mainly harvest water from perched aquifers situated at shallow subsurface depths, which are not directly connected to deeper aquifers abstracted by the borewells in the study area. Furthermore, *suranga* water was preferentially used relative to other sources of water for drinking and domestic purposes. Thus, the right physical and environmental conditions were in place to make the *suranga* system viable in at least the short to medium term. What remains to be answered is whether this development was supported by specific socioeconomic conditions that favoured the development of *suranga*. The next chapter presents the socioeconomic results from the community inhabiting the study area.

Chapter 7 – Socioeconomics of the community

A general survey of *suranga* owners was undertaken to understand the socioeconomic context of the study area and the *suranga* system, followed by in-depth interviews with a select number of those who agreed to take part, which attempted to provide the answer to the last research question of this study.

> **Research Question 5:** What socioeconomic conditions in the study area promote the use of *suranga*?

This chapter has three major sections. Section 7.1 presents the methods used to collect and analyse survey data. Section 7.2 presents the in-depth interview approach taken alongside the method of data analysis used in this study. The results from section 7.1 and 7.2 have been collectively presented in section 7.3. Finally, the results have been summarised in section 7.4.

7.1 Method: Survey research

In the absence of any previously documented information about the *suranga* system, this study started with an aim to collect primary data about the *suranga* system, water resources, and the community in the study area, by conducting a detailed socio-economic survey, with a questionnaire used as an instrument for collecting data for this survey (Thomas, 2013; Gray, 2014). The questionnaire was designed in line with an exploratory approach to quantify the extent of *suranga* in the study area, in the location of where many *suranga* has been mentioned in previous studies, but not quantified. Previous understanding and experience of the *suranga* system and the study area gained during MSc fieldwork helped in the initial design of the questionnaire in the UK. The questionnaire was further developed by reviewing the literature on *suranga* and other water harvesting methods found in India and the rest of the world (Gray, 2014).

The questionnaire was designed to collect the data systematically (Thomas, 2013; Robson & McCartan, 2015) as it comprised a mixture of semi structured, closed, and open ended questions that enabled the collection of quantitative and qualitative data (Yates, 2004). The open ended questions followed the style of a structured interview, achieving maximum objectivity and avoiding interviewer bias in the survey (Gray, 2014). Open ended questions provided an opportunity for farmers and landowners to elaborate on their responses. This allowed for the freedom to ask probing questions to clarify meaning and better understand unclear comments and incomplete answers during the survey (Thomas, 2013; 2011; Gray, 2014). The closed questions in the questionnaire produced quantitative data related to population, total land holdings, and the number of *suranga* and other water resources (Yates, 2004; Robson & McCartan, 2015).

The questionnaire was divided into four sections. The first section comprised basic questions related to the household population and the social and economic condition of a respondent's family. Starting with basic fact seeking questions was twofold: respondents could be categorised and could be revisited if needed, and basic demographic questions helped form some rapport between the researcher and the respondents (Gray, 2014; Robson & McCartan, 2015). In the remaining parts of the survey, there were questions related to agricultural practices, water resources, and *suranga*, construction periods, water rights, scheduling and allocation of water, rituals, conflict resolution, behaviour, and attitudes towards water use that were framed around the conceptual mountain/hill irrigation model that was presented in Chapter 2. To comply with the General Data Protection Regulation 2018, respondents' name, age, and address was removed or coded in the final database and the analysis. A summary of the questions asked in the questionnaire has been summarised in Table 7.1. The complete questionnaire with a subject briefing is presented in Appendix G. The questionnaire was approved by the School ethics committee (ref. LS5/7/12SR) before the data collection from human participants commenced.

Table 7.1: A summary of the various questions in the survey questionnaire.

Sections	**Number of questions**	**Questions related to**
Demographic questions	11	Name, age, address, family size, economic status, occupation, livestock
Agricultural questions	16	Landholdings, agriculture, fertilisers, water resources, irrigation methods, water scarcity and storage
Suranga questions	11	Number of *suranga*, *suranga* history, construction, maintenance cost, water sharing arrangements, water quality
Suranga structural survey	22	*Suranga* dimensions, water discharge, types of *suranga*, *suranga* use

A highly experienced farmer with knowledge and expertise about geography, local communities, and water resources hosted the researcher and facilitated fieldwork in the study area. This acquaintance with the host was established during the first visit to this area in September 2008 in part fulfilment for an MSc dissertation (see Tripathi, 2009). Further help with fieldwork was obtained from local people who acted as field guides. The study area is a multilingual region, such that it was impractical and costly to translate and print out questionnaires in all languages used in the region. As a compromise, the questionnaire initially prepared in English in the UK was also made available in the

Kannada language in the field because Kannada is the most used language in the study area.

Moreover, it was possible in part to communicate in Hindi and English, but Kannada, Tulu, and Malayalam were the main spoken languages in the study area; therefore, the local guides also acted as interpreters between the researcher and the respondents. The guide usually had an excellent local knowledge of geography, agriculture, and water resources in the area. They came from diverse social and economic backgrounds, which eased access to families from different castes and classes. The presence of local guides during the survey also helped in establishing a rapport with the respondents. Obtaining informed verbal consent to answer questions was straightforward in most cases because respondents were put at ease by the presence of a local person.

In the absence of any information about the exact spatial distribution of *suranga*, initial participants were selected on the recommendation of the local host, local guides, and the gatekeepers in the community. These people often had an in-depth knowledge of the region and the community and were well known in the area for their *suranga* expertise. This non-probabilistic, purposive snowball sampling strategy meant that the participants could recommend any other eligible participant in their knowledge who could help with the data collection (Creswell, 2013; Thomas, 2013, Gray, 2014). This approach was highly successful in locating survey participants in the challenging and remote geographical study area characterised by dispersed communities and villages. This approach also unearthed evidence for the transfer of *suranga* technology in the past from the study area to other districts in India. To illustrate this, point the primary population for this survey came from *suranga* users in the villages of Kasaragod and DK districts in India (Figure 3.5). However, the survey was extended to a couple of villages in the North Goa district when a *suranga* worker considered constructing *suranga* in that community. In this case, the snowball approach was used to locate the exact locations of *suranga* in North Goa.

Initially, a postal questionnaire survey was considered, but this proved impossible because the addresses of farmers were unknown. Further to this, if a self-administered paper based questionnaire had been used, some critical information may have been missed because of potential question ambiguity and misunderstanding caused by the translation of key concepts and terms (Robson & McCartan, 2015). Secondly, a telephone survey was considered to save resources and time, but soon it was found impractical because of the limited phone reception caused by the steep terrain and remoteness of the region. It was also considered impractical because too much time would have been required on each phone call, as an interpreter would have been needed to translate questions and answers during the call. Thus, this survey used a face-to-face approach to administer the questionnaire (Gray, 2014; Robson & McCartan, 2015). It was felt that the physical presence of a researcher accompanied by a local guide asking the questions would reassure and motivate respondents and increase the number of responses in comparison to other forms of communication (Thomas, 2013). This also had the advantage of allowing the questionnaire to be delivered to a considerable number of illiterate respondents. In a face-to-face survey, there is the opportunity to ask probing questions, clarifying points, and negotiating meanings, which improved the overall understanding and credibility of these data. In the case of an outlier response, there was the opportunity to rephrase and ask the same question in a different order to the same respondent during the face-to-face questionnaire. Additionally, tone, behaviour, gesture, and body language were also used to indicate information, attitude, and emotion during the survey (Vitelli, 2017; Ratnasari, 2019).

Before setting out on fieldwork, a day plan was decided on by the host, local guide, and the researcher. According to weather conditions and other events, this plan was always provisional and often modified in the field. The survey respondents came from diverse social and economic backgrounds, so to put them at ease, they were approached by visiting them in their homes, fields, farms and at social gatherings, basically when there was any opportunity to communicate face to face with a potential respondent (Thomas, 2013; Ratnasari, 2019). The idea was to make the respondents relax and feel confident in familiar environmental settings. The heads of the families, which were male in most cases, were interviewed because they had the best knowledge about their families' social and economic conditions. Participants were contacted for appointments and implied consent orally, sometimes in advance over the phone, by the local host before visiting them, notably when respondents lived in remote locations to maximise research time and keep associated costs low. A subject briefing with the researcher's identity was provided to the respondent by the local guides before starting the face-to-face questionnaire. This subject briefing explained the aim of the project, provided a burden estimate, and explained the voluntary nature of their participation and that they could withdraw from the survey at any time. It also provided reassurance that all data would be anonymised and treated as confidential. During the fieldwork, respondents were briefed orally to speed up the process and keep farmers interested in the survey.

The interviews usually started with informal discussions about the respondents' agriculture practices so that the respondents became comfortable with the style of questioning before demographic and personal questions were asked. The face-to-face survey questionnaire responses were audio recorded to minimise the time needed for the survey and maximise the information gathering without breaking the flow of conversation. However, an audio recorder could distract and intimidate respondents because it can remind the participants that their responses were being recorded during the whole interview. Thus, a mobile phone was used for the recording that did not attract much attention from the respondents as they often owned mobile phones themselves. This maintained a relaxed, natural, conversational atmosphere. Where possible, responses were translated into English or *Hindi* immediately during the interviews or translated at the end of the day.

The survey interviews were generally followed by quick farm visits to observe agricultural practices and water harvesting, conveyancing, scheduling, and allocation practices. This in-situ corroboration allowed validation of the data and observation of variation in design principles. Photographs of the water resources were taken because they provided a powerful extension of observation and triangulation with other methods in a mixed methods study (Thomas, 2013). Another advantage of taking photographs was that social scenes could be quickly recorded faster than writing notes at the scene, which can always be relived again with minimal memory loss (Robson & McCartan, 2015). The use of image based methods helped improve conversation/relationship with the respondents (Gray 2014, Robson & McCartan, 2015). For example, with consent, photographs were taken of some of the respondents in their natural contexts during the first field trip, some of which were given to the respondents during subsequent home visits. The photographs not only helped as a tool for retaining memory and relocating respondents but also improved cooperation during the fieldwork.

The respondents were often keen to show off their water management systems, and nearly every farmer gave an invitation to visit their *suranga* internally, which enhanced knowledge of *suranga*. These visits to farms and fields also allowed for ground truthing of the respondents' answers. In a few cases, there was nobody available in the house, or the respondent did not have enough time or knowledge for a tour, in that situation the main aim of the survey was to collect the quantitative data for the survey, either by a quick application of the face-to-face questionnaire or by the direct observation of the farm. The aim of this quick survey was to provide basic information about the extension and distribution of the *suranga* system.

The initial questionnaire was piloted on the first ten respondents, which helped identify redundant questions which were removed from the questionnaire. For example, the respondents could not rank their water resources because all water resources were considered equally important to them. Another question asking about the maintenance charges of a *suranga* was also removed because the first ten *suranga* owners could not quantify the cost. Moreover, the initial plan was to record the geographical coordinates of each *suranga* and the dwellings to produce a GIS database. However, the unavailability of a high resolution map of the study area in the GPS unit and the high density of *suranga* in a small area did not allow for recording coordinates for each *suranga*. Similarly, some new questions were added. For example, a question about the family's economic status above (APL) and below (BPL) the poverty line[38] was added to the survey because it was discovered that economic benchmarking is widely used by the state and federal governments to provide subsidised food and fuel to economically weak families (*Anna*

[38] According to Indian government, families are benchmarked into two APL and BPL categories based on the income of the family. Families earning less than 10,000 INR (approx. £115) per annum are given BPL status, and families earning more than this threshold are classed as APL. BPL families are provided rice, wheat, palm oil, sugar, salt, and kerosene oil at significantly subsidised rate than the market price by the government. Since May 2015, Karnataka government has initiated '*Anna Bhagya Yojana*', which will provide rice and wheat to BPL families free of cost. The amount of the commodity is in proportional to the family size ("Anna Bhagya Yojana", 2017; Shetty, 2018).

Bhagya Yojana, 2017; Rajesha, 2017; Shetty, 2018). Some minor changes to the initial questionnaire were also made after seeking opinions from the host and guides because of their familiarity with the study area.

The survey data, which included quantitative and qualitative data, were saved in tabular form in a Microsoft Excel file. In addition, the qualitative data generated during the interviews were saved in text files and were analysed with the rest of the qualitative data that included in-depth interviews. More information about the analysis of the qualitative data is provided in section 7.2. The quantitative data from the survey database was composed of categorical and numerical variables (Robson & McCartan, 2015). In the first stage, the database was analysed to calculate basic statistics of several variables using Microsoft Excel to calculate individual frequencies, mean, and percentages (James *et al.*, 2013) for various individual variables, such as landholdings, number of *suranga* and other water resources. The socioeconomic survey explored underlying patterns and trends among the variables and the observations in the second stage. This was done by using a combination of multivariate dimension reduction and clustering methods, such as Multiple Correspondence Analysis (MCA) and Agglomerative Hierarchical Clustering (AHC) (Branchet *et al.*, 2018; Chen, 2018, pp. 291-301; Hjellbrekke, 2019). A statistical software package known as XLSTAT was used to perform MCA and AHC (XLSTAT, 2020). More details of these two data exploration methods have been provided in the following sections.

7.1.1 Multiple correspondence analysis (MCA)

Multiple Correspondence Analysis (MCA) is a method of multivariate analysis to explore the correlation between categorical variables and observations, applied to the categorical database to explore if there was any association among the variables and observations (Greenacre & Blasius, 2006; Greenacre, 2007; Hjellbrekke, 2019). The database, from the socio-economic survey, comprised 57 categorical variables (columns) and 215 observations (rows). A summary of the socioeconomic survey database is presented in Appendix H. During the MCA analysis, responses and categories were coded in single characters or acronyms to minimise the table's size, ease of analysis, and a scatter map produced by MCA. Analysis with MCA is an iterative and deductive process to optimise the sets of variables and observations that carry maximum weight in combinations. Initially, MCA applied to all 57 variables and 215 observations to understand the data and associations, but the resultant scatter plot was highly homogenous, and it was difficult to establish any correlation among 57 variables. Therefore, in the next stage, the database was grouped into four sub-categories of social and economy, farming and agriculture, water resources, and irrigation (Figure 7.1). Then MCA applied to these four categories individually, with each category having a minimum of three to a maximum of 15 variables. In the third stage, the spectrum of variables analysed was escalated, and variables of similar broad categories were further analysed for correlation. The combinations of a variable which resulted in homogenous scatter plots (or low correlation) were discarded because a correlation could not be established; hence those combinations were made redundant to achieve maximum accuracy in MCA results (Greenacre & Blasius, 2006). The only combinations that established the height correlations were retained, interpreted, and presented in the results section.

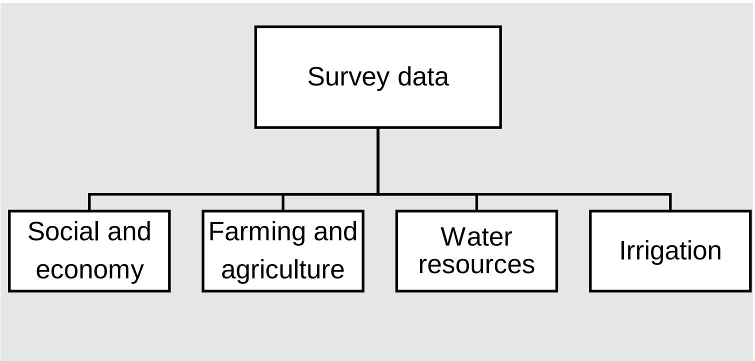


Figure 7.1: Sub-categories in the survey database.

The MCA results are presented in a correspondence map, also known as association plot or scatter plot (Greenacre, 2007; Hjellbrekke, 2019). Variables that were not included in the MCA calculations but were plotted on final correspondence maps are supplementary variables. For example, the category of village names and family's economic status was used as supplementary variables. MCA applied to all observations, but any missing data were removed from the MCA process, which resulted in increased inertia for the analysis and more accurate interpretation of the results. Greenacre (2007) suggested that adjusted inertia was used in generating MCA scatter plots because it provides better information about the association.

Although scatterplots are the graphical presentation of results in MCA, because these maps are produced from MCA results moving from tabular form to graphical form, the interpretation of the correspondence map in isolation can be incorrect (Greenacre & Blasius, 2006; Greenacre, 2007; Hjellbrekke, 2019). However, MCA, followed by Agglomerative Hierarchical Clustering (AHC), can increase the readability and reliability of the results obtained by MCA (Le Roux & Rouanet, 2005, p. 219; Hastie *et al.*, 2009, pp. 501-528; Branchet *et al.*, 2018; Chen, 2018, pp. 291-301; Hjellbrekke, 2019). Therefore, MCA was followed by AHC to create clusters based on similarity among observations and variables in the categorical database (Hjellbrekke, 2019). An explanation of the AHC method used is provided in the following section.

7.1.2 Agglomerative hierarchical clustering (AHC)

Clustering methods are used to organise elements into subgroups or sets in a dataset according to the similarity within a subgroup and difference among the subgroups (Hastie *et al.*, 2009, p. 502; James *et al.*, 2013, p. 385). AHC starts with clustering elements using a bottom-up approach, where similar elements are gradually clustered up into a dendrogram producing a group of clusters in a hierarchical order (Hastie *et al.*, 2009, pp. 520-521; Hjellbrekke, 2019). AHC is a popular clustering method because resultant clusters of observations are grouped into an inverted tree shaped diagram, known as a dendrogram (Chen, 2018; Hjellbrekke, 2019). AHC based on Ward's method was applied (Murtagh & Legendre, 2014) to the observations (n=215) to determine if there was any similarity among the respondents (XLSTAT, 2020), or in other words, if the sample population was divided into subgroups, which was presented through the dendrogram. However, the dendrograms should not be interpreted in isolation (Hastie *et al.*, 2009, p. 502). Therefore, the AHC results for the *suranga* survey were compared with the results from the MCA results, and finally, the clusters maps were plotted with Tableau visualisation software (Tableau Desktop, 2020).

7.2 Method: In-depth interviews

Although a face-to-face questionnaire was an efficient method of data collection for this study to characterise the social-economic conditions of the communities, the spatial distribution of *suranga*, and basic design principles of *suranga* (Walsh, 2001; Robson & McCartan, 2015), it did not produce in-depth information about *suranga* such as the reasons behind physical, social, and economic contexts for development, agriculture history, crop patterns, water availability, water resources, and the reasons for adoption of *suranga* or other water resources (Gray, 2014; Robson & McCartan, 2015). Therefore, in-depth interviews were used to fill this gap by seeking clarification as a follow up on the data collected from the survey, with respondents to understand their perspectives on the matter (Walsh, 2001; Creswell, 2015). For example, an in-depth interview of a *suranga* worker provided their perspective of the *suranga* system, which was extremely useful for the researcher to understand the system. Thus, in-depth interviews collected information about the construction and management principles of *suranga*; the social and cultural aspects of these communities; and helped interpret the quantitative survey results (Creswell, 2013).

Interviewing is a highly subjective technique; thus, there is a high possibility of bias during qualitative interviews (Flick, 2014; Gray, 2014; Robson & McCartan, 2015). For example, a respondent may have a strong opinion and pre-judgments about their farm, agricultural methods and irrigation techniques used compared to other farms. Sometimes, respondents may exaggerate or minimise the importance of information for various personal reasons. Therefore, the data collected from interviews were collated and triangulated with the survey data and field measurements (Robson & McCartan, 2015). The questions for in-depth interviews, which were initially developed during the post analysis phase of the survey, continuously evolved with the use of an inductive approach as subsequent field trips and data analysis enhanced experience (*ibid.*). Unstructured interviews are informal conversation about a topic of interest without a pre-set format of discussion using open ended questions (Thomas, 2013, Gray 2014). The in-depth interviews were carried out between August 2012 and December 2012, whilst several in-depth interviews were repeated between March 2013 and May 2015 to improve the understanding and meaning of the survey results.

The participants for in-depth interviews were mainly selected from the survey sample. In the survey, there were usually two types of participants. The first did not have much information about the *suranga* and other water systems because they employed people to construct and manage their *suranga* or migrated from this area and bought a property that had already *suranga* or other water harvesting resources. Therefore, their knowledge of local history and the development of the *suranga* in their property was limited. The second type of participants had the experience of either constructing or managing a *suranga* and other water harvesting systems and lived in the study area for a significant period. The latter type of participants included *suranga* users, workers, and the local water diviners. Other participants, who were not necessarily *suranga* users, were interviewed as they had knowledge and experience, which helped collect in-depth information about the broader level research context. For example, local government officials were interviewed to collect the social and demographic information about the studied villages. Moreover, it provided an image of the community as perceived by the local government agencies and helps to build a picture of any existing hierarchies. The approach taken was to collect a maximum possible number of in-depth interviews to increase the representativeness of the qualitative data, and data collection was only stopped once the stage of data saturation was achieved, which means that no new patterns were emerging from the data gathered from new participants (Creswell, 2013; Robson & McCartan, 2015).

The length of the interview was generally determined by the experience and initiative of the respondent to pass on the information (Creswell, 2013; Gray, 2014). The interviews lasted from ten to 90 minutes. The interview questionnaire consisted of open ended, semi structured questions, supported by unstructured discussion, to gain an in-depth understanding (Robson & McCartan, 2015) of the *suranga* system and the community. Interviews were undertaken in two phases. In the first phase, short explanatory questions were asked of the respondents. Occasionally, these probing questions were asked concurrently during the survey to explain open ended questions in the survey questionnaire. These questions were semi structured and unstructured. A semi structured approach allowed probe style questions to be used if a detailed response was needed (Gray, 2014), while an unstructured approach let the respondent's perspective guide the discussion indirectly (Yates, 2004). To make a cost comparison between various water resources available, questions were asked to the respondents about the construction, running, and the maintenance costs of different available water resources and structures in the study area, which were *suranga*, dug well, circular concrete well, seasonal check dams, government water supply, and borewell. This cost comparison of various water resources was made in the currency of the Indian Rupee (₹)[39] to compare the economic sustainability of the *suranga* system in contrast to the other water resources and future water demands.

These interviews, therefore, developed a shared perspective between the respondent and interviewer, making it the most logical method for collecting data for exploratory meaning and mainly dealing with feelings and experiences (Yates, 2004; Gray, 2014). In conjunction with the survey method employed in this study to follow up issues and seek explanations, interviews were also used to collect information about a respondent’s knowledge, experience, feelings, and attitudes towards a topic (Gray, 2014). It was necessary to mix easily with the respondents under study, causing a minimum disturbance as this then provided in-depth details of the situation supported by the evidence collected (Thomas, 2013). Moreover, it was advantageous to behave like a counsellor by collecting the accounts and narratives of the case and providing an explanation for the issues (Thomas, 2013; Robson & McCartan, 2015). This naturalist approach of data collection led to the construction of a narrative of the perspective of participants (Creswell, 2013; Robson & McCartan, 2015). These interviews yielded information based on fact, opinions, attitudes, or any combination of these as the information needed to analyse these data carefully (Yates, 2004; Thomas, 2013; Gray, 2014). Perspectives of each participant can vary to the other participants; thus, a large number (n=173) of open ended, small and large interviews were completed to find the commonality in all participant’s

[39] The Indian Rupee (Code: INR, Sign: ₹) is the currency of India, and 100 INR was equal to 1.15 GBP on 30 September 2017.

understanding. The number of these interviews depended on the access and availability of the respondents.

Group interviews and focus groups were at first considered for this project as a means of collecting qualitative data (Gray, 2014; Robson & McCartan, 2015). A focus group trial was undertaken during the initial stage of the interviews, but the language gap did not allow the researcher to facilitate or moderate the focus group or comprehend the in-situ discussion. Moreover, it was a time consuming, complicated process, and it was difficult to retain focus during the conversations and negotiate meanings until the local guide interpreted the proceedings at the end of the focus group discussion. As a result of this, it was decided to focus only on the individual interview method.

The open ended questions produced qualitative data that were transcribed and analysed using content analysis (Creswell, 2013). These data collected from the survey questionnaire and in-depth interviews were then explored for emerging themes using thematic and categorical analysis methods (Braun & Clarke, 2012), which are explained in the next section.

7.2.1 Thematic analysis

An edited, intelligent transcription approach was used to transcribe the interviews. In edited transcripts, the transcriber can omit parts, and clutter in the data, while keeping the meaning intact (Braun & Clarke, 2012; Robson & McCartan, 2015). A verbatim transcription approach was not used because the interview data was not collected first hand, but the local guide interpreted it during the interview; thus, capturing the subtle expressions and language details was not possible in these interviews. The main idea of these interviews was to collect in-depth information (Gray, 2014) about the *suranga* system and the community, rather than observing psychological and physical behaviour and feelings; therefore, unnecessary data was omitted (Braun & Clarke, 2012). Interview transcripts were edited soon after the interview to retain an understanding of the data. This was a time consuming process because of the need to be selective and experienced with these data (Gray, 2014). Thus only relevant information was retained, and the transcripts were presented in an easily readable text (Braun & Clarke, 2012; Robson & McCartan, 2015). The examples of three interview transcripts have been provided in Appendix I. Once all the interviews and observations were transcribed, a basic word frequency query produced a word cloud (Figure 7.2), which provided initial directions to code the data (Braun & Clarke, 2012; Robson & McCartan, 2015). Thus, the textual data was coded for qualitative analysis in NVivo Pro 11 software. Coding was undertaken using a computer because it made the analysis process time efficient and flexible (Skalski *et al.*, 2017, p. 226). The other advantages of electronic coding were an easy electronic backup and the availability of the data to a broader public for later examination if needed. A snapshot of the codes and their hierarchical order has been presented in Figure 7.3. The complete codebook has been provided in Appendix J.

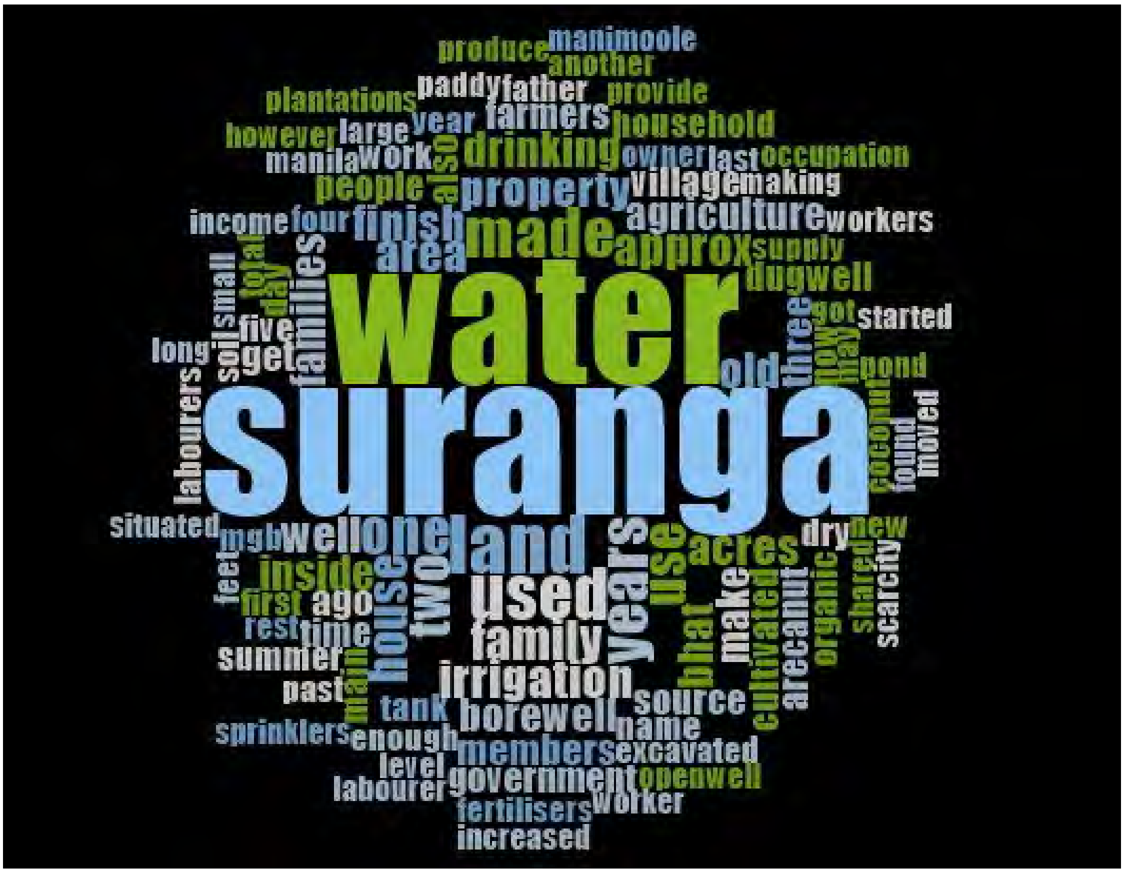


Figure 7.2: A frequency word cloud produced from the interview transcripts.

Row	Name	Sources	References
2	Water	159	1535
3	Traditional water harvesting	155	1106
4	Suranga system	150	948
5	Excavation process	88	207
25	Design principles	99	201
66	Hydrology	98	170
90	Origin	102	137
98	Use and benefits	87	121
113	Future	24	42
130	Spatial distribution	11	17
137	Management	13	15
140	Workers	9	15
148	Water quality	13	13
149	Ecology	6	10
150	Flora	5	6
151	Fauna	3	4
152	Wells	63	84
163	Water divining	32	41
166	Kere	18	20
167	Katta	5	7
170	Others	3	6
171	Traditional knowledge	5	10
172	Kai-dambe	1	1
173	Madaka	1	1
174	Yeta	1	1
175	Water resources	97	163
201	Water issues	60	82
209	Water Sharing	49	78
213	Future water plans	35	43
225	Drinking water	22	23
231	Water management	18	21
240	Groundwater	16	19
245	Land, society and economics	156	559
337	Agriculture	135	417
412	Geography and climate	63	123
441	Miscellaneous	21	33

Figure 7.3: A screenshot of the codes used for the analysis of the in-depth interviews.

The thematic analysis technique was used to analyse data for emerging patterns and themes (Creswell, 2013; Skalski *et al.*, 2017) based on agriculture, irrigation, land management, and local life. Content analysis was also used on the data collected from archival documents, written and cartographic, media outlets like the Indian Water Portal and Karnataka, and Kerala government report (Braun & Clarke, 2012; Robson & McCartan, 2015). Photographs and video clips from local researchers and journalists were also used as documentary evidence; however, the documentary evidence may not be completely free from bias and errors (Gray, 2014). Therefore, they were never analysed in isolation and connections were made between different sources to validate the information and provide greater credibility to the results. The results from the survey questionnaire and in-depth interviews have been collated in the following section.

7.3 Results: Socioeconomic characteristics of the community

The geography of the study area is undulating, ranging from flats valleys to steep hills with a maximum height of 300 metres above sea level (Sarath *et al.*, 2020). Puttur, Bantwal, Kasaragod, and Mangalore are situated in the flat regions, while village centres are usually located in and around the valleys of the hills. The dwellings are sparsely distributed in the small valleys and on hillslopes and are often connected by narrow roads and unpaved paths cutting across these hills (Figure 7.4).

Figure 7.4: A view of Manila village in the study area from the hilltop.

Overall, *suranga* appear to have provided in the medium term a simple, adaptable technology with dependable and, based on a preliminary survey, high quality water supply. Therefore, it becomes essential to fully understand the research area's complex socioeconomic characteristics to better understand if *suranga* are still relevant to this community and offer potential resilient and sustainable futures in the long term. Therefore, this section presents the results related to socioeconomic characteristics, such as where farmers sit on the poverty line as either APL or BPL, the present settlement patterns, water harvesting strategies, irrigation approaches, autonomy, conflict resolution approaches and the present status of *suranga* in the community.

Thematic analysis of qualitative data (n=173) with Nvivo produced four broad categories: community and economy, management of water resources, and farming and agriculture. Figure 7.5 presents the relationship among these categories. For example, agriculture relies on the management of water resources, which is governed by the community and their economy, shaped by the study area's climate and geography.

Figure 7.5: The main themes that emerged from the qualitative analysis of interviews, and their relationships to each other.

This section presents the results of the MCA of the survey data related to socioeconomic characteristics such as economic status, occupation, landholdings, and livestock. In the MCA, the financial status of families was used as a supplementary variable. Supplementary variables do not influence MCA calculations but are plotted in the correspondence map (symmetrical plot) to show relative locations of supplementary variables to the analysed variables. To maintain the continuity of the results, only correspondence maps, which are the final product of MCA, and their interpretations have been presented in this Chapter (see Appendix K for detailed MCA results). A correspondence map for socioeconomic characteristics in Figure 7.6 suggests an economic division in the community in the study area, which is based on the financial status of the families and the size of their landholdings.

For example, Cluster 1 is a group of highly likely farmers that have a minimum of one hectare of land. These respondents had small to large landholdings and were highly likely to be APL families. They prefer to rear cows to chickens or goats. These farmers rarely had a secondary occupation. In contrast, Cluster 4 includes BPL families. These families were landless or had marginal landholdings, which means they hold less than one hectare of land. These families were highly likely to be labourers, and they do not have the resources to rear cows, but they are highly likely to rear chickens and goats. Cluster 3 is of the people in skilled employment, and these were likely to have farming as a secondary occupation.

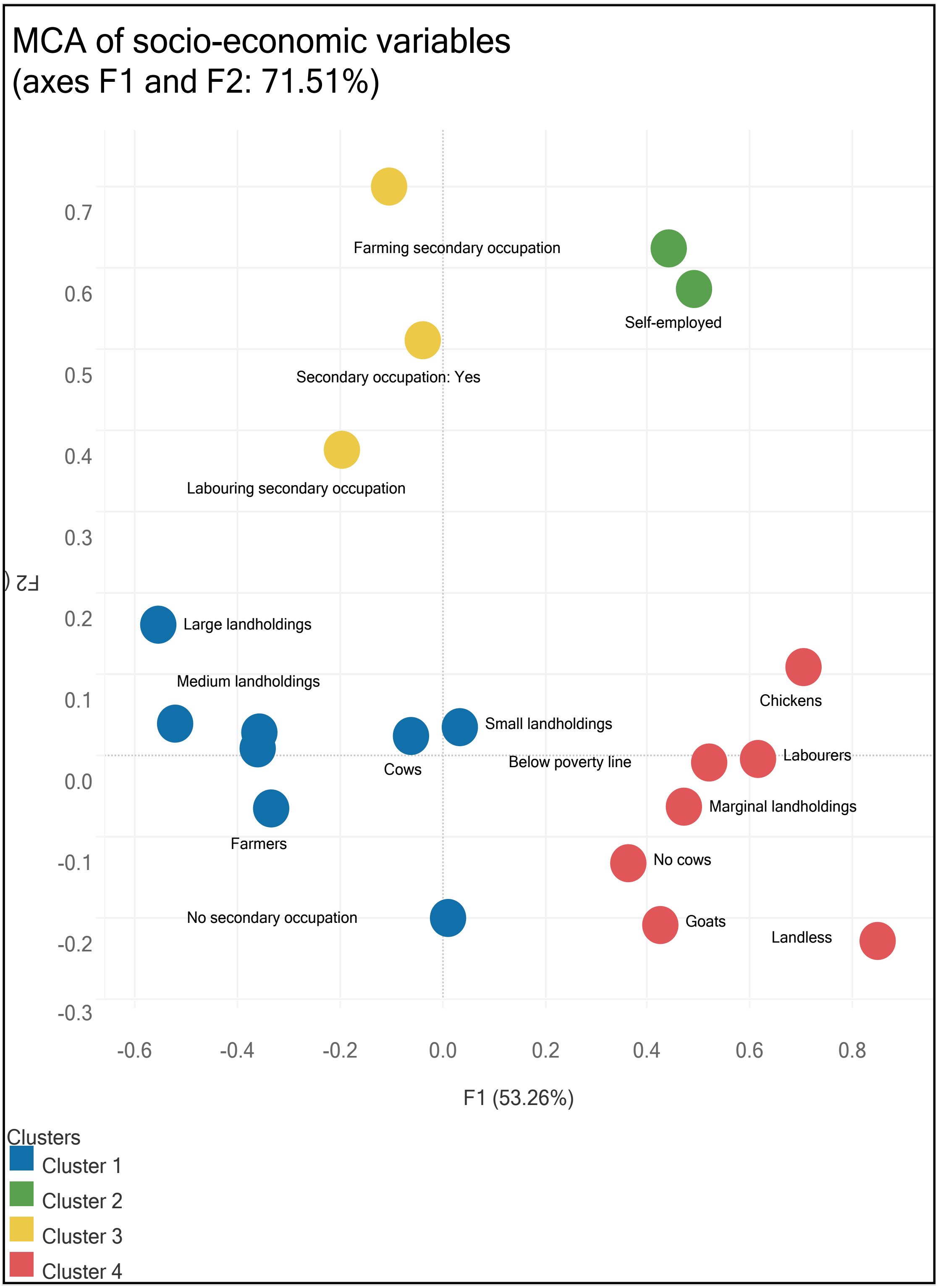


Figure 7.6: Correspondence plot of socioeconomic variables.

Figure 7.7 presents the MCA of observations, where respondents were numbered with their economic status. All five clusters are grouped and dominated by the economic status of the respondents. For example, there are mainly APL families in Cluster 2, Cluster 3, and Cluster 4, while BPL families are grouped in Cluster 1 or Cluster 5.

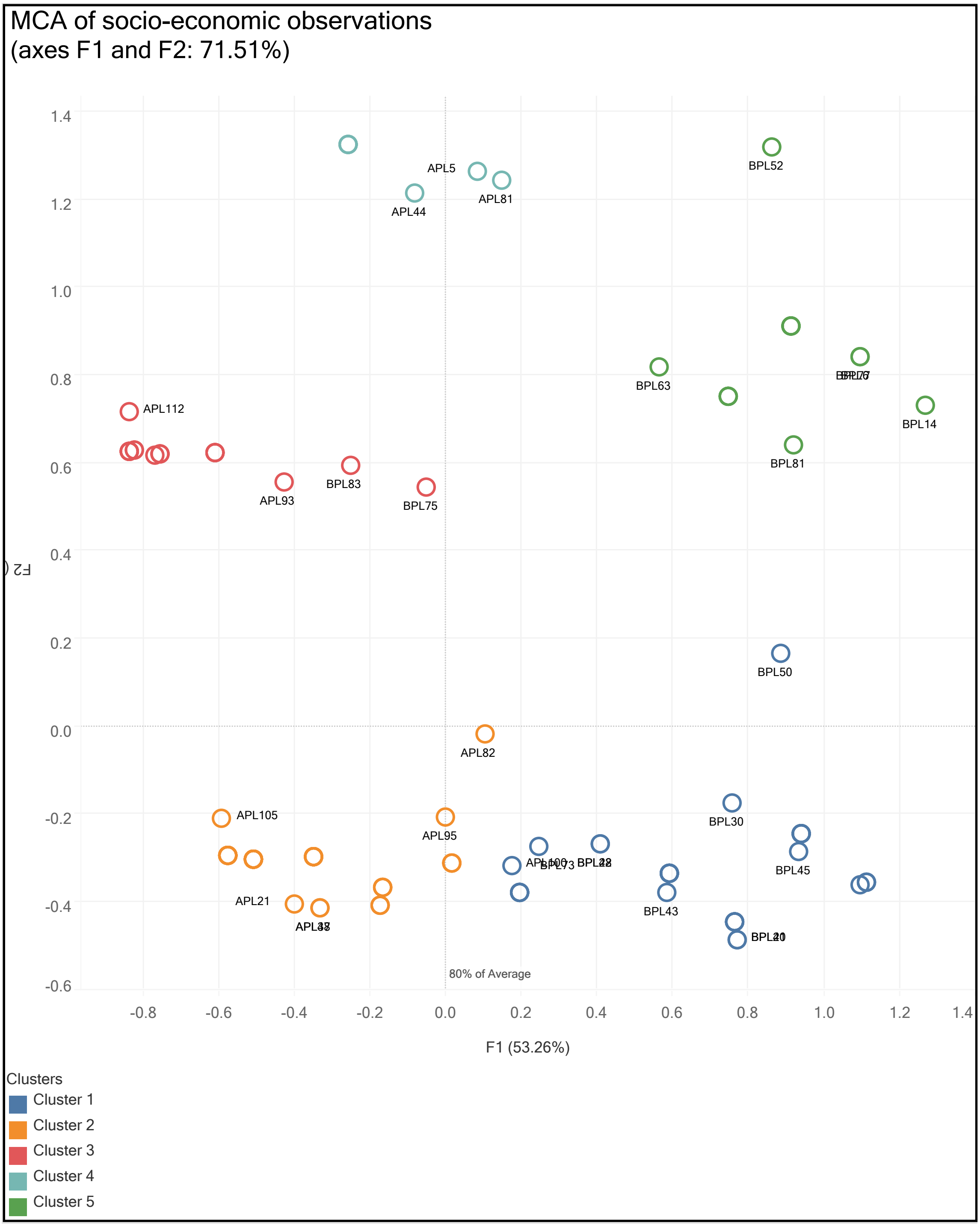


Figure 7.7: Correspondence plot based on the economic status of the respondents.

In summary, MCA results shown in Figure 7.6 suggest that farming and farm labouring are the dominant occupational patterns in the study area, and there appears to be a strong correspondence between main occupation and family status. For example, farmer families are likely to be APL, and labourers and farmworkers are likely to be BPL families. Figure 7.7 appears to support the idea of an economy based dichotomy existing in the community.

Farm and agriculture related occupations were found to be most common in the survey. Farming (60%) is the primary occupation in the villages, followed by farm related labouring (34%), which collectively account for 94% of the total professions in the study area. A small percentage of people were in skilled employment (4%), such as medical doctors, teachers, engineers, and bank employees, while 2% of the population was self-employed, consisting of vehicle drivers, small shopkeepers, electricians, cooks, and businesspeople. Figure 7.8 presents the distribution of primary occupations rounded up into percentage values. Most families did not have a secondary occupation, but 28.5% of families did, and they all fit within a general category of farming and agriculture as a secondary profession. The secondary occupation of 32 families was farming, with 18 of these families in skilled employment: 12 families in self-employment and two families labouring. Thus, labouring was the least popular secondary occupation. The evidence above shows that the study area is still predominantly an agricultural region with an agriculture based economy.

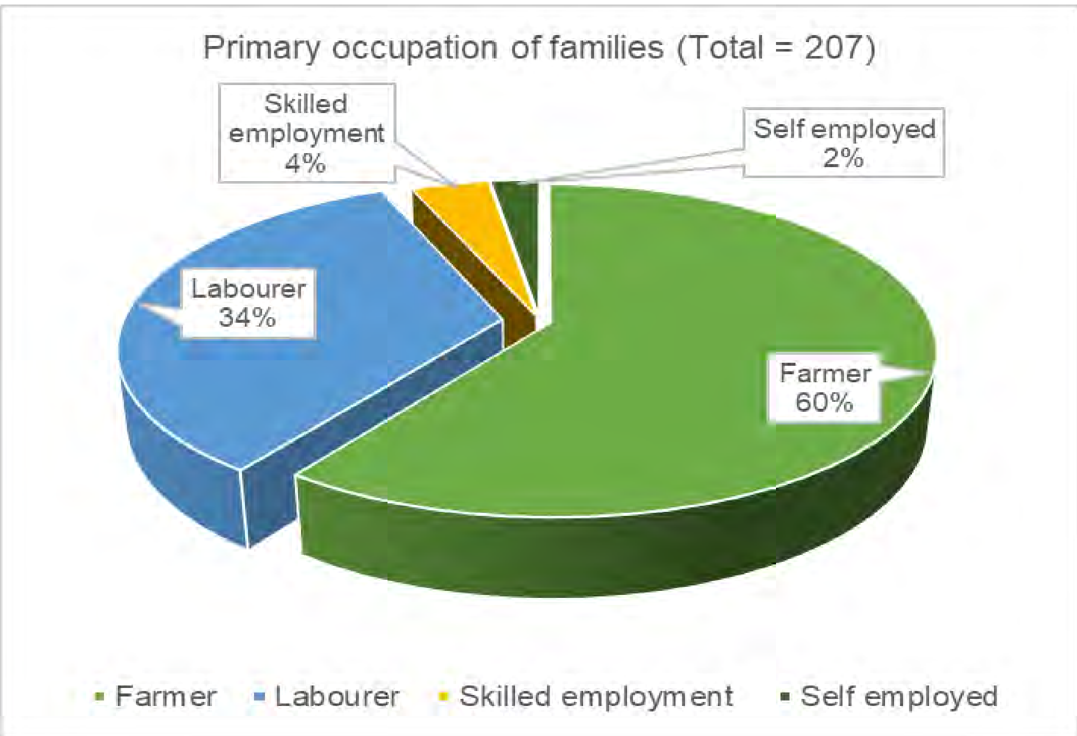


Figure 7.8: Primary occupation of the respondents in the study area.

There is a direct association between the families' primary occupation and financial conditions in the study area; for example, all 70 labourers interviewed were BPL. Most of the farming families (n=112) were APL, and only 12 farmer families were below the poverty line. However, there does not appear to be a direct association between a family's financial status and their secondary source of income because, in both APL and BPL families, only a small number of families had (approximately less than one-third) a secondary occupation. Thus, it is evident that the primary occupation repeatedly determines the economic condition in the study area, and the farmers are in better financial condition than the farm labourers. Agricultural and agricultural related labouring being the largest occupation categories, it was necessary to explore agricultural land availability. Thus, the following text presents the results related to landholdings.

Farmers in India are classified into several categories according to the total size of their landholdings, as shown in Table 7.2 (Department of Agriculture, 2015). The landless category is often merged into the marginal category, but in this survey, landless has been recorded as a separate category to understand the land distribution by increasing the resolution of the data. Table 7.2 also presents the results of the landholdings in the study area and the percentage of socioeconomic survey respondents. The marginal (31%), small (29%), and the small medium farmers (23%), collectively hold 83% of the total landholding, with landholdings ranging between 0.1 - 4.0 hectares. A small number of families were landless (2%) and large farmers (2%), while 13% of the population had landholdings between 4.0 – 10.0 hectares.

Table 7.2: Landholdings and the percentage of respondents.

Category	Total landholdings (ha)	% of families in the survey
Landless (LL)	Less than 0.1	2
Marginal (MA)	0.1 - 1.0	31
Small (SL)	1.1 – 2.0	29
Small Medium (SM)	2.1 - 4.0	23
Medium (MM)	4.1 - 10.0	13
Large (LA)	10.1 or more	2

There appears to be inequality between APL and BPL families based on the relative proportions of total land holdings, cultivated and uncultivated land (Figure 7.9). On average, APL families owned more land than BPL families. For example, APL families formed 60% of the survey population and owned 85% of the total land, while the BPL families, who constituted 40% of the survey population, held only 15% of the land. Moreover, an APL family owned 2.99 hectares of land on average, while a BPL family had 0.78 hectares of land (Table 7.3).

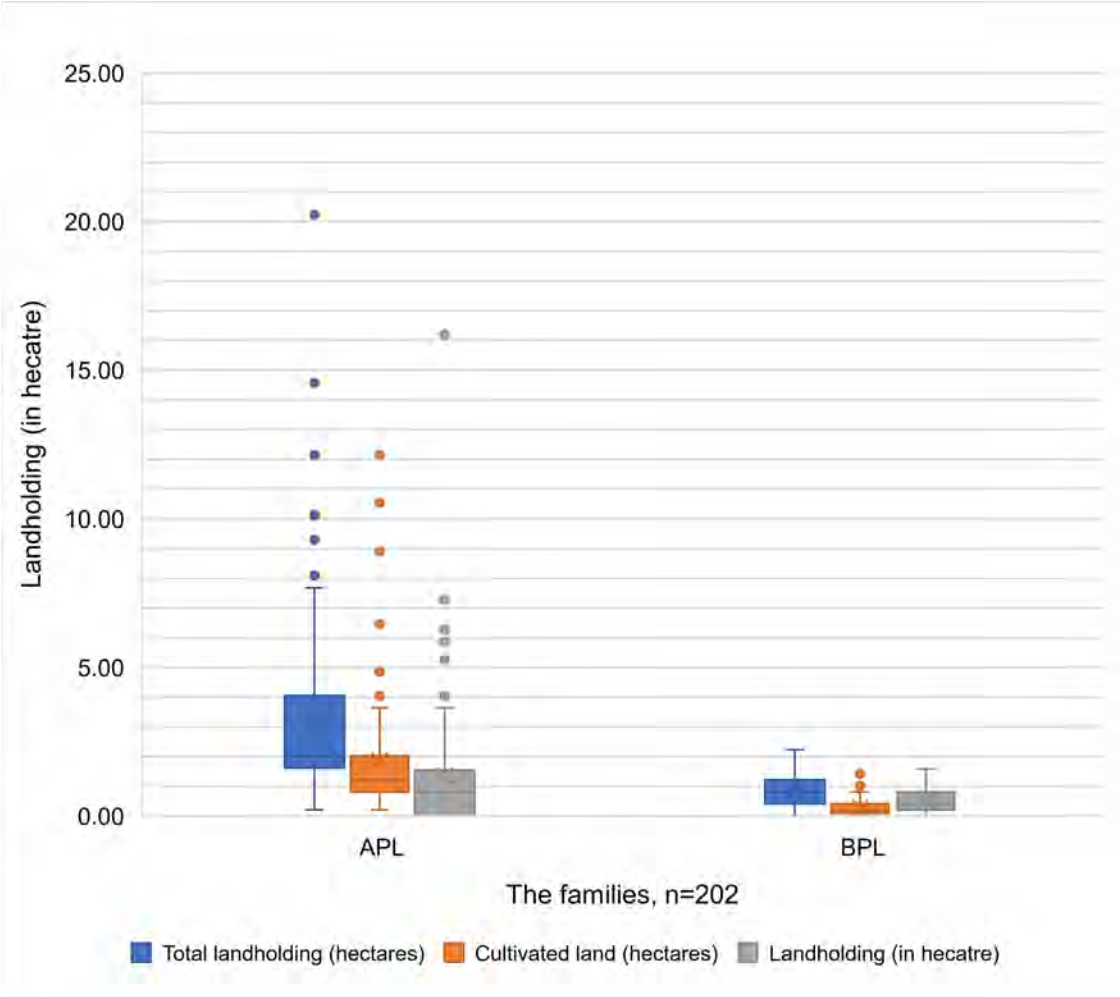


Figure 7.9: Land distribution between APL and BPL families in the study area.

Out of 451.37 hectares of the total landholding in the sample, only 55% of the land was cultivated, and the remaining 45% of the land was uncultivated dry forest area. Thus, BPL families not only owned less land compared to APL families (Figure 7.9), but the BPL families cultivated only 35% of their landholdings compared to 58% cultivated land of the APL families, who owned 85% of the total land (Table 7.3). Therefore, there seems to be a positive association between the size of landholdings and the financial conditions of the families in the study area.

Table 7.3: Summary of the economic status of families, landholding, and cultivated area.

Families (N=215)	Population percentage	Total landholdings (in ha)	Percentage of the total land	Land per family (in ha)	Cultivated land percentage
APL (n= 128)	60%	383.27	85%	2.99	58%
BPL (n= 87)	40%	68.10	15%	0.78	35%

This section summarises the MCA results of agriculture variables in Figure 7.10 with two main clusters, 1 and 2 (see Appendix L for detailed MCA results). Cluster 1 is of the respondents with small (27%), small medium (21.9%), and medium (12%) landholdings. The farmers in the cluster 1 group have approximately 61% of the total landholdings in the survey. These farmers are highly likely to be APL and primarily rely on various cash crop plantations, mainly areca nut, coconut, cocoa, banana, cashew, rubber, and black pepper. In addition, these farmers reported the use of a mix of organic and chemical fertilisers.

Figure 7.10: Correspondence plot of agriculture characteristics in the study area.

Farmers with large landholdings (2.3%) with land over 10 hectares are also likely to follow the above characteristics, but they are not common. Cluster 2 comprises families who are landless (1.4%) or have marginal landholdings (29.3%), which means farmers in this group have less than one hectare of total land. These farmers normally do not grow any crops, and they were highly likely to be farmworkers and were BPL.

7.3.1 Multiple water harvesting strategies

The valleys are the most fertile with sufficient water availability, followed by terraced farms on hill slopes. *Suranga* are mainly found in undulating terrain, while dug wells are the primary water source in flat areas. The dispersed pattern of dwelling shows the agricultural nature of villages (Shannikodi, 2013), and it also suggests that fertile fields were not abundant in the past, so people made their dwellings near to water sources where agriculture could be started. Hill slopes and valleys were the water rich areas in these villages. Thus, homes and fields are usually found on hill slopes and in the valleys of small hills in the area. Houses are often constructed on the land produced by terracing hill slopes; therefore, often *suranga* are built at the back of the house to harvest water for drinking and household usages, as seen in Figures 7.11 and 7.12.

Figure 7.11: An elevated *suranga* excavated into a hill slope in the backyard of a house.

Figure 7.12: Another elevated *suranga* excavated in the backyard of a house.

Terraced farming is practised on hill slopes and valleys, with terraced fields of different shapes and sizes often protected by a stone wall, soil, and grass (Wei *et al.*, 2016; Suseelan, 2008). There is no centralised water supply system for the communities because the undulating terrain does not allow centralised water supply systems because of technical limitations, such as insufficient water pressure maintenance and regular power cuts. The government electric supply was first introduced to Manila village in the late 1990s (R1, R3). According to the respondents, the local government attempted to provide drinking water to at least low income families from government managed borewells, but this approach was unsuccessful because of frequent technical and bureaucratic issues (R5, R20, R21, R46). Currently, new plans are being drafted by the local government to ensure reliable drinking water supplies (R5, R46). Such plans usually consist of a shared borewell constructed at a suitable communal place in the community with water pumped to a small concrete overhead tank situated at the top of a hill, from where the water supply is rationed to the low income families. To date, this regulatory strategy has had a limited impact; thus, farmers rely on traditional water harvesting methods discussed below.

Several traditional water harvesting structures are found in the study area, and these are mainly small scale, family managed, seasonal water harvesting structures, such as *suranga*, pond (*kere*), well (*bavi*), dug well, seasonal check dam (*katta*), and semi natural ponds (*madka*). All respondents in the survey were *suranga* users. Dug well were found to be the second most popular water harvesting structure among the 215 farmers interviewed. Dug well, also known as open well, are shallow depth wells without linings on the walls and are generally rectangular but can be of any shape and size (Figure 7.13). The yield of a dug well depends on the hydrology and subsurface water availability of the area. Other traditional water harvesting systems such as dug well, well, and springs constitute 83% of water resources (Figure 7.14).

Figure 7.13: A typical dug well in the study area.

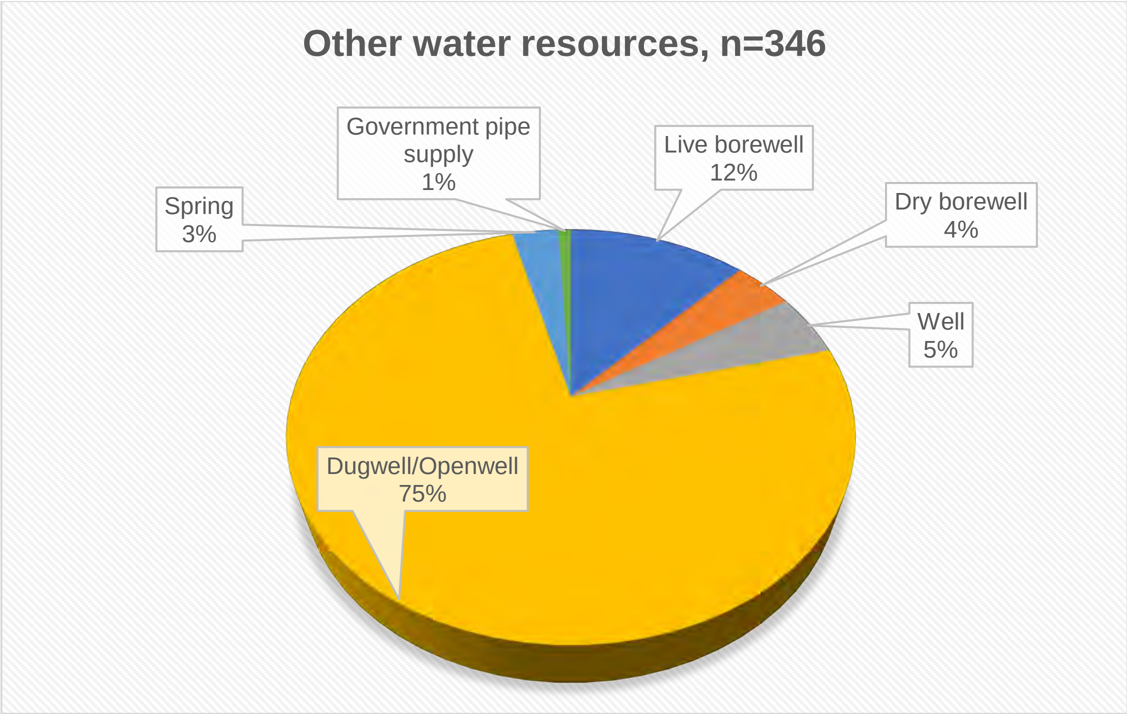


Figure 7.14: Water resources used in the case study area, in addition to *suranga*.

Most of the rivers in the region are seasonal, and when rivers dry up, families living next to the riverbanks often construct a makeshift, temporary well on the riverbed, as shown in Figure 7.15. For example, this well supplies water for irrigation for families living on the banks of the river *Shriya* in Manila village during the dry season. It is a temporary water source during the driest season, but otherwise, farmers pump water from the river if they have no other water source available.

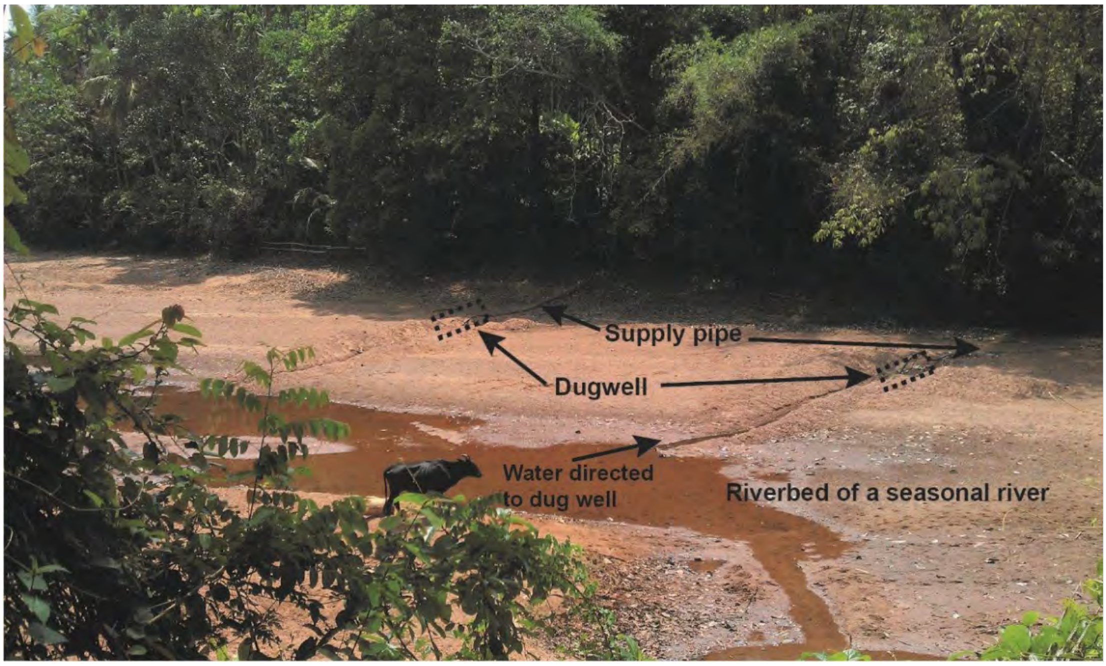


Figure 7.15: Makeshift dug wells on a seasonal riverbed.

Seasonal check dams (*katta*) made of soil and sand are also constructed on streams and the river in dry summers to store water for irrigation and household purposes. These seasonal check dams are made privately or by a group of farmers, depending on the size of construction and the number of stakeholders involved (Figures 7.16 and 7.17). These check dams are usually washed away in the monsoonal rain every year; however, small streams vented check dams (*kindi-aane-kattu*) are made of concrete and wooden planks, which can be removed during the rainy season.

Figure 7.16: A temporary check dam made of soil and rocks on a seasonal stream.

Figure 7.17: A temporary check dam on a seasonal river made by sandbags.

This study was focused on *suranga* users; therefore, all the respondents (n =169) in this socioeconomic survey were *suranga* users, and none of the respondents received a government water supply. Therefore, *suranga* do not appear as a water resource in the MCA results. However, *suranga* as a water resource for drinking and household appeared in the broader analysis because all respondents did not use *suranga* for drinking and household water supplies, but a small number of families used *suranga only* for domestics and agriculture usages. Moreover, the family's economic status did not seem to show high correspondence in space with any water resources, which means resources are not directly correlated to a family's financial position. Figure 7.18 summarises the MCA for water resources in the survey (see Appendix M for details).

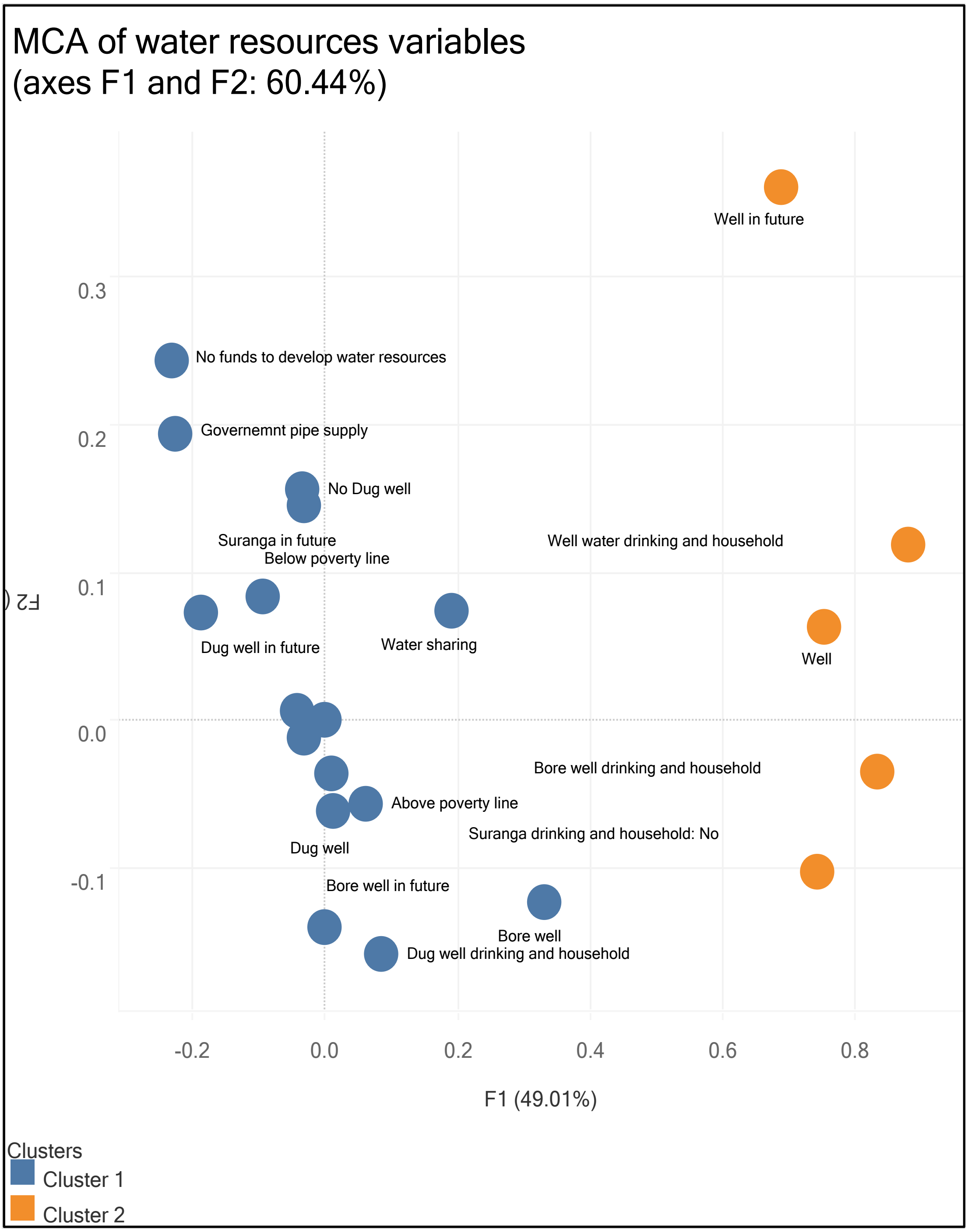


Figure 7.18: Correspondence plot of water resources in the study area

There are two clusters in Figure 7.18. Cluster 1 is the largest group and includes APL and BPL families, and these families use *suranga*, wells, and borewells. People in this group are likely to share water among families. These families do not have any government water supply. In Cluster 2, there are a small number of families who rely on well and borewell for their drinking and household usage because *suranga* are not successful in their area. Cluster 1 is so vast and widely spread that it covers most of the farmers in the survey, which indicates that both APL and BPL families often use multiple water harvesting strategies to get water for drinking and household use in the study area.

7.3.2 Pragmatic irrigation approaches

Irrigation water availability is the key to thriving economically in the study area as it is an agricultural region. Table 7.4 summarises the climate conditions and irrigation requirements of the village. The southwest monsoon rains usually start in the first week of June in the study area, which brings copious, torrential rain for the first three months and lasts until late September. From September to November, the amount of precipitation decreases gradually, and there is occasional rain in December and January, which is caused by the retreating northeast monsoon. No irrigation is usually required between June - November, but rainwater management and water from seasonal streams and springs are needed to minimise the damage caused by flooding to farms, water storage ponds, and wells. The first crop of paddy is planted in June, and it takes between 90-120 days to be harvested. A typical paddy field is shown in Figure 7.19. Paddy fields are irrigated with rainwater. Humidity is at a peak in the rainy seasons and starts to decrease from November, and at these times, farmers start irrigating their crops and plantations. The irrigation continues until the onset of monsoon in late May or early June or until water storage is exhausted. Though in the dry weather, the plantations of areca nut, coconut, and banana may survive without irrigation, the quality and quantity of the yield decrease significantly for oncoming years, which is not a favourable economic situation for farmers. Therefore, all measures are taken by the farmers to irrigate their farms. In the past, rice and sugarcane were the staple crop of this region, mainly irrigated with seasonal rainfall. Borewells are usually not required during the monsoon season because there is enough water available from rainfall. Thus, there are two contrasting seasons of nearly equal duration in a year. There is an excess of water in the first, and there is acute water scarcity in the second.

Table 7.4: Usual climate pattern of Manila village.

Months	Climate	Irrigation needed
June	Start of the rainy season, highly humid	No
July	Heavy rain, highly humid	No
August	Heavy rain, highly humid	No
September	Heavy-moderate rain, highly humid	No
October	Moderate rain, Moderate humidity	No
November	Low rain, Moderate humidity	No
December	Low rain, Moderate climate	Yes
January	Occasional rain, Moderate climate	Yes
February	Dry summer season	Yes
March	Dry summer season	Yes
April	Dry summer season	Yes
May	Dry summer season	Yes

Figure 7.19: A typical paddy field in a valley with coconut trees on the boundary.

As explained in the last section, much of the population was found to depend on traditional water harvesting methods for drinking and household requirements. A similar approach is used for water for irrigation, and the primary sources of water for irrigation in the study area are rills, springs, dug well, coalescing streams, seasonal rivers, round wells, *suranga*, and borewells.

Dug wells are the primary source of water for irrigation, and a combination of ponds, round wells and seasonal check dams are used on terraced farms to store the water flowing from springs, *suranga*, and streams. However, not all farmers have a reliable water source to last in the driest summers; in that case, borewells are used to abstract groundwater for irrigation and other needs. According to a respondent, borewell was introduced in the study area in the mid-1990s. Traditionally, irrigation was carried out manually and through open channels, but nowadays, farmers use a combination of variable effective distribution methods, such as hosepipe, open channels, drips, foggers and sprinklers according to water availability. Where water is plentiful, irrigation with a hosepipe and open earthen channels is usually undertaken in November, December, and early January because there is enough water available, and it must be utilised before it runs off to streams and rivers. However, largescale water storage capacity in the study area is usually low because of the hilly landscape and torrential nature of rainfall.

All the farmers may not have reliable water resources to last in the driest summers. In that case, borewells with electric submersible pumps are used to abstract groundwater for irrigation and other needs. Borewells mainly were used during the dry summer months. Nowadays, bank loans are available to farmers for agriculture development, and many farmers who do not have reliable water for irrigation or water scarcity for irrigation have taken loans for the construction of borewells. However, just sinking a borewell is not a guarantee of finding groundwater in this region, mainly because of the undulating topography and highly variable geology area (see section 6.1 and 6.4). Many dry borewells were found during the survey. Therefore, borewells are costly to construct, and there is always uncertainty concerning the successful finding of water.

Thus, the community in the study area uses irrigation methods that include traditional methods operating alongside the latest technology. However, the MCA of variables related to irrigation presented in a symmetrical plot (Figure 7.20) suggests a clustering within the group (see Appendix N for details). For example, the BPL families in Cluster 1, if they do any agriculture with their minimum land, usually rely on rainfall, and any other available water sources such as *suranga*, spring ponds, and earthen water channels.

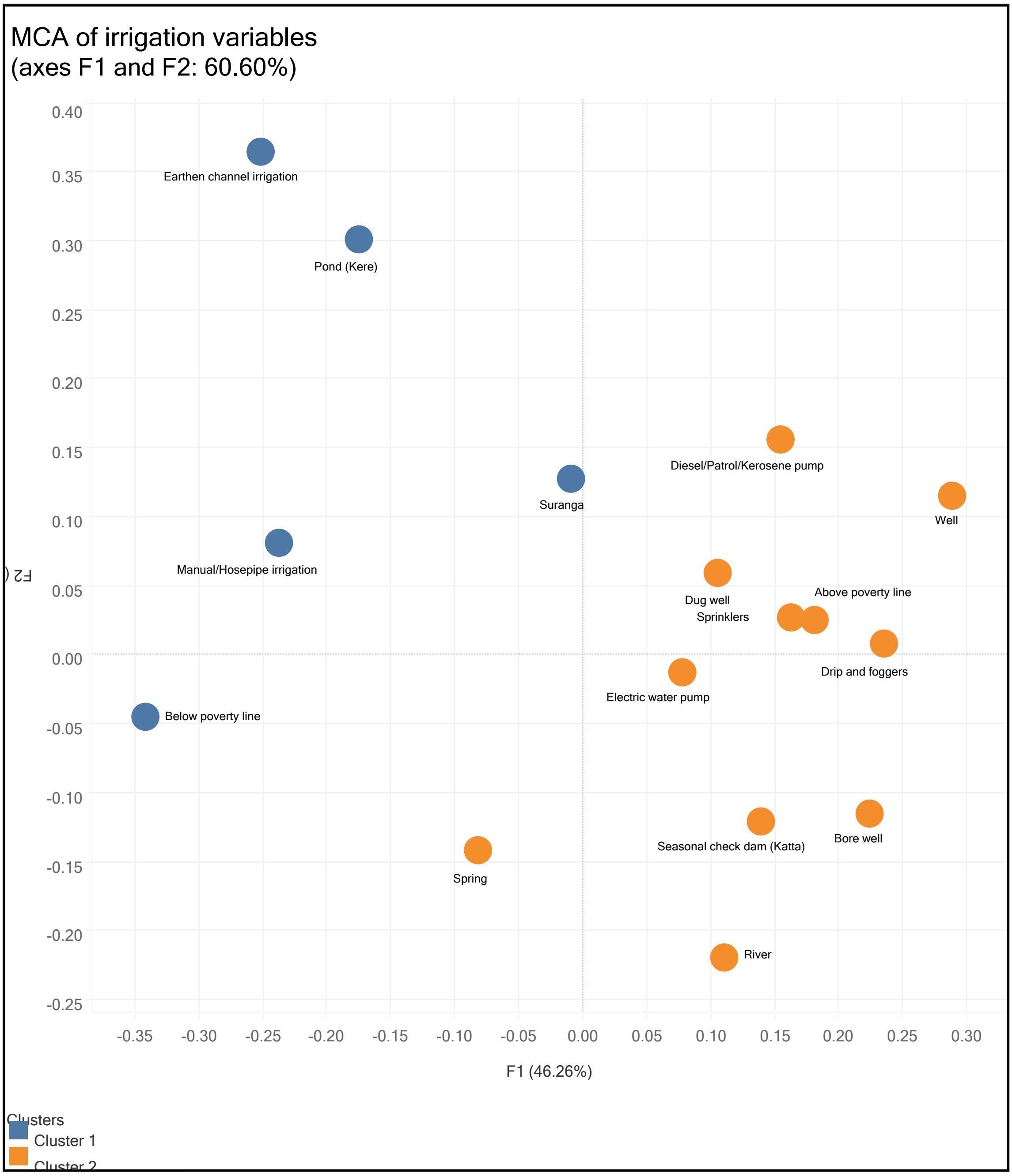


Figure 7.20: Correspondence plot of irrigation characteristics in the study area.

The second group of farmers, Cluster 2, who are usually APL, use a mix of irrigation methods in combination to achieve irrigation water security, for example, borewell, drips and foggers, and sprinklers. These farmers are very unlikely to practice manual irrigation; instead, they are likely to use electric pumps. However, wells, which includes dug well, are widely used for irrigation in this group. All the farmers in this survey had *suranga*. Therefore, this group also have *suranga* in their farmsteads, but they do not rely entirely on *suranga* for irrigation. Instead, they have developed diverse water resources.

7.3.3 Autonomy, conflict, causes, and resolution

Some families did not have any water source for clean drinking water for many years, and *suranga* solved their drinking water problems (R62; R144; R159; R173). In the past, *suranga* were the only available water resource for drinking water on this hilly terrain because no other water source was possible on hilltops or hill slopes, so *suranga* was the only successful water harvesting technique (R43; R55; R122; R154; R165; R173). When the local topography of undulating terrain did not allow for the construction of a dug well, the farmer made a *suranga,* and free flowing water was collected in ponds and dug well (R149).

> *"Twenty years ago, we used to have water shortages. From April until the start of the rainy seasons, people had to walk long distances to fetch water. Then we heard that there is somebody who makes suranga then we can have more water. So, my father went in search of Appaya and then he came to our property. Every summer season, he made a suranga for us. Out of the three suranga, we found water in two suranga" (R63).*

Some families still wholly rely on *suranga* water for all water requirements, especially those living on hilltops and hill slopes (R149; R153; R166), where a borewell is not a suitable alternative because groundwater is insufficient (R165) and because some hill areas are inaccessible for borewell sinking vehicles and machinery (Figures 7.21 and 7.22). In one example, a family made a *suranga* specifically for drinking water requirements in another property, around one kilometre from their home, and water is transported to the home through plastic pipes under gravity (R125). On 19% of farm units, *suranga* was the only drinking and daily household water resource available (thirty BPL and eleven APL). These families depended on *suranga* water because they cannot afford to dig a borewell, and dug wells were too difficult to construct on hilly terrain, making *suranga* the only viable water resource option on hilltop slopes (R149).

Figure 7.21: A borewell being constructed in Manila village in 2013 CE.

Figure 7.22: A typically completed borewell in the study area.

Most families (84%) do not share their water, but a few families (16%) had arrangements to share water with other families. Water sharing takes places only in two conditions. First, water for drinking and the household is done on a humanitarian basis. For example, a family with an abundant water supply often allows their water poor neighbour to take water for drinking and domestic purposes. Second, when a joint family is divided into smaller families, the water is also shared between the core families to consolidate their supplies (Kumar & Krishna, 2015). In these cases, depending on the water availability, water may also be shared for irrigation by smaller families. However, the process of water sharing for irrigation in the study area was found to be more complicated than water sharing for drinking and household uses, as usually, families do not share water for irrigation. Irrigation water was only shared after inheritance resulted in written agreements and obligations. Usually, all parties (riparian and usufruct) are legally bound to share a water source under mutual agreement and affinity rules. This represents inheritance, known as impartible partibility that consolidates landholdings (Marian, 2019). The land is fragmented on the joint family division, and associated water rights are also clearly divided (Kumar & Krishna, 2015). In several examples, families shared a common water source by rationing water on an hourly or daily basis in turns, and users also had a proportional maintenance obligation. These water rights are inherited and transferable and owned mainly by the land's new owners after the sale.

Several disputes among the agricultural users were caused by unfair water exploitation from a shared water source. The following example demonstrates the embodied experience of water sharing. A sizeable joint family divided into five smaller family units in the 1950s in the study area. A large dug well/tank situated at a higher point of the valley and situated in the property of the first family decided to share the water with the remaining four families living downstream from this shared well. The first family did not have any right over the water of the dug well situated on their property. Water pumps and electricity were not readily available, and the diesel pumps were costly and were not introduced. As the first family's lands were situated at a higher level from the shared well so technically, the first family could not exploit the water as efficiently as the rest of the four families whose properties were downstream from the shared well. So, the first family was compensated by allowing water rights from different water sources from the original joint family.

At present, the shared water tank, shown in Figure 7.23, is in disrepair because of reduced capacity caused by silt accumulated over the years of neglect from the four stakeholder families. This had resulted from a lack of cooperation among the four families. After some years, when electric pumps became popular in the region, the first family changed their mind and indirectly claimed water rights on the shared dug well situated in the first family's property, which the four user families refused. In retaliation, the first family prevented access to the dug well to the other four families on the grounds of trespassing. As a result, maintenance work could not be carried out on the shared dug well, and it silted up gradually. This issue was ongoing in a civil court at the time of this survey. However, when this dispute started, all the five families had either developed other water resources or were working on constructing some new water sources initially, such as *suranga* and ponds, and lately, a borewell was introduced. Thus, the private water resources of these five families are maintained and are in working condition.

Figure 7.23: A neglected shared water tank in need of maintenance.

It indicates that forced water sharing was not very successful in this case, and where there is a private water resource, families want and opt for water independence. On the other hand, though, there are some cases where shared water systems are in perfect working condition because the weight of cooperation is better than developing individual private water resources. This typically happens where there is a very high water rich source, and this cooperation for sharing is needed only for the dry seasons, so the seasonal monsoonal rain has also provided water freedom to the locals. Borewells are generally privately owned, except those constructed by the local government to provide drinking water supplies to the families; therefore, there was no official record of the number of active borewells in the region.

To avoid disputes, *suranga* are typically extended within the bounds of the private property (R60; R69; R90; R171; R172), and there have been a few cases when *suranga* were abandoned during construction because if it were further excavated, it could extend into a neighbour's property and generate tension between the different landowners (R72; R140). Very occasionally, *suranga* are found extending through farms with informal or oral authorisation from the neighbour (R149).

7.3.4 Status of *suranga* development

The popularity of *suranga* surged in the early and mid-20th century. Therefore, many *suranga* were constructed in the study area in the last century, and most families made at least one *suranga* on their property (R84), and the excavation of new *suranga* has not entirely stopped (R154). A family reported that they made their first *suranga* in 2000 CE (R136), and a new *suranga* excavation was going on in at least five families at the time of the survey in 2012-13 (R51; R74; R94), with another *suranga* excavated in May 2018. Many families in the survey suggested that they had sufficient water resources for their current requirements; therefore, they did not have any plans to develop new water resource. However, 26 families in the survey (Table 7.5) were planning to construct a minimum of one new *suranga* each soon (R168) either to increase the amount of drinking water in summer (R70; R137), to extend agriculture (R72; R131), or because they could not afford to construct a borewell (R124). The low income families who did not have enough funds to make new *suranga* were planning to excavate their *suranga* themselves (R136; R99). Plans to convert a seasonal *suranga* into a perennial *suranga* by extending or making branches were also reported (R152).

> *"To increase the water availability, I am making one more suranga for my family in part-time" (R74).*

Moreover, twelve families were planning to construct dug wells. However, only eight families suggested planning to construct borewell to meet their water requirements (Table 7.5).

Table 7.5: Future water plans of the survey respondents.

Future water plan	**Number of families**
Water sufficient, no future water plans	130
No information	38
Suranga	26
Dug well/Well	12
Borewell	8
Katta	1
Total families	**215**

Presently, the numbers of expert *suranga* workers have decreased because many *suranga* workers have either retired or stopped *suranga* work to start other less risky and challenging jobs to earn similar wages (R51). In the past, being a *suranga* worker was an attractive occupation among adventurous workers because *suranga* workers were paid higher wages than an ordinary worker (R51). However, new workers are not interested in learning *suranga* work because excavating a *suranga* is challenging and risky, and there seems to be less demand for *suranga* workers as farmers are now more interested in making borewell (R79; R116). If a farmer wants to make a *suranga*, finding an expert *suranga* worker is difficult because of a shortage of professional *suranga* workers (R51; R133). Therefore, it is a cycle where less and less *suranga* are being made because farmers think there are no *suranga* workers, and the new workers are not learning *suranga* work because they believe there is no demand for *suranga* in the area because of competition from borewells (R49; R73).

> *"Ambu chose to be a suranga worker because at that time, a normal labourer would get paid 0.50-0.75 Rs, while even a suranga assistant worker could get 2.00 Rs per day. He used to be the suranga assistant of his uncle at the age of 14 and enjoyed a higher wage in comparison to a normal labourer" (R51).*

> *"If farmers show interest in suranga and the demand goes up, then naturally worker will start learning the art of making suranga"* (R79).

Decreasing groundwater levels in *suranga*, round well, and dug well also motivates farmers to adopt borewell more freely (R53). A total of 130 families were not planning to develop a new water resource because they had a sufficient water supply (R43; R68). On a broader level, migration to cities continues at a rapid pace reducing reliance on agriculture (R78) and indirectly affecting the viability of the *suranga* system. *Suranga* are not a panacea for all water shortage. For example, in some areas, *suranga* are unsuccessful because of hard rock layers encountered when digging (R124) (Figure 7.24). Moreover, largescale farms may find it difficult to rely entirely on traditional water harvesting systems for irrigation (R112), so large farmers must adopt new technology such as borewell, especially as they can usually afford to construct a borewell (R45).

> *"We started using borewell five years ago because we did not have enough water for agriculture and suranga water used to reduce in summer" (R112).*

Figure 7.24: An abandoned small length *suranga* with hard rock dead-end.

Another reason for not maintaining *suranga* and other traditional systems is because there is an increasing reliance on borewell systems in the study area. For example, a family from the study area that has many members who have migrated to Gulf countries for work have robust finances and send back remittances to the remaining family who can rely on a borewell and neglect maintenance of their *suranga*, even though the *suranga* still produces enough water. This family (R144) is a classic example of new technology supported by new wealth, replacing traditional methods.

> *"Thirty years ago, when our family moved into this place then there was water scarcity, so we excavated a suranga and used to use it for our water requirements. There was no borewell in that time… Earlier neighbours used to take water from this suranga as well, but now we have borewell, so we do not maintain this suranga" (R144).*

Thus, the rate of new *suranga* construction is low, but despite borewells becoming popular, water yielding *suranga* are maintained and used for domestic and irrigation use.

7.4 Chapter summary

This chapter presented the socioeconomic results, which showed that there are both endogenous and exogenous pressure on maintaining the extant *suranga* system, despite the system's overall favourable design and operational principles. The next chapter discusses the implications of these results for the future success and viability of the *suranga* system in both the study area and beyond over the long term here defined as the next 30 years because of the rapid development of the study area. It starts by discussing the new origin theory of *suranga*, followed by evaluating the relevance of the hill irrigation model to study the *suranga* system. The following chapter brings together all the results from Chapters 4 to 7 to evaluate the sustainability of the *suranga* system and by identifying the vulnerability and resilience of the *suranga* system to both endogenous and exogenous forces.

Chapter 8 – Discussion

This chapter aims to address the research aim and objectives (see section 2.4) by discussing the results (chapters 4 to 7) and comparing these with the broader literature on Indian water harvesting whilst presenting an evidence based argument for the current vulnerability and resilience of the *suranga* system and offering a critical perspective on the potential sustainability of the *suranga* system. The chapter starts by critically analysing the origin and history of *suranga* and comparing it with similar systems from other parts of the world in section 8.1. Next, an appraisal of the hill irrigation analytical framework as a tool for studying *suranga* is presented in section 8.2 alongside the observed 'real world' divergence from this framework, including a critique of community management practices. This provides a platform to examine the vulnerabilities and resilience of the *suranga* system based on a nuanced application of resilience theory that incorporates the results from this study and a comparison to the broader literature (section 8.3). This then allows for a dynamic assessment of the sustainability of the *suranga* system by arguing for a temporally and spatially constructed sustainability model based on four sustainability components: structural and functional; environmental and ecological; social and cultural; and economic benefits (section 8.4). Finally, section 8.5 presents the methodological limitations of this study, and section 8.6 provides recommendations for future work on the *suranga* system.

8.1 A new origin theory of *suranga*

Previous studies on *suranga* often claim that the introduction of *suranga* came through Arab and Persian traders on India's western coast via the sea route during the 7th century (Nazimuddin, & Kokkal, 2002; Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Mujumdar & Jain, 2018). These authors tend to make an unsubstantiated association between the fundamental structural design of *suranga* and *qanat* to justify their claims. However, this widely shared notion of *suranga* origin seems to be based on conjecture because of the absence of evidence to support this theory. To some extent, this misconception can be explained by the fact that the *suranga* system, like other small scale springs and associated tunnels in hilly regions, are not often recorded in historical travel literature, official documents or indeed research (Ron, 1985 p. 151; Palerm-Viqueira, 2004), perhaps because of their smaller sizes and limited spatial distribution compared to other well documented large scale TWM systems, such as tanks in India (Agarwal & Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008) and *qanat* in the Middle East and beyond (Mahan *et al.*, 2015; Nasiri & Mafakheri, 2015; Ein Mor & Ron, 2016; Dahmen & Kassab 2017; Mokadem *et al.*, 2018; Khorramrouei & Nasiri, 2019; Yechezkel *et al.*, 2021).

Therefore, the dearth of information on the *suranga* in national and regional archives, historical travel documents and research literature led to the epistemological approach of arguing for a new theory of *suranga* origin based on silence and by understanding the socioeconomic and environmental factors behind the historical development of the *suranga* system through an investigation of local culture and history. Thus, what follows is a historical argument based on the presumption of silence as mentioned in subsection 4.2.2 (also see Elvin & Crook, 2003; Crook & Elvin, 2013). The genesis of this idea as applied to *suranga* was first published by Crook *et al.* (2015), a methodological technique that was refined for this project by also concomitantly searching for any references to *qanat* and other traditional water harvesting structures like wells and tanks in the region where the *suranga* system is now found to check the nomenclature used and toponyms in the historical records. The argument followed that if a reference was made to other similar sized water harvesting structures in the region but did not mention *suranga,* this indicated that the system did not exist. The first official record of *suranga,* of course, does not infer the start date for the use of the technology, as the official recording of this is a product of scale, as the value and importance of a new system or technology become worthy of recording, usually because of the desire to tax or extract tithes from farmers using an agricultural innovation like *suranga*. To advance this argument, it becomes essential first to outline the societal preconditions for accepting a new agricultural innovation like *suranga* in farming communities.

As mentioned earlier, the study area in the early 19th century was a remote, isolated, and hilly region with dense forests, a sparse population, and dispersed settlements

(Shannikodi, 2013) ruled by local feudal rulers (see Chapter 4). A small number of dispersed communities inhabited the forests and used to trade timber, fruits, medicinal herbs, and other produce to the nearest villages and towns for grains and goods (Miley, 1875, pp. 46-47; Fisher, 2018, p. 99), there was no largescale permanent land use for agriculture in these densely forested hills. The forest-dwelling communities used a slash and burn method to clear undergrowth to create land for cultivation within the forests, and ash was used as fertiliser (Hunter, 1887, p. 348; Madras District Gazetteers, 1938, p. 159; Fisher, 2018, p. 27; Viswanath *et al.*, 2018). What permanent settlement there was, were small, dispersed farm units situated near fertile, water rich valleys, where families could more easily cultivate food for subsistence (Shannikodi, 2013). Thus, with only a subsistence level of farm production, local feudal rulers had a minimum economic incentive to extract agricultural tithes (Bhat, 1998; Bhat, 2001). Rice and other commodities were grown seasonally in the flatlands of valleys where water availability was reliable. Paddy crops were always given priority over plantations in deciding and dividing water shares (Department of Agriculture, Madras, 1925; Madras District Gazetteers, 1938, pp. 206-210; Kumar & Krishna, 2015). Once all available fertile land was cultivated, people needed some solution to meet the increased demands for food by enhancing agricultural production and improving irrigation water supply. It is difficult to say when this happened precisely, but probably in the early 20th century, farmers in the study area made the jump to practising agriculture throughout the year, which led to improved yields. This jump required irrigation in the summer season, which was clearly a technical challenge that demanded innovation. During the dry seasons, the necessity for water must have challenged the communities to develop ideas to capture the abundant seasonal supply of water and extend it to the dry seasons by diverting and storing rain and surface water. This water was most likely captured using storage methods such as ponds or by harvesting subsurface water from shallow depth aquifers in flat and hilly regions. This was only possible using small scale indigenous methods of water harvesting or storage like wells, *keni*, and *suranga*, which were suited to the local limitations presented by geography, topography, and geology (Sutcliffe *et al.*, 2011). Diversion of rainwater and water from surface water bodies, by methods of channels and embankment, not only stored water for drier seasons but helped in avoiding floods caused by monsoonal rains (*ibid.*). Thus, perennial water supplies were developed gradually, incorporating improvisation and improvement over several generations, but the question remained how did these ideas spread? As the population grew incrementally over generations, the most favourable valley areas for sedentary agriculture were taken up, and new extended families were forced to settle permanently onto nearby hillslopes. Families started prospecting on government land or forest department land, which was earlier barren or dry forest land, and with their efforts, the land was cultivated over the years using streams, rivulets, and springs that were available to them as water sources. To increase the agricultural surface area on these relatively steep slopes, farmers quickly adopted stone walled terraces and rice terraces (Wei *et al.*, 2016; Deng *et al.*, 2021) in the study area. The structural qualities of the local laterites made this a relatively easy technical adaption. Following on from this populating of the landscape, agriculture expansion was essential to meet growing food requirements. Thus, the subsistence based farming system was gradually transformed in the process of intensification and innovation that mirrors the experiences of other mountain areas (Vincent, 1995, pp. 74-75). From around the mid-19th century, some farmers gradually switched from growing subsistence crops on their lands to growing new cash crops, such as cashew, areca nut, pepper, and rubber that was linked to growing regional export markets (Kumar & Krishna, 2015), which provided families with money that could be used to buy other commodities. In the early 20th century, the British Indian Government facilitated further agricultural expansion onto hillslopes through agricultural initiatives such as the ‘grow more’ campaign in response to population pressure (Department of Agriculture, Madras, 1925; Madras District Gazetteers, 1938). Thus, government lands were gradually allocated to farmers on request to develop farms and improve their living conditions. As the population gradually increased, the number of independent families increased because of the traditional patterns of partible inheritance and family division (Madras District Gazetteers, 1938; Marian, 2019). During the division of a large joint family into smaller families, the house, land for agriculture, and water resources were often divided among the new families (Kumar & Krishna, 2015). As a side note, this transition towards sedentary agriculture on the slopes appears to have been slow enough not to create a dispute with slash and burn farmers who slowly stopped this transhumant practice.

Water security and irrigation played an essential part in this agricultural transformation, and both systems also went through innovations within the same timeframe outlined above, intending to increase water availability (Vincent, 1995). As seen in Chapter 4, farmers found ways to capture and store seasonal streams and springs effectively for their agriculture to ensure annual water supplies (Hunter, 1887, p. 363; Kokkal & Aswathy, 2009). Based on existing indigenous knowledge of water harvesting, the preferred choice would have been to make large ponds (tanks) (Mate, 1969; Agarwal & Narain, 1997; Pande, 1997; Gokhale, 2006; Singh, Dey *et al.*, 2020), but this idea was still neither practical nor safe in the hilly terrain with torrential monsoonal rain. However, springs on hilly landscapes have been used for irrigating terraced fields since ancient times in several places around the world (Ron, 1985; Kokkal & Aswathy, 2009). Thus, the idea for the invention of *suranga* may have germinated from efforts to solve localised water scarcity caused by the geography and hydrology in terrain where no other water resource could be developed (Crook *et al.*, 2015; Crook *et al.*, 2016).

The knowledge of the *suranga* systems would have been progressively shared, and ideas evolved as happened in other similar spring fed water tunnels found in Israel and Mexico (Ron, 1985; Palerm-Viqueira, 2004; Yechezkel *et al.*, 2021). It is highly probable that in increasing water availability for household requirements and irrigation, some farmers would have used the instinct to follow a receding, seasonal spring by digging to widen the spring's face to minimise any water loss and increase the discharge. This process would have successfully increased discharge from the spring by making a small tunnel to encourage gallery filtration. The idea of *suranga* may also have received motivations from the natural springs and water bearing natural caves, such as on the *Possadigumpe* hill in Bayar village in Kasaragod district (Kokkal & Aswathy, 2009). Inspired by the initial success of hillslope *suranga* in the early 20th century, well owners may have been attracted towards *suranga*, which would have given birth to the later idea of constructing a *suranga* in a well as hybrid technology in the study area. Gradually this idea further developed into slightly more extended and broader tunnels known as *suranga* that were similar in scale to spring tunnels (locally known as *niqba*) found in the central mountains and Jerusalem Hills of Israel during the Middle Bronze Age [2200–1550 BCE] and Iron Age II [1000–586 BCE] (Ein Mor & Ron, 2016; Yechezkel & Frumkin, 2016; Yechezkel *et al.*, 2021). Likewise, Dahmen and Kassab (2017, pp. 1269-1273) refer to the work of Cornet (1952), who mentions a system, which is a network of short tunnels, called *chegga* in the Gurara region of Algerian Sahara. A *chegga* is usually excavated by following a dry source (possibly a dried-up spring), which again shows similarity to the *suranga* system. Similar types and scales of horizontal water harvesting tunnels from springs formed through weathered rocks and surface exposure of water bearing strata have also been mentioned by Vincent (1995, p. 48). A small number of spring tunnels are still in use in Mexico and are often linked to early colonial or even pre-Hispanic origin, though they are most likely introduced in the early 20th century (Palerm-Viqueira, 2004). Ron (1985) and Yechezkel & Frumkin (2016) have proposed a similar origin to *niqba* based on a limited number of literature references; see the below quotations from Ron (1985, p. 157).

> *In the Jerusalem Talmud, reference is made to the Shiloah spring: 'The Shiloah discharged water poorly, and it was said: 'Let us widen it so as to increase its water.'* (Succah, 85).
>
> *If one rent from his friend an irrigated field... If the spring dries up he must provide another spring. What is the meaning of 'Another spring?' says Rabbi Isaac: If the dry spring was two cubits deep, and he can deepen it by three cubits so it could be used again-the owner of the field is obliged to deepen the spring so that the one renting the field could use it for irrigation* (Baba Metsiah, 103).

There is a significant time gap between the development of *niqba* and the *suranga,* but they share organic origins in their design. As it has been observed in other small scale water harvesting techniques evolved in arid and semi-arid regions (Lasage & Verburg, 2015); the argument is based on the common themes of critical water shortage and the natural human instinct to dig a receding water source into increasing water availability to sustain life. Furthermore, the distribution of *suranga* is contained within a relatively small geographical region similar in scale to *niqba* in the central Highlands of Israel (Ein Mor & Ron, 2016; Yechezkel & Frumkin, 2016). This demonstrates that small scale technological adaptions like *suranga* and *niqba* are limited in their spread by unique geohydrological and local conditions (one laterite the other karstic), which are very different and restrict their application to other contiguous areas (Crook *et al.*, 2020; Yechezkel *et al.*, 2021). In the case of *suranga*, a small number of technology transfers to other parts of South India, in Shimoga and North Goa, are found, with similar geohydrological conditions. In these instances, word of mouth was the clear conduit for the technology transfer, which happened at different times. This demonstrates that the transfer of technology does not follow continuous and contiguous patterns; instead, they are random and dispersed, which provides lessons for historians studying the spread of ideas and technology (Ron, 1985; Palerm-Viqueira, 2004; Ein Mor & Ron, 2016; Yechezkel & Frumkin, 2016) to be cautious about how technology transfer occurs. Moreover, in comparison to the similarities between *suranga* and *qanat,* there are numerous differences in design principles and nomenclature, as already been discussed by Crook *et al.* (2020) and summarised in Table 8.1 below.

Table 8.1: Key differences between *qanat* and *suranga* systems

(adapted from Crook *et al.*, 2020).

	Qanat	***Suranga***
Age	~3000 years old	~100 years old
History	Documented in ancient text and documents from 4^{th} century BCE	No documented history available
Technical language	Detailed terminology available for various parts of the gallery, excavation process, and water management system	No specific terminology
Topography	Found in mountains, hillslopes, and flat regions	Mainly found in hillslopes
Origin	Iran (Fertile Crescent)	Foothills of the Western Ghats in India
Catchment areas	Large catchment area, linking a wetter mountainous area to lower drylands	Micro-catchment, such as a hillslope or in a well
Spatial distribution	Minimum 32 countries, from the Maghreb, Central Asia to China	Southern Karnataka and northern Kerala. Shimoga, Ponda (Goa),
Tools	Some specialised named tools	Basic construction tools are used
Planning level	A high level of planning	Little prior planning
Geomorphology	Mostly excavated in alluvial fans	Highly weathered soil profiles, such as laterites
Groundwater sources	Deep aquifer in alluvial fans	The shallow, perched aquifer in weathered rock profile known as laterite
Water collection	Water harvested from the mother well through the gallery	Water is harvested from hewn springs inside the gallery
Numbers	30000+	Approx. 3000
Lengths	100m to 100+ km long	2-200 metres long
Design	Gallery system with many interconnected vertical wells (shafts)	A short gallery filtration system
Excavation process	A team of several experts and many workers	Involves 1-2 workers.
Construction time	Several years	Less than a year
Cost burden	Community funded	Family funded
Stakeholders	Community	Private
Ownership	Village, shared	Single family, unique
Unit	Long single tunnel	Typically, multiple depending on the land owned
Conveyance area	Large geographical regions	Private land and farmsteads

These differences distinguish the previous theory of *suranga* origin from that of the *qanat* systems (Nazimuddin, & Kokkal, 2002; Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Mujumdar & Jain, 2018) and add weight to the view that *suranga* technology was developed independently and organically free from explicit outside sources or design influence and driven by acute necessity (Crook *et al.*, 2015; Crook *et al.*, 2020) in the same way that it is suggested for *niqba* water systems in Israel (Ron, 1985; Yechezkel & Frumkin, 2016; Yechezkel *et al.*, 2021). Furthermore, the oral history results also indicate that the *suranga* system is a relatively recent vernacular intervention, and the earliest *suranga* in the study area was constructed sometime in the 1920s. This explains why it is impossible to find any documentary or archival evidence to the *suranga* system because *suranga* have been developed in the study area sometime in the early 20th century (Crook *et al.*, 2015). With the origin date tentatively established, it becomes essential to discuss precisely where *suranga* fit within the hill irrigation model presented in Chapter 2 in response to the five research questions.

8.2 Appraisal of the analytical framework

The analytical framework for this study (Chapter 2) was based on a hill irrigation model adapted from Vincent (1995). This model provided the basis for an overarching research strategy that guided data collection using a logical and systematic approach. The analytical framework also provided a theoretical foundation and epistemologically, leading to the development of new emergent concepts that are important for enhancing understanding of the *suranga* system. This section reflects on and reviews the success of the application of the model in defining what was observed in the field, paying attention to any divergences in the model rather than reiterating the congruence of the *suranga* system with the model. Much of the model was applicable and helped frame the data collection, the discussion centres on the significant divergences from it that were linked to the community management of resources (Figure 8.1).

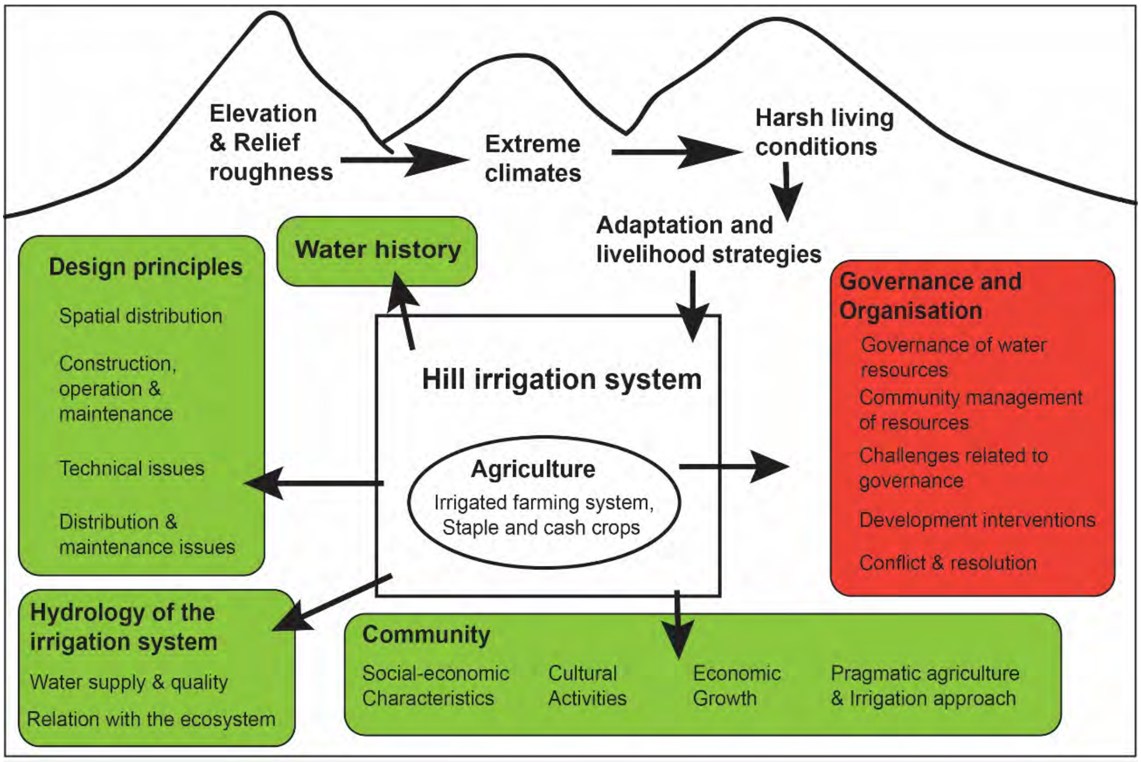


Figure 8.1: An improved hill irrigation model based on the *suranga* system.

The *suranga* system showed high correspondence to the hill irrigation framework in four broad components: Water history, Design principles, Hydrology, and Community aspects; however, the Governance and Organisation component does not apply to the *suranga* system because *suranga* are exclusively owned and managed at the family level. Therefore, the following section goes into detail to explain this divergence and provide context for the oncoming sections on the resilience and sustainability of the *suranga* system.

Community management of natural resources to achieve development or conservation of natural resources has often shown significantly positive results in managing natural resources in the mid and late 20th century around the world, and especially in developing countries (Ostrom, 1990; Parthasarathy, 2000; Agrawal & Ostrom, 2001; Meinzen-Dick *et al.*, 2002; Dietz *et al.*, 2003; Gerber *et al.*, 2008; Basurto & Ostrom, 2009; Mishra *et al.*, 2011; Nagrah *et al.*, 2016; Chaudhry, 2018). For example, the community management of water resources has allowed for the sharing of water resources locally and more effectively than a state owned system. Therefore, throughout the extensive literature on traditional water harvesting structures in India (e.g., Agarwal & Narain, 1997; Rautela, 2000; Chakravarthy *et al.*, 2006; Iyengar, 2007; Bhattacharya, 2015; Shanmugasundaram *et al.*, 2017; Singh *et al.*, 2021) and beyond (English, 1968; Crook & Jones, 1999; Bainbridge, 2001; Ghanbarpour *et al.*, 2007; Adeel *et al.*, 2008; Strauch & Almedom, 2011; Behailu *et al.*, 2016; Buhk *et al.*, 2019; Mahan *et al.*, 2019; Megdiche-Kharrat *et al.*, 2020; Ghorbani *et al.*, 2021) it has been shown that community management of these systems predominates, at least initially when fully operational and economies of scale exist.

In the rural and remote areas where government water supply is not available in India, TWM systems are still looked after privately because they are the only water source for drinking, household, and irrigation (Agarwal & Narain, 1997; Mosse, 1999). The National Water Policy of the Government of India of 1987 and 2002 also supports the idea of self-management of irrigation resources by the farmers, and it has shown promising results in overall agriculture development (Parthasarathy, 2000, p. 3147; Mishra *et al.*, 2011, pp. 43-44). Therefore, decentralisation of powers and the delegation of water rights to people can help restore water resources, and this idea is supported by the results from the study area, where the communities rely on TWM systems. Therefore, this study suggests that community management is not the panacea for managing all natural resources at all scales because others have also debated the efficacy and efficiency of community management at more minor scales (Dietz *et al.*, 2003; Chaudhry, 2018; Hutchings, 2018; Huston *et al.*, 2021).

The majority of the adaptation strategies of mountain agriculture (see Table 2.3) were found to be embedded in the *suranga* system, which are vertical control, mixed farming strategies, acclimatisation of crops and cattle, use of indigenous techniques and technologies, religious and mythical association to local history and natural resources, off-farm employment as an additional source of income, strong association with their land, and sex specific allocation of responsibilities in agricultural communities. However, the only missing characteristic was the deep-rooted community management of resources in the study area. Furthermore, in the mountain irrigation typology (see Table 2.5), the *suranga* system fits into the category of the collection system (Vincent, 1995), where water is collected from a small source, such as a spring, into small interconnected cisterns and ponds. Like the *niqba* tunnels (Ein Mor & Ron, 2016; Yechezkel & Frumkin, 2016; Yechezkel *et al.*, 2021), the springs are often excavated to increase water supply in the *suranga* system. Thus, this study provides an example of an irrigation system that can be effectively and efficiently managed at a non-community level based on several specific circumstances, which are discussed below.

If the fundamental reasons for managing a common become redundant because of changing socioeconomic and environmental factors caused by regime shift, a system may collapse. Extensive, sudden, and continual changes, for example, caused by climate change or other natural forces, can cause reversible and irreversible state change and impacts on the social-ecological system, shifting the identity, function, feedback, and structure of the system by moving it into a new state. This state change is often known as a regime shift (Rockström *et al.*, 2014, pp. 69-71; Reid *et al.*, 2015). For example, there have been small scale regime shifts in the *suranga* system linked to water availability. A small number of water pond sharing arrangements were in the study area, and these were mostly borne out because of the fragmentation of joint families in the early 20th century (see section 7.3). Results suggest that gradually increasing water demands were caused by an increasing population, friction among stakeholders, and apathy towards the regular maintenance of these shared water resources, resulting in decreased water efficiencies, as observed with the tank systems in south India (Mosse, 1999; Shah, 2008). Emerging alternatives water resources, such as *suranga*, dug well, ponds and borewell, also made the shared water resources redundant over a period. So, this process was enhanced by an alternative technology or a stakeholder reaching economic stability. As a result, stakeholders started to increase water security by developing private water resources such as dug well, *suranga*, and borewell on their land. Almost every homestead and farmstead operated an independent management unit, primarily focused on efficiently harvesting their agriculture water. Small farm units, high precipitation, and seasonal irrigation requirement mean water requirements in the study area were not excessively high. Thus, once these families achieved water self-dependency through private water resources, shared water resources were further ignored and abandoned. However, not all forms of shared management have disappeared as several seasonal shared water resources are still used in the study area, particularly seasonal check dams (*katta*).

Furthermore, the geography and scale of a system and its impact on the community are essential factors for introducing and managing commons because communities often come together to develop and manage shared resources such as water to achieve economic development (Agarwal & Narain, 1997; Meinzen-Dick *et al.*, 2002; Mukherji *et al.*, 2019). For example, people depending on seasonal rivers often construct seasonal dams (*katta*) to store water for the dry periods in the study area. On a medium sized seasonal river, a check dam cannot be constructed individually for two reasons: the river is a shared resource with riparian rights and the large scale natural and human resources required to construct the dam. Therefore, individuals may not have any other choice than to try collective efforts to construct the check dam and share the benefits within their rights. Moreover, affinity principles often underpin the group and collective actions, which means groups are likely to operate efficiently in these community managed systems (Mosse 1999; Agrawal & Ostrom, 2001; Meinzen-Dick *et al.*, 2002). However, in other cases, an enormous common scale may not allow community management (Meinzen-Dick *et al.*, 2002). For example, the construction of a large hydroelectric project needs long term planning, specialised skills and construction equipment, and a significant investment, which is usually complicated if done through community action. In the same vein, community management may be considered excessive for a significantly small scale natural resource, or an unacceptable level of natural resources management can collapse the system (Chaudhry, 2018, p. 5; Hutchings, 2018; Huston *et al.*, 2021). For example, small dug wells are owned and managed privately in the study area because they are situated on private lands and managed as a private water resource. However, a small well, situated on private land, constructed, and managed by a community may fail because there will be an optimum size beyond which management of a group becomes saturated, which can result in conflicts among the stakeholders, resulting in decreased resource efficiency and the collapse of the group, as seen with the tank irrigations system in south India (Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008). Therefore, an inappropriate scale community managed irrigation system may either fail or split into the smaller, individually managed water systems.

The undulating hilly geographical conditions and torrential seasonal rainfall did not support the construction and management of largescale water resources in the study area. Unsurprisingly, the region also lacks large scale hydroelectricity projects because of the topography like other mountain regions (Mukherji *et al.*, 2019). The undulating terrain of the study area with hills, slopes, dense forests, and difficult access indirectly divided farms units and bound the water resources available to them through discrete hydrological catchment dynamics. The dispersion of farms and homestead within this natural environment created a decentralisation of power and community. Clear boundaries of water and land management appeared because of this natural divide. That is why community water and land management were for the most part missing in the case study region, in contrast to larger tank systems found in the Eastern Ghats of India (Mosse, 1999; Shah, 2008). The evidence from this study is that *suranga* will fail if managed communally because of the low investment required to construct them, which is better suited to the family level, not operated as a shared water resource. Thus, this study argues against, by providing the example of the *suranga* system, the use of community management as a panacea for management of natural resources of all scales and sizes but suggests that the size of the resources and associated right should define the most appropriate management level, which is apparent in the *suranga* system that has been successfully constructed and managed at a family level. Therefore, the epistemic lessons learnt from applying a hill irrigation analytical framework make it possible to offer a bespoke hill irrigation framework based on the privately managed *suranga* system (Figure 8.2).

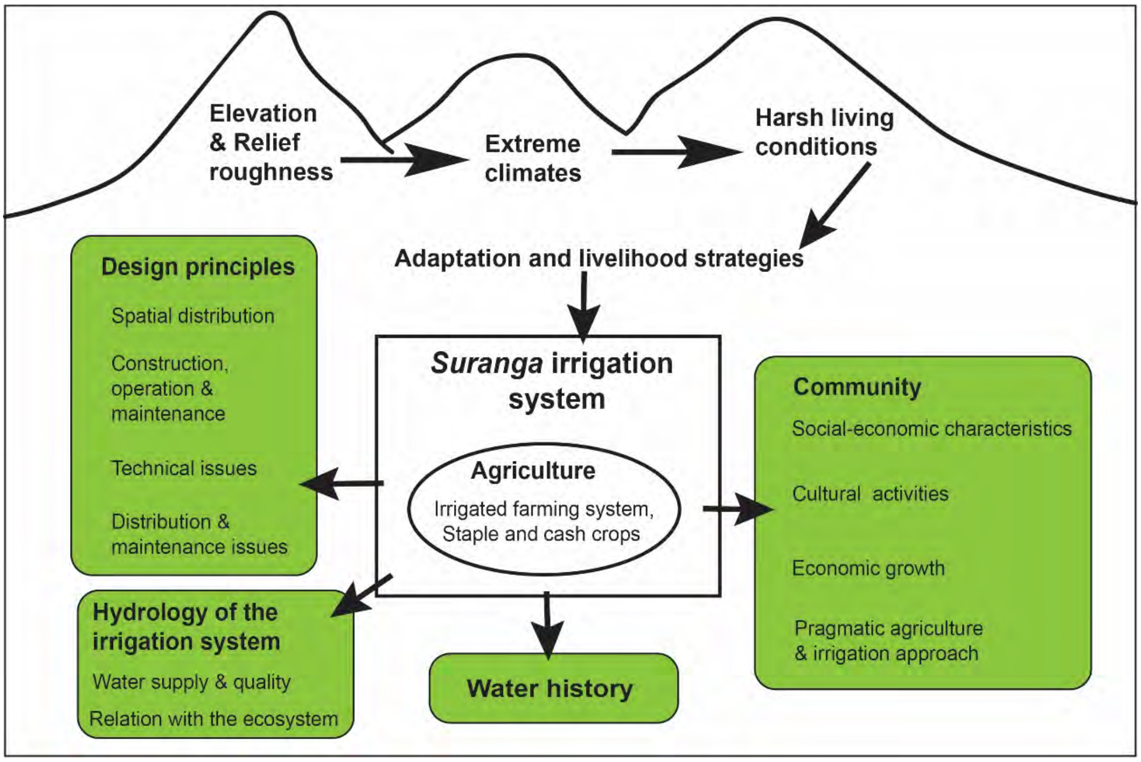


Figure 8.2: A new model of hill irrigation framework based on this study.

Thus, based on the improved understanding of the origin, development, and management of the *suranga* system to present, the following section presents a historical timeline of the key events, endogenous and exogenous disturbances, and pressures on the *suranga* systems to appraise the vulnerability and resilience of the *suranga* system with reference to the community in the study area.

8.3 Comments on vulnerabilities and resilience

This section starts with a narrative of the vulnerabilities and various endogenous and exogenous disturbances and pressures that can affect the resilience of the *suranga* system. Then, based on these findings, the resilience of the *suranga* system has been explained through four stages of the adaptive cycle (Holling & Gunderson, 2002), also known as panarchy.

8.3.1 Agricultural dynamics in the study area

The socioeconomic survey and in-depth interview results recognised several past and emergent exogenous and endogenous pressures faced by communities in the study area. These results emerged from the 2nd and 3rd level thematic analysis of the qualitative data that provided a development model of the agricultural community in the study area. This model helps to build an understanding of the community's development dynamic that, in turn, increases understanding of the vulnerability and resilience of the community to future changes. It suggests that the development of the farming community in the study area is based around five vital interlinked stages (Figure 8.3), which are: (1) Tipping points that can often cause change, (2) emerging issues that manifest themselves in the form of changes to the system, (3) adaptation measures that attempt to negate the effect of these changes caused by emerging issues and are followed by the (4) optimisations of available resources, leading to (5) economic growth in the community. These five stages may appear in a cyclic order, oscillating back and forth. However, occasionally, the boundaries between the two stages may overlap. For example, tipping points may directly lead to adaptation with hidden emergent issues.

The tipping point denotes an evident, distinguishable change in the social, environmental, economic, or political characteristics (Rockström *et al.*, 2014; Walker, 2020) in the study area. Exogenous and endogenous forces may drive these changes (Thorén & Olsson, 2017; Rockström *et al.*, 2014; Xu *et al.*, 2020). In this study, the community of the study area comprised of two main components: community members, the farmers and workers, and core resources like land, water, forest, and livestock, because the community can exist without the latest technology, but not without land and water. The tipping point can increase vulnerabilities for the community and its resources. The vulnerabilities caused by the tipping point often manifest themselves in emerging issues in the community. These emerging issues are often absent or negligible in the state before the tipping point (Rockström *et al.*, 2014). The changes caused by emerging issues are dictated by the community and its resilience, which uses adaptive responses to counteract the changes caused by the tipping point. These responses may also adapt to reach a new point of balance in the changing environment to minimise the disturbances caused by the tipping point (Walker, 2020). Adaptation to manage emerging issues may also appear to mitigate response by the community to stay relevant in the new paradigm (*ibid.*).

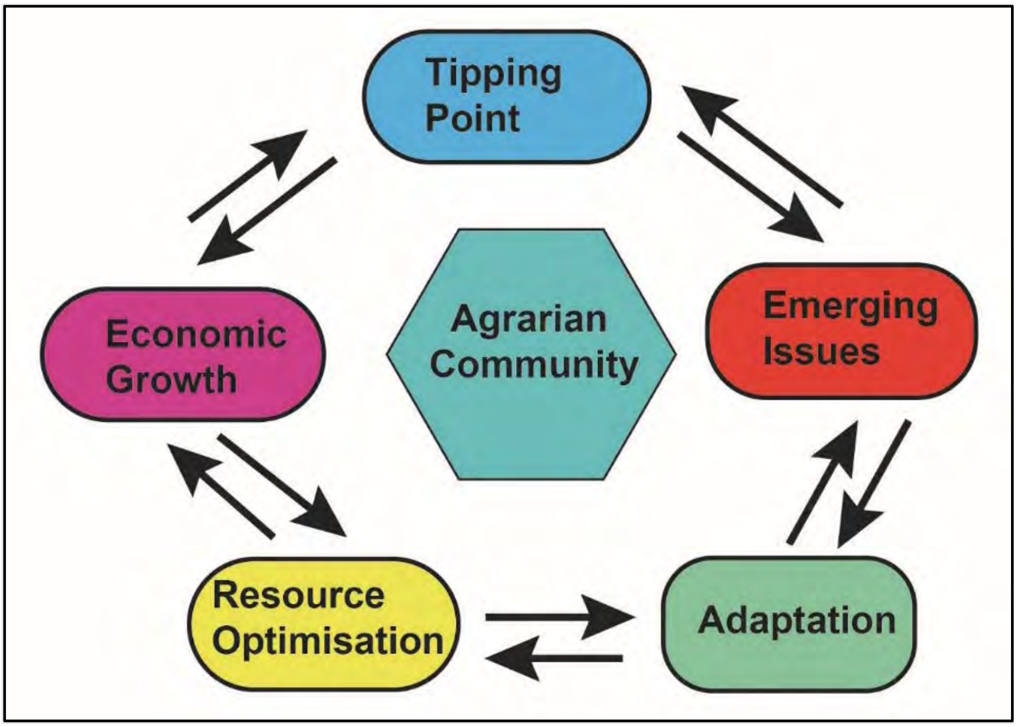


Figure 8.3: The process of development of an agrarian community in the study area.

Based on previous experiences of the users and stakeholders, the adaptation measures are further adjusted to optimise available resources and to increase efficiencies of the system. Solving emerging issues with adaptation measures, followed by resource optimisation to increase overall efficiencies, often lead to community economic growth. At some point, the economic growth is often followed by another tipping point, and gradually with new emergent issues. Thus, this sequential process of agricultural development continued on a temporal scale covering the early 20th century to the present day. This cyclic agricultural development model is further explained with more examples from the study area from the past in Figure 8.4.

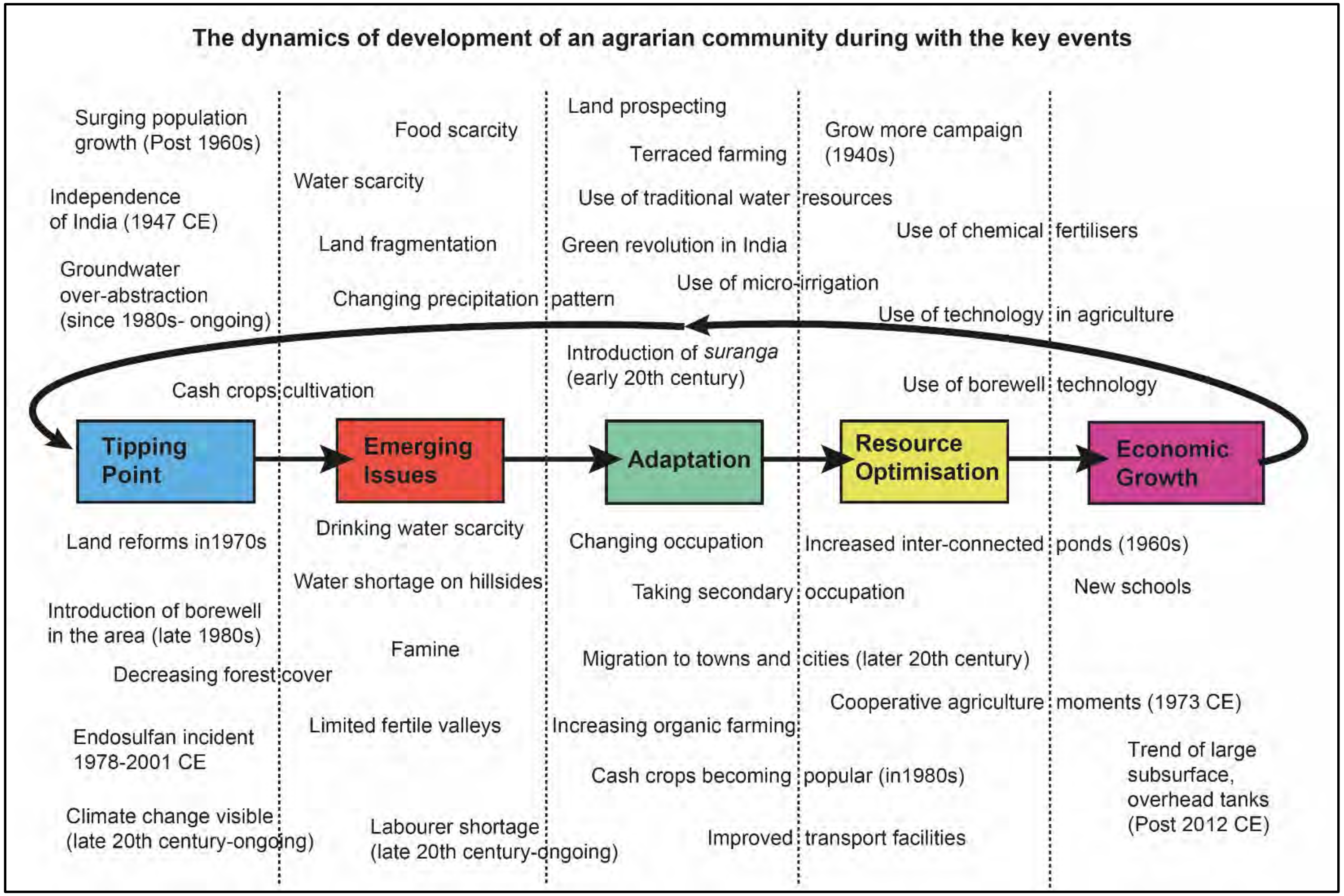


Figure 8.4: The development dynamics of the agrarian community in the study area with the key events.

The population of the historical South Kanara district (presently DK and Kasaragod districts) increased from 91 people/km^2 to 457 people/km^2 between 1871 to 2011 CE (see Appendix C). The regional population surged post-Independence of India in 1947 CE, which motivated farmers to convert land, intensify agriculture, and use new technologies introduced during the green revolution in agriculture (Narayanamoorthy, 2007, Shah, 2008). As seen in section 8.1, the *suranga* technology was developed as an adaptive survival measure in response to water shortage caused by the monsoon seasonality and undulating terrain in the study area. At first, *suranga* were built to solve drinking and household water issues during the dry period, but as the number of *suranga* increased, they were also used to support irrigation on terraced hillslopes to increase subsistence agricultural production for a growing population. Thus, a high number of *suranga* were constructed in the study area in the 20th century, which implies the overall success of the *suranga* systems. However, over this period, some key socioeconomic events impacted the study area and significantly changed the speed and scope of development of the *suranga* system. These are discussed below.

8.3.2 Land reforms

During radical and highly debated land reforms in Karnataka, the state abolished land tenancy, and land ownerships were conferred to the tenants, and marginalised labour families were awarded land for agriculture under the Tenancy Acts of 1961 and the Land Reforms (Amendment) Act in 1974 (Thimmaiah & Aziz, 1983; Damle, 1989; Kumar & Krishna, 2015). These land reforms increased the number of small farmers and the extent of cultivation but decreased the number of farm labourers. However, it also caused the demise of largescale farms, resulting in land fragmentations and an increase in small, low income farm units (Kumar & Krishna, 2015). Gradual population growth also resulted in gradual divisions of joint families and further land fragmentation. In the study area, the marginal (31%), small (29%), and the small-medium farmers (23%), collectively hold 83% of the total landholding with landholdings ranging between 0.1 - 4.0 hectares (section 7.3).

8.3.3 Poverty and migration

Tipping points related to water resources in an agricultural region may often lead to poverty traps; a poverty trap indicates a self-enforcing situation of low resources supported by minimal diversity and a low level of connectedness that causes a persistent state of poverty for the small farmer in arid and semi-arid (Rockström *et al.*, 2014, p. 87;) and mountain regions in the form of recurrent water shortages, droughts, and floods (Mukherji *et al.*, 2019). However, poverty traps can often be destroyed by building upon social and community mechanisms, increasing diversity and connectivity (Rockström *et al.*, 2014, pp. 69-93), as happened in the case of *suranga* and other TWM systems in the study area. Historically, the *suranga*, in association with other local TWM systems, have helped the farmers break the poverty trap by increasing water availability for subsistence agriculture during times of severe seasonal water scarcity (Chapter 4). Similarly, various community management systems of natural resources in arid and semi-arid regions are good examples of overcoming poverty traps by increasing diversity and connectivity within the systems (Agarwal & Narain, 1997; Agrawal & Ostrom, 2001; Chakravarthy *et al.*, 2006; Singh *et al.*, 2021). Similar contextual water development measures have been reported in the hilly regions of Israel (Ron, 1985; Ein Mor & Ron, 2016; Yechezkel & Frumkin, 2016) and Mexico (Palerm-Viqueira, 2004) to combat water shortages.

Still, India has the highest number of low income families, with around 300 million poor people, with 200 million of these in severe poverty with no access to food, potable water, and sanitation (Alok, 2020). Poverty affects consumption, health, and education and leads to a lack of resources and heightened vulnerabilities (Alok, 2020). Overall economic conditions may have slightly improved in India, but still, with the increasing population of India, a large population live in rural areas, and the poverty level is significantly higher in these areas (Alok, 2020; Panagariya & More, 2020), and specifically high in Scheduled Cast (SC) and even higher in the Scheduled Tribes (ST), who live in remote rural areas, and are cut off from the mainstream population (Panagariya & More, 2020) and some of these communities rely on traditional sources of water for their water requirements such as *suranga* in the study area.

However, because of the continually increasing population, a gradual migration of the young population from low income, rural agricultural areas to the cities has occurred. These out-migrants go in search of better education, living conditions, occupation and income in cities and towns, but often they send back remittances to the parent family, a practice that has been a common feature of mountain areas both historically in the European Alps (Fontaine & Siddle, 2000) up to present in India (Vij *et al.*, 2021), and it is also reflected in the study area, which is mainly an agricultural region (Shannikodi, 2013; Kumar & Krishna, 2015; Alok, 2020). A gradual migration trend in the low income families to cities such as Mangalore, Udupi, Bengaluru, Mumbai, and the neighbouring towns such as Puttur, Vitla, and Kasaragod occurred to work predominantly in the construction industry and has been noticed in the study area (Kumar & Krishna, 2015). In addition to youth migration, the study area is also at higher risk of an ageing population caused by low mortality and fertility (Chandran, 2020). The migrations of the young population from the rural areas and an ageing population have caused a shortage of human resources in the study area, which has affected the agriculture pattern in the study area (Shannikodi, 2013; Kumar & Krishna, 2015).

A significant number of local people have migrated to Middle Eastern countries who send remittances back to their families. This practice has negatively affected agriculture in the region because now families can opt out of agriculture all together adding greater stress to the growing problem of a shortage of farmworkers (Kumar & Krishna, 2015). In other cases, the remittances are used to develop farmsteads, but because of a shortage of farmworkers, cash crops such as areca nut and rubber plantations have become more popular because these cash crops are perennial and require fewer human resources and less irrigation compared to paddy cultivation. Historically, paddy cultivation was the main subsistence crop in the study area; however, post-independence in 1947 CE, the area of paddy crops decreased significantly because of land fragmentations, shortage of farmworkers, limited water availability for irrigation, and poor economic returns (*ibid*). The Land Reform Act in the 1960s is also directly associated with a decline in paddy cultivation because most of the reformed lands, which were transferred to the poor land tenants, were paddy fields. Therefore, many farmers threatened by the loss of their paddy fields during the Land Reforms Act converted them to cash crops plantations to avoid any further land loss (*ibid*). Similar land use change has been noticed in the Western Ghats, including parts of Kerala and Karnataka, where agricultural land is gradually changing into non-agricultural land use (Kale *et al.*, 2016; Reddy *et al.*, 2016). For example, paddy cultivation has decreased in area by up to 70% between 1983-2011 in the Wayanad district, mainly because of economic challenges, population growth, shortage of farmworkers, urbanisation, and increased cash crop plantations such as rubber plantations, all resulting in reduced infiltration and groundwater recharge (Sheeja *et al.*, 2011; Jose & Padmanabhan, 2015; John *et al.*, 2020; Panda & Sarkar, 2020).

8.3.4 Cash crops and water resources

Cash crop cultivation initially started because of high financial returns, easier perennial cultivation and shortage of farm labourers (Kumar & Krishna, 2015). They increased further during the 1990s, as the Indian economy opened to the world market through the economic policy reforms in India (*ibid*). The most recent monoculture trend is to convert drylands, which were earlier paddy fields and cashew/coconut plantations, into rubber plantations (Shannikodi, 2013; Kumar & Krishna, 2015; Malhotra, 2017). These transformations are usually on medium to large farm units owned by APL farmers. These moves are economically supported by locally situated state owned rubber organisations, aiming to increase rubber plantations in the region. Rubber trees (*Hevea brasiliensis*) have a lifespan of about 25 years and usually start yielding good returns from the seventh year and do not require any form of irrigation (Koilparambil & Kamath, 2015). However, these monoculture rubber plantations have no understorey and are associated with tropical biodiversity threats, decreased groundwater level, and increased environmental vulnerabilities (Chakraborty *et al.*, 2018; Panda & Sarkar, 2020).

Smaller subsistence farmers gradually adopted cash crops such as areca nut, black pepper, cashew, rubber, and cocoa, often intercropped and with a productive understorey of useful wild crops and materials (Malhotra, 2017; Tripathi & Mishra, 2017). These cash crop plantations were less labour intensive and water demanding than rice and sugarcane crops (Shannikodi, 2013). These cash crops were suitable for terraced farms with limited water availability, mainly irrigated from *suranga* water. As a result, cash crops became popular because they have improved the financial conditions of the small farmers in the study area (Shannikodi, 2013; Malhotra, 2017).

Furthermore, the introduction of agricultural cooperative organisations such as the Central Areca nut and Cocoa Marketing and Processing Cooperative Limited (CAMPCO), found by a group of local farmers in Mangalore city in July 1973 also protected the economic viability of these cash crop small farm units. Two other small cooperative organisations that preceded the formation of CAMPCO, were active in the region, South Canara Agriculture Cooperative Marketing Society (SKACMS) and the Kasaragod Agriculture Cooperative Marketing society (KACMS). These small societies worked in association with local registered commission agents. The CAMPCO started procuring areca nut, cocoa, and rubber from the farmers, which made the local agriculture commission agents redundant, and small farmers started receiving better prices for the crops, which in turn improved livelihoods and popularised cash crops in the region.

The financial stability has allowed the farmers to extend and intensify agriculture by land conversion of forest and drylands to terraced farms and shifting from paddy cultivation to extensions of cash crops (Tripathi & Mishra, 2017). These situations have also increased the use of fertilisers to achieve enough crops from small landholdings (Kumar & Krishna, 2015). Thus, as small farmers moved to cash crops and alternative occupations, which affected the scale and nature of agriculture (Kumar & Krishna, 2015), these situations created the need to develop more water resources, which appeared in the form of diesel or electric pumps and borewell technologies to southern India in the 1970s and 80s (Nagaraj *et al.*, 1994; Bahinipati & Viswanathan, 2019), and in the 1990s in the study area to meet the increasing water demands for irrigation. In the study area, where in the past, families could not afford a borewell, the original preference was to build a TWM system in response to this problem. Recent improvements to family unit financial conditions meant that some farmers can now afford to abstract deep groundwater aquifers using borewells, which exacerbated the problem of the abandonment of *suranga* and other TWM systems in the study area since the late 20th and early 21st century. Furthermore, the number of *suranga* workers decreased in the area because *suranga* excavation was a significantly demanding and risky job, while the existing *suranga* workers either migrated or changed their professions, and new people do not take on this occupation but prefer to migrate to cities for better living conditions leading to a reduction in social capital.

There are numerous examples of when rainfed agriculture gradually turned into groundwater based irrigated agriculture in the second half of the 20th century (Kuper *et al.*, 2017). The popularity of borewell seems to have increased in the study area because it provides access to private, regular supplies of water, and several families can now afford to sink a borewell because of their agricultural growth based on water from the TWM system, including *suranga*. However, the introduction of borewell technology has removed the concept of 'available water' because now farmers could abstract as much groundwater as required, which has consequences such as over-abstraction (Kuper *et al.*, 2017). Because of this, there has been a recent surge in the use of private borewells in the study area. However, nowadays, groundwater levels are under threat across India as farmers become more affluent and can afford borewells. Unregulated expansion of privately drilled borewells and an evident lack of a legal database reduces transparency and has resulted in cataclysmic overexploitation of deeper and shallow aquifers, including water quality issues related to mainly geogenic arsenic contamination of groundwater resources across India, causing severe health issues such as arsenicosis after prolonged consumption (Bhattacharya, 2015; WaterAid, 2017, pp. 14-15; Coyte *et al.*, 2019, p. 1217; Joseph *et al.*, 2020, p. 18; Shaji *et al.*, 2021). Arsenic contamination has been identified in the coastal district of Kasaragod and other parts of the foothills of the Western Ghats (Shaji *et al.*, 2021), neighbouring Bangladesh, China, Pakistan, and Nepal; affecting 230 million people in approximately 107 countries around the world (Fischer *et al.*, 2020; Shaji *et al.*, 2021). Despite this, loans for sinking borewells are available for low income farmers, and these often entice poorly informed farmers to sink borewells in unsuitable locations with undulating topography and highly variable geology. There have been numerous examples when low income farmers took loans from banks to sink borewell, but the borewell did not yield sufficient water, and the farmer could not repay the loan.

Thus, improvements in socioeconomic conditions, migration, adoption of cash crops, and increase reliance on borewell technology (Reynard *et al.*, 2014, p. 11) have left a significant impact on TWM systems, including *suranga*. However, *suranga* still retain their popularity when used in combination with other TWM systems in the community as one of the most popular and successful water resources on hilly terrain where borewell cannot be dug, primarily because of the quality of water in *suranga.* People in the study area still use *suranga* preferentially for drinking and domestic water supplies. However, the number of new *suranga* constructed is limited, a phenomenon often attributed to the easily available alternative of borewell technology, reducing demand for *suranga* coupled with the vanishing number of expert *suranga* workers. To some extent, a saturation of *suranga* has occurred in the region because there are already approximately more than three thousands of them in the study area. Although most of the *suranga* were constructed in the 20th century, some new *suranga* were still being excavated at the time of this study's fieldwork. *Suranga* construction has not entirely stopped in the study area, but most respondents said they have sufficient water supply from existing *suranga* and other TWM systems; therefore, they do not need to develop any new water resource.

In contrast, to borewell, *suranga* draw water from perched aquifers situated at shallow depths in the subsurface. Thus, it is suggested that decreasing groundwater levels in the region may not directly affect water availability in *suranga.* However, it would be prudent for farmers to capture unused *suranga* water during the non-irrigation season (June-November) to recharge groundwater through infiltration in the study area and avoid runoff into the Arabian Sea through rivulets, streams, and rivers. Therefore, there is a need for informing the broader *suranga* users and other farmers to utilise the runoff during rainy seasons to recharge the groundwater to improve groundwater availability. Furthermore, the local schools in the study area can also improve the level of education in students about the need for groundwater recharge, which can improve the understanding of the (geo) hydrological principles in the community. Patel *et al.* (2020) have shown positive results from community based groundwater recharge systems in the arid region of Gujrat state in India as a community response to decrease groundwater level caused by over-abstraction through borewells in the 1990s. Despite these salient lessons from other parts of India, land use change and land conversion continue to cause deforestation and forest cover loss, which in turn lead to soil erosion, increased runoff, and decrease infiltration on hillslopes in the foothills of the Western Ghats (Narayanamoorthy, 2007; Kale *et al.*, 2016; Reddy *et al.*, 2016). Dry periods and droughts have also been found to be positively associated with wildfires in the Western Ghats regions, increasing deforestation and ecological collapse (Kodandapani & Parks, 2019). These impacts may not directly affect the structural stability of *suranga,* but discharges may decrease significantly, leading to abandonment. Thus, deforestation and uncontrolled land conversion can be highly perilous for the survival of the *suranga* system. As the next section goes onto show anthropogenic activities can lead to other environmental problems as well.

8.3.5 Impact of pollution on *suranga*

In the neighbouring state of Tamil Nadu, it was found that anthropogenic activities can easily pollute shallow aquifers as well as deep aquifers (Karunanidhi *et al.*, 2021b), so a precautionary principle is needed. *Suranga* are highly vulnerable to external surface pollution and water contamination because *suranga* are primarily recharged with the precipitation that percolates into the subsurface, and this groundwater is harvested from shallow depth aquifers. For example, a pesticide, Endosulfan, was sprayed by helicopters on state owned cashew plantations in thirteen village *panchayats* in Kasaragod district between 1978-2001 (Thanal, 2009; Neethu & Miriam, 2018; Khuman *et al.*, 2020). This largescale spraying caused a plethora of irreversible medical issues and lifelong disabilities among affected people and newborns in several villages in the study area (Thanal, 2009; Crook *et al.*, 2013). In addition, cattle, wildlife, and bio-indicators insects such as butterflies were also negatively affected in the study area (Thanal, 2009; Raghavendra *et al.*, 2020). Approximately 4000 people died, and 9000 people were seriously affected by this tragedy (Mathew, 2009). Direct exposure to Endosulfan is suggested to be the leading cause of death, followed by Endosulfan entering the food chain through contaminated soil and water (Thanal, 2009; Khuman *et al.*, 2020). Traces of Endosulfan were reported in water samples from well, *suranga*, streams, ponds and blood samples from school children (Jayaprabha & Suresh, 2016). Although the use of Endosulfan has been banned in Kerala state, several organochlorine pesticides (OCPs) and hexachlorocyclohexane (HCH) residues were still being traced in the region (Khuman *et al.*, 2020). This emergent incident exposed the vulnerability of *suranga* and other water bodies to pollution, and as a result, the use of pesticides seems to have decreased, and organic fertilisers appear to be becoming popular among the respondents as a positive adaption to this negative stimulus.

In India's rural areas, households primarily use concrete and laterite bricks lined, subsurface septic tanks to dispose of excreta and domestic sewage (Bhallamudi *et al.*, 2019), which largely negates this conduit of pollution if maintained well, but cow dung and other manures can pollute subsurface water groundwater (Karunanidhi *et al.*, 2021b). Aside from this, the highly polluted wastewater from small scale rubber sheet manufacturing plants located chiefly within the rubber plantations in the study area can also pollute the surface and shallow depth groundwater resources (Koilparambil & Kamath, 2015). Furthermore, the *suranga* are also vulnerable to internal water pollution from bats roosting inside the *suranga*, as bat guano can contaminate water and be harmful to humans (Wacharapluesadee *et al.*, 2013). Therefore, people often cover the entrance of their drinking water (domestic) *suranga* by access covers or gates. However, such practice was not ubiquitous, perhaps because bat guano enriched water can provide nutrients and act as a natural organic fertiliser for crops (Wurster *et al.*, 2015; Ünal *et al.*, 2018).

8.3.6 Rigidity traps

Focus only on increasing the yields of crops for economic reasons can place stress on the broader ecosystem, increasing the vulnerabilities of the overall agricultural ecosystems in a process referred to as a rigidity trap (Rockström *et al.*, 2014, p. 83). Moreover, the high availability of (water) resources and connectedness can also cause rigidity traps that resist any change in the system, resulting in decreased system resilience (Rockström *et al.*, 2014, p. 87; Walker, 2020), which is happening in India. For example, extensive reliance on abundantly available groundwater for agriculture in India has created a rigidity trap for the agriculture ecosystem, which may collapse to any regime change in groundwater availability and reliance in the future, increasing the number of BPL families (Bahinipati & Viswanathan, 2019). Moreover, presently India is the largest producer of areca nut, which is also the main cash crop in the study area, and the economy of the region is highly dependent on areca nut cultivation. Areca nut is consumed by approximately 600 million people in India and other south-east Asian countries traditionally (Arora & Squier, 2018; Papke *et al.*, 2019). However, India's nationwide growing demands to ban areca nut based on its addictive and carcinogenic nature when used with tobacco, betel leaves, and often in the form of sweetened, flavoured, chewing, mouth-freshening products (Arora & Squier, 2018; Papke *et al.*, 2019; Chatterjee *et al.*, 2021) could threaten the viability of many areca nut plantations in the study area. Therefore, the communities in the study area seem to have been trapped in an oncoming rigidity trap caused by too much dependence on areca nut plantations. Similarly, in the study area, agriculture has shifted to focus on cash crops because of higher return, and some farmers now gradually move towards a monoculture of rubber or concentrate on areca nut plantations which makes farmers vulnerable to fluctuation in demands and price variations in the future (Kumar & Krishna, 2015; Malhotra, 2017; Tripathi & Mishra, 2017). Like other parts in India, reliance on borewell is gradually increasing in the study area with the abandonment of TWM systems, including *suranga*, which may decrease the water resilience of the community in the study area by being trapped in a rigidity trap (Walker, 2020) like northern parts in India with decreasing and polluted groundwater levels (Saleth, 2011; Mukherjee & Singh, 2018; Bahinipati & Viswanathan, 2019; Kumar, 2019; Kurwadkar, 2019; Singh *et al.*, 2019; Subba Rao *et al.*, 2019; Lone *et al.*, 2020; Patel *et al.*, 2020; Shaji *et al.*, 2021; Vij *et al.*, 2021).

8.3.7 Climate change

Historically, agrarian communities, cities, and civilisation found in the monsoon zone have witnessed the rise and falls because of the monsoon variability caused by climate change (Buckley *et al.*, 2010; Singh, Dey *et al.*, 2020). For example, a decrease in the monsoon variations was reported in the central higher Himalaya between 4000 cal yr BP -3500 cal yr BP and an increase in the monsoon post 3000 cal yr BP (Phadtare, 2000). Similarly, the precipitation decreased significantly in the region of the Western Ghats in India between 3500 yr BP – 2200 yr BP resulting in periods of stasis and instability/uncertainty in water supplies, but after 2200 yr BP, high monsoonal rainfall patterns established and subsequently monsoon climate has been stable (Bentaleb *et al.*, 1997; Singh, Gupta *et al.*, 2020). At times, the ancient civilisations showed resilience to climate change by incorporating indigenous knowledge and developing TWM systems; however, these communities still collapsed during the decades and centuries after long term climate variability (deMenocal, 2001). Still, the invention of various TWM systems and crop diversification strategies helped communities buffer the effect of climate change in the past (Schelwald-van der Kley & Reijerkerk, 2009; Shanmugasundaram *et al.*, 2017). Resilience to climate change gradually increased over time because of increased knowledge and technological development. The Indian subcontinent is highly exposed to the impacts of climate change, such as increasing overall temperature, intense heat episodes and increased snow melting rates (Masroor *et al.*, 2020; Rao *et al.*, 2020; Vijay *et al.*, 2021), which will cause sea level increase and submergence of densely populated coastal areas (Chakraborty & Shukla, 2020), temporal and spatial change in the monsoon pattern, further causing cyclones, floods, droughts, reduced crop yields (Masroor *et al.*, 2020; Rao *et al.*, 2020), which can be the tipping point for one of the densely populated regions of the world (Fisher, 2018, p. 253). Therefore, global warming may have diverse impacts on mountain regions (Kohler & Maselli, 2012), including the study area situated in the foothills of the Western Ghats. Based on data from 1901-2018, there is an indication that global warming has weakened the Indian summer monsoon (ISM) and precipitation over the Western Ghats and has increased the average temperature and relative humidity in the study area (Krishnan *et al.*, 2012; Rao *et al.*, 2020; Vijay *et al.*, 2021). However, significantly increased extreme rainfall events have already been noted over the western coast of India (Attri & Tyagi, 2010, pp. 18-19; Masroor *et al.*, 2020; Vijay *et al.*, 2021).

The impact of climate change on the *suranga* system has not been assessed in any previous studies (Prasad *et al.*, 1991; Nazimuddin & Kokkal, 2002; Doddamani, 2007; Halemane, 2007; Suseelan, 2008; Tripathi, 2009; Balooni *et al.*, 2010), but if as expected climate change significantly disturbs the Indian monsoon pattern and increases monsoonal precipitation with an increased frequency of extreme weather events in the Indian peninsula then these impacts may become very real (Chakraborty & Shukla, 2020; Rao *et al.*, 2020; Mahendra *et al.*, 2021). Then, increased intensive precipitation phases may increase surface erosion and soil piping incidents, which are already common in the study area (Sarath *et al.*, 2020). The increased soil erosion may cause structurally vulnerable *suranga* to collapse, or water flow in the subsurface may be affected. However, the remaining yielding *suranga* will become more indispensable during seasonal water shortages in such situations. On the other hand, if climate change also decreases the overall rainfall in the area (Vijay *et al.*, 2021), then some *suranga* may dry up sooner or may not get recharged. Still, water yielding *suranga* will become vital for the community to meet drinking water requirements. Thus, in both climate change scenarios, water yielding *suranga* will retain their relevance but still will be highly vulnerable to the impacts of climate change.

Over-abstraction of groundwater through pumping methods since the introduction of borewell technologies in the 1970s (Patel *et al.*, 2020) has shifted the regime from available groundwater to depleted groundwater. Reduced precipitation and altered vegetation can further support this regime change. The new groundwater regime, depending on water use, may affect water availability for communities, health issues, and crop production (Rockström *et al.*, 2014, pp. 72-72). The vulnerabilities to regime shifts can be reduced by building resilience in ecosystems and through better management (Rockström *et al.*, 2014, p. 83).

Table 8.2 summarises the above mentioned past and future key events and pressures that had changed or have the potential to destabilise the *suranga* system. These events and pressures have been compared to see if the *suranga* system will maintain structural, functional, and feedback identity (see section 2.3.1) based on potential disturbances caused by various future pressures.

I_1 Structural: Will *suranga* survive/adapt their design and structure?

I_2 Functional: Will *suranga* be able to produce water after endogenous and exogenous disturbances?

I_3 Feedback: Will *suranga* still be relevant in the future for water requirements as other water abstraction systems steadily become more popular in the region?

Table 8.2: The past and potential pressures and disturbances on the *suranga* system.

Disturbances (D)	Structural identity (I_1):	Functional identity (I_2):	Feedback identity (I_3):
Population growth	Yes	Yes	Yes
Independence of India and the green revolution	Yes	Yes	Yes
Land reforms of the 1970s	Yes	Yes	Yes
Migration	Yes	Yes	Yes
Socioeconomic changes	Yes	Yes	Yes
Ageing population	Yes	Yes	Yes
Land fragmentation	Yes	Yes	Yes
Land use change	Yes	Yes	Yes
Agricultural intensification	Yes	Yes	Yes
Introduction of cash crops	Yes	Yes	Yes
Introduction of agriculture cooperatives	Yes	Yes	Yes
Introduction of borewell	Yes	Yes	Yes
Climate change: increased intense rainfall	**No**	**No**	Yes
Climate change: decreased overall rainfall	Yes	**No**	Yes
Forest cover loss	Yes	**No**	**No**
Decreasing groundwater level	Yes	Yes	Yes
Pollution and contamination	Yes	Yes	**No**

Like other mountain regions in India (Bhagawati *et al.*, 2017), the remote, agricultural hill communities scattered in the study area with traditional, mainly rainfed agricultural practices may find it challenging to meet the increased demand for natural resources and are highly likely to be affected by climate change (Malhotra, 2017). The indigenous knowledge from the hill communities can help develop adaptation and mitigation policies to minimise the impact of climate change (Bhagawati *et al.*, 2017).

8.3.8 The dynamic history of *suranga* based on Hollings's adaptive cycles

So far, a number of pressures and vulnerabilities related to the *suranga* system have been identified, which can be used to explain the dynamic history of the *suranga* system based on Holling's concept of the adaptive cycle, also known as panarchy (Holling & Gunderson, 2002; Walker *et al.*, 2004; Derissen *et al.*, 2011) as shown in Figure 8.5, and the key events and pressures have been summarised in Table 8.3.

The focus of the following discussion in Figure 8.5 is based around four different dynamic states (n-1), n, (n+1), and (n+2) of the agrarian community in the study area over a temporal period. Each state represents an adaptive cycle made of four phases: growth (r), conservation (K), release/collapse (Ω), and reorganisation (α). The release/collapse (Ω) stage, often triggered by various tipping points, moves the state of the system into a completely new dynamic state, and this cycle continues on a temporal scale. For example, the discussion here starts with a state (n-1), which is assumed as the earliest state in this study's range, between the mid-19th century-early 20th century, based on the results collected in this study. State (n-1) can be characterised by the early agrarian developments in the study area, with a relatively low population and small cultivated area. During the later stages of the state (n-1), the increase in population, land conversion, and seasonal water scarcity in the study area created a state of collapse (Ω), and these pressures may have given birth to the concept of *suranga.* The system then moved to another state called state n here. During the reorganisation (α) phase of state n, the *suranga* system further evolved and became more popular. The popularity and numbers of *suranga* increased during this state (between the early 20th century -the 1960s) because of the increased agricultural area and economic incentives that steadily led to the growth (r) stage of *suranga* in the study area. During the mid and late 20th century, the *suranga* system achieved the conservation stage (k). The front loop stage between growth (r) and conservation (k) is a slow, gradual, and most prolonged process when *suranga* gradually established in the study area.

However, disturbances and pressures such as further population growth, land fragmentation, migration, intensive crop cultivation, and the introduction of the borewell technology in the study stressed which destabilised the *suranga* systems in the conservation stage (k) of state n, and collapsed (Ω) the state n, into a new cycle of state (n+1). This new state (between the 1960s - first half of the 21st century) can be characterised by increasing dependency on groundwater leading to improved economic conditions and the start of cash crops with a trend towards the introduction of monoculture in the regions. The current state of the study area is very much likely to be at the growth (r) stage of the state (n+1). The state (n+2) is a potential state based on the current understanding from this study.

Thus, a tipping point can cause changes in the stages and the state of a system. However, if *suranga* are resilient, then it will attempt to reorganise (α) itself and find a renewing state in the new circumstances. The back loop from Ω to α is a fast phase of fall, followed by regeneration (Holling & Gunderson, 2002). Once a new stable state is achieved by adapting to the circumstances, the system steadily achieves growth (r). It gradually achieved the conservation (K) phase, the highest energy state for a dynamic system. For example, with the introduction of the borewells in the study area as a primary resource for irrigation, the *suranga* adapted to a new state where it became an essential source for the drinking water supply. Thus, there was a slight change, but with an adaptation, the *suranga* system managed to remain in the loop and quickly achieved the growth (r) stage.

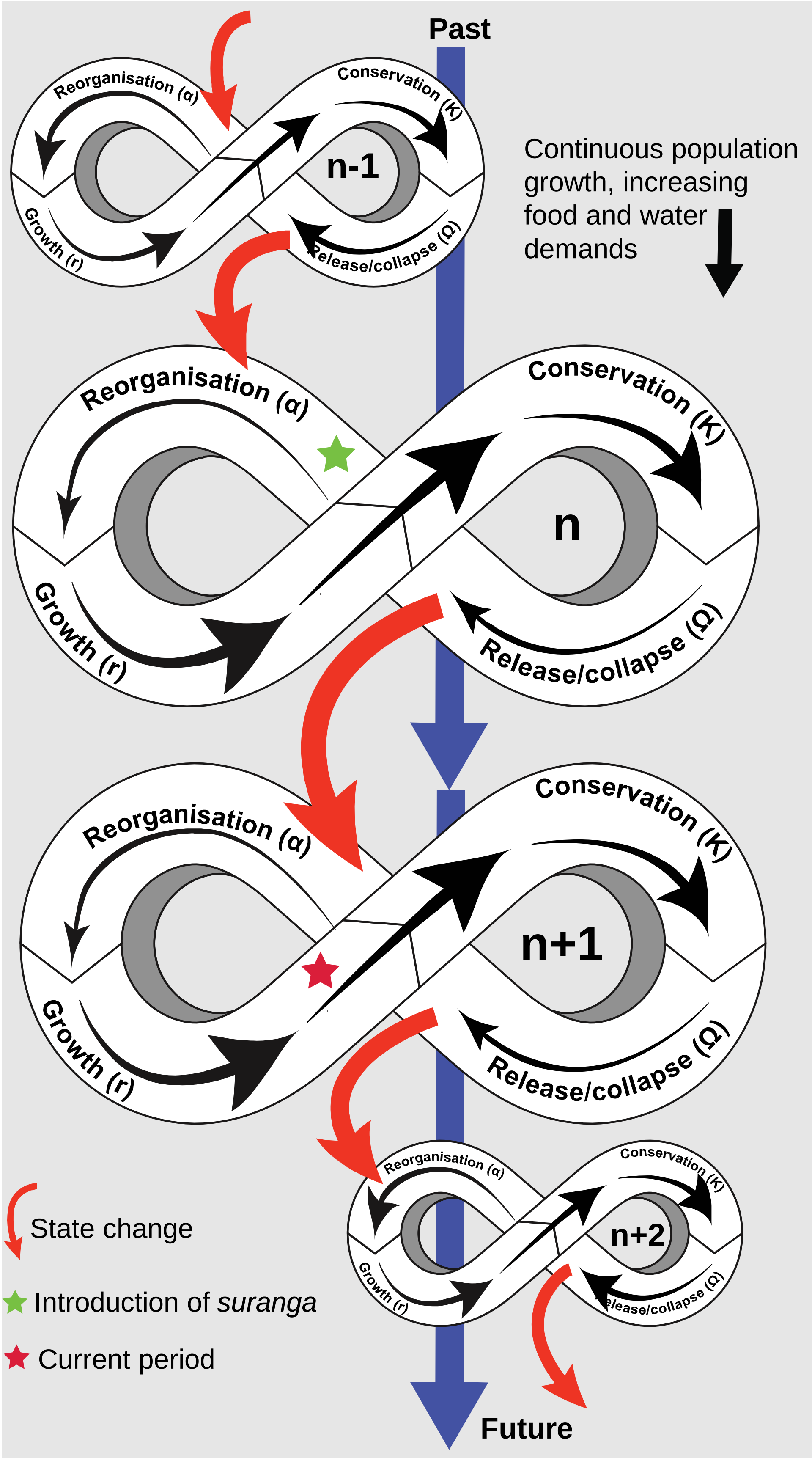


Figure 8.5: A multi-adaptive cycle concept to explain the dynamic of the *suranga* system.

Table 8.3: Various phases and key events in explaining the dynamics of *suranga*.

State	Collapse phase (Ω)	Reorganisation phase (α)	Growth phase (r)	Conservation phase (k)
(n-1) Mid-19th century-early 20th century	Water scarcity, food scarcity for the increasing population Low income Poverty	Migration into the interior frontiers, Land prospecting, land conversion, and terraced fields, use of ponds to store runoffs	Increased subsistence farming, with rainfed agriculture	Population growth Increasing settlements and subsistence agriculture in the rural forested area
n Early 20th century - 1960s	Increasing population causing water and food insecurities	**Birth of the *suranga* system**, caused by increased water demands	Increased farming, and increased water availability	Population growth, improved economic conditions, the introduction of cash crops and increased cropped area
(n+1) The 1960s - first half of the 21st century	Land fragmentation caused by population growth, migration to cities, shortage of farmworkers and labourers, increased water requirements for irrigation, the introduction of land reforms	Decreasing paddy cultivation area, Introduction of cooperative organisation for cash crops Introduction of borewell in the area	**Current Phase,** Improved economic conditions, Migration to cities Cash crops becoming increasing popular. Borewells are becoming more popular, Decreasing use and maintenance of *suranga*	Cash crop cultivation leading to monoculture. Unsustainable groundwater abstraction and extremely high reliance on borewell Possible abandonment of the *suranga* system, but still used for domestic water supplies
(n+2) Sometime in the first half of the 21st century onwards	Climate change visible, Ageing population, Ban on some cash crops (such as areca nut), The possible return of TWM systems.	…	…	…

Similarly, the overall adaptation strategy for climate change is to decrease the runoff and increase the infiltration in the *suranga* catchment area, which can be done by increasing afforestation, green cover, and constructing water recharge wells on upper hillslopes. These activities were occasionally noticed in the field but not practised on a large scale. In addition to several government agriculture organisations in the region, such as the Directorate of Cashew Research[40] and local agriculture centres often known as *Krishi Vigyan Kendra* (KVK), private organisations such as the Varanashi research organisation and organic farm[41] have been active in promoting organic farming and providing advice in the region since 1991 and promoting traditional seasonal check dams on streams and rivers (*katta*) in the area. A monthly agriculture magazine name *Adike Patrike*[42] is popular among the local farmers. Finally, a small number of local water and agriculture activists and journalists, such as *Shree Padre*, help the farmers and popularise traditional agricultural practices to promote water harvesting and conservation with TWM systems and the *suranga* system. However, with these ongoing adaptation measures, *suranga* can continue to be resilient during future disturbances such as moderate climate change, groundwater depletion, but the main vulnerability to *suranga* is transboundary pollution issues and socioeconomic changes. From the example of the Endosulfan incident in the study area, it is evident that *suranga* may become useless in the event of largescale pollution. However, it seems that the communities have learnt lessons from the Endosulfan tragedy, which has motivated farmers towards organic farming. Thus, in the current state, the *suranga* system seems highly resilient to exogenous disturbances and pressures.

Finally, the rigidity traps caused by high dependence on borewell groundwater abstraction and monoculture can be weakened by developing alternatives and increasing diversity to face potential future changes in the system (Tripathi & Mishra, 2017; Walker, 2020). This increased functional and response diversity can help increase the resilience of the ecosystem to potential regime shift by reorganisation after any disturbance (Rockström

[40] www.cashew.icar.gov.in

[41] www.varanashi.com

[42] www.adikepatrike.com

et al., 2014, p. 83; Walker, 2020). Historically, the study area has relied on growing diverse crops supported by a combination of TWM systems for their irrigation requirements, which raised the resilience of the community. Thus, *suranga* and other TWM systems have increased the resilience of the agriculture community in the study area to break the poverty trap caused by monsoon variation and water scarcity on limited agricultural land. However, a gradual move towards monoculture and groundwater abstraction with borewell technology in the study area will limit the diversity of this agriculture ecosystem (Tripathi & Mishra, 2017), causing an increased rigidity trap and decreased community resilience towards any regime changes in the future (Walker, 2020).

Furthermore, Figure 8.6 provide a conceptual scale of water discharge, management level, command area, water rights, and impact of over-abstraction on the environment of various water resources, including *suranga* and the borewell systems in the study area.

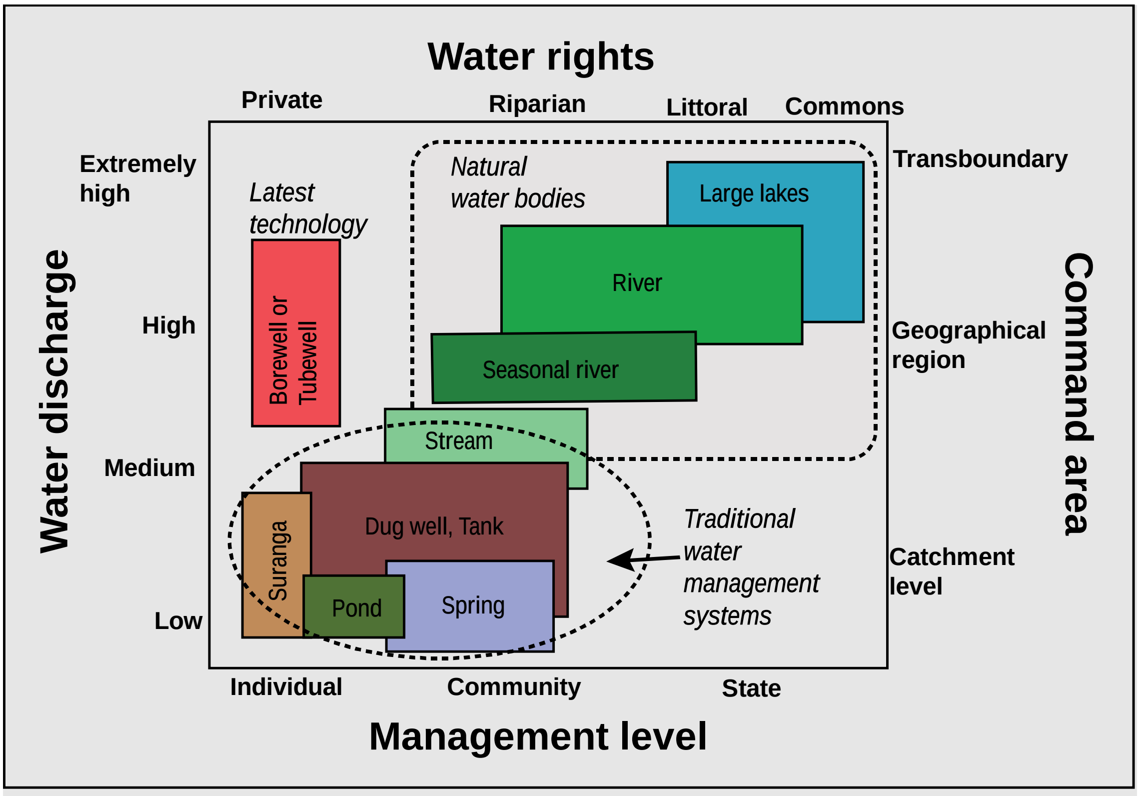


Figure 8.6: Water resources with water discharge, management level, command area, water rights, and impact on the environment.

The *suranga* system shares common characteristics with other TWM systems, such as localised, basic flexible design, easy adaptability, low investments, and usually cannot be over abstracted. However, the *suranga* system differs from the community managed TWM systems in their scale and individual management mode. Thus, the *suranga* system can avoid the weakness of community management in the present socioeconomic scenario, while other TWM systems are failing. Like the *suranga* system, borewells also enjoys private ownership. Thus, borewell and *suranga* owners can easily avoid riparian/littoral water disputes. However, an unlimited amount of water can be abstracted from borewells compared to the *suranga* systems, favouring the borewells among medium and large farmers. In the past, when borewell technology was not available, and until it became affordable to the families in the study area, the *suranga* system allowed the communities to survive and develop by providing domestic and irrigation water security. However, population increase, technological advancements, agricultural intensification, and improved socioeconomic conditions have popularised borewells in the study area among the farmers. Nowadays, even small scale farmers can afford or apply for loans for sinking borewells and enjoy unrestricted water use for their crop intensification and agricultural development. Still, many low income families in the study area wholly rely on *suranga* water for their domestic water requirements. The good water quality of *suranga* water makes it the most preferred choice for domestic water supply in the study area among most of the families. The overexploitation of groundwater with borewells has a significantly higher impact on the natural environment and can incite transboundary issues. The *suranga* system, which is naturally self-regulated and cannot be over abstracted, can be easily recharged with seasonal rainfall. These characteristics make *suranga* a unique water resource, which usually produces low medium water supplies.

In summary, the *suranga* system has shown high level adaptability to past exogenous and endogenous disturbances and pressures, such as migration, population growth, socioeconomic changes, changing cropping patterns, the introduction of borewell, by maintaining its structural, functional, and feedback identities yielding water to meet external pressures and drivers. The above discussion shows that although *suranga* are likely to be resilient against future disturbances such as groundwater level decrease but can be highly vulnerable to the disturbances caused by the development of alternative water technology such as borewell, climate change, forest cover loss, pollution, contamination of groundwater, and improved economic characteristics can negatively affect the functional and feedback identities of the *suranga* system. The next section focuses on the sustainability of the *suranga*, which aims to evaluate the longevity of the *suranga* system and asks if *suranga* will continue to remain relevant by providing water equally to the future generations economically, without compromising environmental integrity.

8.4 Comments on sustainability

This section discusses the sustainability of the *suranga* system based on historical, contemporary and future contexts (Marchese *et al.*, 2018), covering from the early 20th century to the mid-21st century by discussing the results of temporal changes on the quality, quantity, and supply of the freshwater resources, design principles, adaptive capacity, economic aspects, and social frameworks (Wiek & Larson, 2012; Schneider *et al.*, 2015; Hellström *et al.*, 2000; Maurya *et al.*, 2020; Siebrecht, 2020), and because of the diverse and complex nature of the mountain communities typical of interdisciplinary, context based research (Vincent, 1995; Wilson *et al.*, 2018; Otero *et al.*, 2020). The sustainability framework of the *suranga* system in this study (see Table 2.7) was framed in the first instance around four sustainability components: structural and functional; environmental and ecological; social and cultural; and economic benefits. Thereafter these four components were further divided into 16 sustainability indicators (see Figure 2.4), similar to those used by other studies to explore the sustainability of a water system (Wiek & Larson, 2012; Schneider *et al.*, 2015; Wilson *et al.*, 2018; Hellström *et al.*, 2000; Maurya *et al.*, 2020). This section starts with a narrative based on these four sustainability components and associated sustainability indicators. The results are also summarised in a table covering the strengths and weakness of the *suranga* system based on sustainability indicators (presented in section 2.3.2) that affect the sustainability of the *suranga* system. Finally, two sustainability wheels based on the sustainability indicators results attempt to present a visual summary of *suranga* sustainability for the past and future.

8.4.1 *Suranga* and poverty alleviation

Water is essential for life and a thriving economy in these marginalised, agricultural based hill communities because food availability at a subsistence level in these villages is tied to both (Vincent, 1995; Kreutzmann, 2011; Suri, 2018; Mukherji *et al.*, 2019; Balasubramanya & Stifel, 2020). This study started focusing on *suranga* as an irrigation source for agriculture, but during fieldwork, the *suranga* systems were found to be a preferential source of water for drinking and household use around the year. The significance of *suranga* water magnifies during the dry summer seasons when water shortage is exceptionally high. There are no other water harvesting methods that would have been successful on the hilly terrain because steep hills, highly weathered soil profiles, and torrential seasonal rainfall may not allow large scale, community managed water storage structures, unlike those usually found in other mountain regions with moderate precipitation patterns (Vincent, 1995; Crook & Jones, 1999; Kreutzmann, 2011; Dörre & Goibnazarov, 2018; Suri, 2018; Megdiche-Kharrat *et al.*, 2020; Alokhunov, 2021). Moreover, the government water supply, which is usually provided to the financially weakest families by sinking local borewells in the villages under the Karnataka state rural water supply schemes (Government of Karnataka, 2021), are not reliable because of the undulating terrain and the dispersed nature of settlement (Shannikodi, 2013) which make providing drinking water within a centralised supply system technically unviable.

TWM systems are often an integral part of the communities and their cultures, reflected in their prevalence throughout India (Narayanamoorthy, 2007; Singh *et al.*, 2021). This study found 700 *suranga* in the study area (Crook *et al.*, 2020). If aggregated to other discrete studies covering neighbouring areas, there is a minimum of 3000 *suranga* in the two districts of DK and Kasaragod, and nearly all these *suranga* were made in the last 100-110 years (Nazimuddin & Kokkal, 2002; Halemane, 2007; Balooni *et al.*, 2010). The number of *suranga* in the study area is far higher than the 210 spring tunnels constructed between 2200–1550 BCE in mountain regions in Israel (Yechezkel *et al.*, 2021). The high regional density of *suranga* in a relatively small region indicates their significance, structural suitability, popularity, and effectiveness in supporting the communities from diverse economic and social backgrounds to achieve water security for drinking and household in the hilly terrain, especially in the past when borewell technology or government water supplies were not available. This idea was supported by the survey results, which did not associate *suranga* usage with specific economic conditions of the respondents but showed that *suranga* are popular among both APL and BPL families.

The majority of the TWM systems in India are often low cost water resources (Narayanamoorthy, 2007; Singh, Dey *et al.*, 2020). However, it was challenging to present a formal cost benefit analysis of *suranga* because, like the tank system in India, the variation in size, flexibility in design, and bespoke nature of their structures and use (Mosse, 1999; Narayanamoorthy, 2007, Shah, 2008) made this difficult. Still, a simple comparison of the capital costs, maintenance, and operational costs of the *suranga*, dug well, concrete circular well, and borewell (see Table 5.3) indicates that the *suranga* system is the most economical water resource available to agricultural communities in the study area. Like strategies found in other mountain irrigation systems and TWM systems, the use of readily available basic construction tools coupled with low maintenance costs makes *suranga* an affordable choice for the marginalised community (Narayanamoorthy, 2007). Usually, people hire *suranga* workers to construct a *suranga*, but, on numerous occasions, low income farmworkers or labourers excavated their drinking water supply *suranga* themselves to reduce the costs because of financial constraints.

Drinking water quality is a significant issue in India (Mukherjee & Singh, 2018; Kurwadkar, 2019; Singh *et al.*, 2019; Subba Rao *et al.*, 2019; Kurwadkar *et al.*, 2020; Lone *et al.*, 2020; Karunanidhi *et al.*, 2021a), especially in children in remote rural and indigenous communities where access to safe drinking water and wastewater treatment can cause health, malnutrition, and education related issues, especially among girls and women (Yadav & Lal, 2018; UNDP, 2020, p. 66). However, the water quality analysis of *suranga*, ponds, dug wells, and borewells did not suggest any significant water quality issues in the study area similar to what was observed by Razeena and Mini (2016) except low pH, attributed to the iron rich, weathered geology. On other parameters, *suranga* water samples were superior in quality to the borewell samples. Thus, the water quality results supported the local opinion of preferentially using water from *suranga* for drinking and household because it is assumed to be the best quality as slow filtration occurs through the soil layers. These results are crucial because 19% of the families (thirty BPL and eleven APL families) in the survey solely rely on *suranga* for their water supply (Chapter 5). Furthermore, though no bacterial contaminations were found in *suranga* water samples, the use of boiled water for drinking was a widespread practice in the study area, which prevented any potential bacteriological contamination issues arising in their water supplies (Clasen *et al.*, 2008). A similar practice of using boiled water as a household water treatment has been noticed in other parts of India (McGuinness *et al.*, 2020), including Tamil Nadu and Puducherry (Ahmed *et al*., 2007; Juran & MacDonald, 2014). In summary, the *suranga* water samples met the primary drinking water standards based on Indian drinking water standards IS 10500:1992.

Although *suranga* are primarily used for drinking and household water supplies because of their superior quality, excess water from the *suranga* is typically stored in earthen ponds and dug well situated in farmsteads and is used to irrigate kitchen gardens agriculture crops, and plantations. BPL families, with minimal land, rely on rainfall followed by available water resources, including *suranga,* to irrigate their kitchen gardens and agriculture. Small farmers, with up to two hectares of landholdings, often used a network of *suranga* systems efficiently to provide enough water for irrigation. There were some examples where medium sized farmers with up to ten hectares of land have efficiently used a network of *suranga* and ponds in their farms to meet their agricultural water requirements. The undulating geography presents technical challenges that often limit a farmer's reliance on using a single type of water resources for irrigation. Therefore, farmers often use multiple water harvesting strategies using a mix of TWM systems and the latest borewell technology.

Although, traditionally, irrigation was done manually and through open channels, nowadays farmers use a combination of distribution and irrigation techniques, such as a network of drips, foggers and sprinklers in their farms, to improve irrigation water distribution efficiencies. Irrigation efficiency is often based on the economic concept of more crops per drop for farmers (Sowthanya & Shanmugam, 2019), as observed with tank irrigation systems, and attempts to increase cultivation from the available water supply in India (Mosse, 1999; Narayanamoorthy, 2007). Irrigation efficiency, however, is a very complex construct demonstrated by the fact that agricultural improvements have been shown to increase water consumption to be classed as efficient in several studies (Lankford, 2012; Kuper *et al.*, 2017; Bahinipati & Viswanathan, 2019; Balasubramanya & Stifel, 2020; Lankford *et al.*, 2020). For example, highly subsidised micro-irrigation techniques, which include drips, foggers, and sprinklers, are often seen and popularised as a water saving system with increased agriculture production (Gleick, 2010, p. 21302; Sowthanya & Shanmugam, 2019). Thus, water efficient, micro-irrigation systems are highly subsidised (up to 90% of the cost) in India and in the study area by the state government under the *Krishi Bhagya scheme* and *Pradhana Mantri Krishi Sinchayi Yojane Watershed Development* (Niti Aayog, 2018, p. 118; Government of Karnataka, 2021). Similar types of subsidies on micro-irrigation systems are reported in other groundwater based agricultural regions around the world (Closas & Rap, 2017; Kuper *et al.*, 2017; Sowthanya & Shanmugam, 2019). There is scope for further extension in India because the average irrigated area covered by micro-irrigation systems is around 10% of the total irrigated area, far less than the other countries (Niti Aayog, 2018, pp. 118-120). The micro-irrigation techniques reduce water consumption at the crop level, energy and labourer costs (Gleick, 2010, p. 21302; Niti Aayog, 2018; Sowthanya & Shanmugam, 2019; Balasubramanya & Stifel, 2020). However, a note of caution is that some studies have shown that micro-irrigation systems supported by subsidised energy and groundwater use (Pfeiffer & Lin, 2014; Closas & Rap, 2017; Kuper *et al.*, 2017; Balasubramanya & Stifel, 2020) may lead to increased overall water consumption because of agriculture intensification and groundwater overexploitation to meet the irrigation demands leading to increased salinity and groundwater pollution. Furthermore, overexploitation of groundwater can affect water availability during the dry seasons in this coastal region, which can cause long term issues such as seawater ingress and groundwater pollution from other geogenic and anthropogenic activities, as reported in other parts of India (Patel *et al.*, 2020).

However, most farmers in the study area still rely on water from TWM systems, including *suranga*, to feed their irrigation network supported by drip systems. An irrigated system, in this case, is a farmstead irrigated by the available water resources, which means groundwater cannot be over abstracted because of limited water availability and self-regulation through natural compunction in use. Therefore, using water efficient irrigation systems in this context may bring benefits to the farmers without severely harming the groundwater level. However, the increasing trend of using borewell systems to feed the water efficient irrigation network, like other parts in India and the world, for agriculture can also be seen in the study area, which is a cause of concern and adds to the complex debate around irrigation efficiencies, as suggested by Kuper *et al.* (2017), Balasubramanya and Stifel, (2020), and Lankford *et al.* (2020).

8.4.2 Structure and function

Simple design, structural flexibility, functional adaptability, and affordability are the key characteristics of TWM systems found in India (Singh, Dey *et al.*, 2020; Singh *et al.*, 2021) and other parts of the world, especially gallery filtered tunnel systems (Ron 1985, Yechezkel *et al.*, 2021 Palerm-Viqueira, 2004). Similarly, *suranga* follows a basic tunnel design and structural flexibility approaches to make *suranga* affordable and prominent in the study area. The structural reliability of *suranga* is good because of the gradual hardening quality of laterites when exposed to air because of the high iron content in laterite soil (Buchanan 1807; Aleva & Creutzberg, 1994; Schellmann, 2017). This structural reliability allows for flexibility and improvisation in design even when constrained by local geography and geology, allowing farmers to safely excavate a pragmatic, bespoke *suranga* with a good water source inside the tunnel. Such water resource development often relies on a combination of trust in the structural properties of the tunnel and the location for digging, which is supported by the accumulated social knowledge and cultural capital found in the community, as seen with the tank irrigation systems in India (Mosse, 1999, Shah; 2008). This, in turn, makes it possible for farmers to acquire an agency that allows them to transform their small farm units by adding new water sources by building *suranga* to grow a greater variety of crops or increase the yield of existing crops, thereby improving their diets. Thus, constructional flexibility and improvisation allow otherwise vulnerable farmers to obtain a maximum yield with minimum financial commitment and effort. Therefore, the design, excavation process, and water use process of a *suranga* have adapted and improvised over time and are part of a comprehensive evolution process of agriculture and the community in the study area, which historically led to the development and transformation of *suranga* and other TWM systems on terraced farmers to support subsistence agriculture and cash crops. Furthermore, the flexible design approach supported by technological advancements have facilitated the range of adaptations in *suranga* design, construction, and usages to minimise water loss inside the *suranga* throughout. Similar advancements and adaptations have been noticed in other TWM systems such as the *bisses* mountain irrigation system in Switzerland (Crook & Jones, 1999; Crook, 2001), *qanat* systems in the Middle East (Stiros, 2006; Lightfoot, 2012; Mahan *et al.*, 2019), and the *niqba* in Israel (Ron, 1985; Yechezkel *et al.*, 2021).

8.4.3 (Geo) hydrology of *suranga*

In this study, data were collated to better understand the hydrology and geohydrology of the *suranga* system because none of the previous studies on *suranga* had so far focused on either and in trying to address issues of sustainability, it is necessary to estimate the long term availability and security of water to farmers using *suranga* (Prasad *et al.*, 1991; Basak *et al.*, 1997; Nazimuddin, & Kokkal, 2002; Suseelan, 2008; Tripathi 2009; Balooni *et al.*, 2010). The discharge rates from five different *suranga* showed a positive association with seasonal rainfall patterns in the study area, such that during the dry seasons, discharge from *suranga* decreased and increased following the onset of monsoon in the study area. This demonstrates a natural compunction in water availability during times of seasonal scarcity, which then regulates use because *suranga* self-regulated by gravitational flow, naturally reduce flow during times of groundwater scarcity. *Suranga* thus only returns to full flow when precipitation recharges the perched aquifer. Trenches, recharge pits, ditch and furrow systems are constructed on the crest of hills to capture rainfall, have increased discharges in *suranga* and serve to recharge the aquifers. Similar practices to increase rainfall infiltration and groundwater recharge have been observed in other parts of India (Dutta & Dan, 2020; Muppidi *et al.*, 2020; Veeranna & Jeet, 2020; Alam *et al.*, 2021) and other parts of the world (Haq, 2017; Khadra & Stuyfzand, 2019; Ashiq *et al.*, 2020). Therefore, it seems that *suranga* harvest water from small scale, discrete aquifers perched at shallow depths in laterite profiles. Similar, shallow depth, perched aquifers in laterite soil have also been reported in other parts of the world (Ollier & Galloway, 1990; Eggleton & Taylor, 1999; Cable Rains *et al.*, 2006; Bonsor *et al.*, 2013). These discrete perched aquifers are discharged during the dry period and are recharged during the wet season by rapidly infiltrating rainwater because of their shallow depths (Chapter 6). Inside the subsurface, the excess water from a perched aquifer is percolated further down to recharge confined aquifers situated at deeper levels. Thus, perched aquifers are mostly not directly connected to deeper aquifers, and that is why discharge from *suranga* is often not affected by the presence of borewells. However, a

perched aquifer may be connected to deeper aquifers, and in these cases, the water availability in *suranga* may get reduced by the presence of borewells.
Furthermore, tapping water from perched aquifers in large quantities may affect the recharge in deeper aquifers in the long term. Therefore, during the rainy seasons, the water from *suranga* and other water resources can be used to recharge the deeper aquifers; otherwise, the uncontrolled runoff quickly flows through to the lowlands and eventually the sea. Therefore, it seems logical that attempts are made to capture better and store the excess water of the monsoon to recharge groundwater during this time of no water demand for agriculture. These results are crucial and support the perched aquifer hypothesis to explain the hydrology of *suranga*, which answer the unique existence of *suranga* in the study area. This hypothesis also explains the reason for seasonal fluctuation in *suranga* discharge.

8.4.4 Ecological impact of *suranga*

Another aspect of sustainability is the ecological impact of the *suranga* system may have on species composition and communities (Wiek & Larson, 2012; Siebrecht, 2020). In this biodiversity rich region of the Western Ghats (Chitale *et al.*, 2015; Sarvalingam & Rajendran, 2016; Arumugam *et al.*, 2018; Chitale *et al.*, 2020), the water rich humid *suranga* appears to support ecological diversity (Mini & Razeena, 2013) by providing new habitats and water for a variety of flora and fauna. Moreover, abandoned dry *suranga* can also provide a vital niche ecosystem for flora and fauna. The species identified inside *suranga* in this study have been provided with their scientific names in section 5.6. Fauna within *suranga* consist of root systems, lichens and moulds of greater interest are the water indicator species found in the recharge catchment areas of *suranga.* A variety of reptiles, snakes, animals, and insects are found inside *suranga*. Colonies of two different species of small sized leaf nosed bats (*Hipposideros apeoris,* and *Hipposideros ater*) are found inside *suranga* (see section 5.6). Malaria and chikungunya have been endemic in the study area, and these bats predate on insects such as mosquitoes (Srinivasulu *et al.*, 2015), which can be the vector of Malaria and chikungunya. However, this serendipity is negated as bats can also be a vector of some zoonotic viruses, such as the Nipah virus (Wacharapluesadee *et al.*, 2013; Moratelli & Calisher, 2015; Plowright *et al.*, 2019).

Although *Pteropus mediusi* is the primary vector for the Nipah virus in south India, serology studies have suggested that some other bats species found in south India have shown Nipah exposure, including the *Hipposideros ater* that roosts inside the *suranga* (Plowright *et al.*, 2019). Moreover, Rat snakes (*Ptyas mucosa*) are encouraged to keep rodent numbers down, but they are predated on by King Cobra (*Ophiophagus hannah*), which can also threaten the health of farmworkers. Farmers are more typically vulnerable to pit viper (*Trimeresurus gramineus*) and Indian cobra (*Naja naja*) bites whilst working in their fields. These bites have been treated up until recently using traditional Ayer Vedic herbal medicines by a local doctor, who must now, because of health and safety regulations and concerns over liability, only use recognised medical vaccines. However, there is no reference and record of snakebite incidents related to the *suranga* systems in the available literature on *suranga* and other TWM systems (Prasad *et al.*, 1991; Basak *et al.*, 1997; Nazimuddin & Kokkal, 2002; Tripathi 2009; Balooni *et al.*, 2010). Overall, it seems that the *suranga* system supports and possibly increases biodiversity in the study area, which is important as the region is part of a designated global Biodiversity hotspot. Quite possibly, broader conservation movements to protect genetic diversity and ecosystem level in the Western Ghats may indirectly protect the environments of the foothills of the Western Ghats where *suranga* are found, which may, in turn, strengthen their chances of survival and ensure continuity of use.

8.4.5 Water rights and *suranga* ownership

The water rights in the study area are a mix of riparian land ownership for the flowing water resources such as rivers and streams; and a minimal number of historically priority based water rights for storage ponds and shared dug well (Scott & Coustalin, 1995). For example, stream and rivers, which can be seasonal, often have riparian rights. In comparison, dug wells and ponds are used under priority based agreements. Water rights for some shared water resources, such as a shared pond or a dug well, are quantitative and allocated using a fixed usage timing and days in the study area. There are no static water bodies; hence littoral rights are not in practice in the study area. The evolution of water rights in the study area seems to have occurred over generations, with complex social and political issues emerging, such as water demand and availability, agriculture related issues, population increase, and the fragmentation of joint families and water resources. The water rights in the study area, often acknowledged by property law, are mainly characterised by appurtenance, which means the water rights are based on ownership of the land upon which water rests or flows. Hence water rights are associated with the property or land and are transferrable with the sale or change of the land ownership. However, some examples of prior-appropriation based water rights from the past were the primary cause of water issues in the study area. The idea of prior-appropriation based water rights deals with water shortages on non-riparian land (Gopalakrishnan, 1973; Scott & Coustalin, 1995). Such rights were decided with mutual agreements during the fragmentation of a joint family so that new families could use water for daily needs and non-riparian lands, using narrow water channels (locally called *khani*) passing through other users. These water rights and usages are often recorded in land documents and managed by the users. However, these types of water rights caused issues with time because water abstraction rules were not honoured after some generations and caused water issues among the users, including the neglect caused by the drawback of community management of these systems.

Individual families owned the 700 *suranga* surveyed. The *suranga* systems are private water resources owned by the families; therefore, the *suranga* water is rarely shared for agriculture, except for domestic usages in a minimal number of cases among the nuclear families formed by a joint family division or on humanitarian reasons. Thus, individual rights in suranga have pre-eminence, and there is no right of withdrawal, as usually seen in centralised water systems where users can apply to get a right of withdrawal after paying a fee to the provider. In the case of *suranga*, management, exclusion, and alienation rights are vested to the owner, unlike centralised systems where these rights are with the state (Agrawal & Ostrom, 2001, pp. 489-492).

There have been no community managed *suranga*, unlike other community water harvesting structures like *katta* (seasonal check dam), wells, ponds in the study area and the tank system found throughout southern India (Agarwal and Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008; Sutcliffe *et al.*, 2011). Like borewell systems, *suranga* water rights are not based on the concept of water as a community resource because these water sources are physically situated anywhere within a land distribution, not necessarily adjacent to the property as in riparian water rights from rivers and streams. The land is fragmented in the joint family division, and associated water rights are also clearly divided. In several examples, families shared a common water source by rationing water on an hourly or daily basis in turns, and users also had a proportional annual maintenance obligation. These water rights are inherited and transferable. If the owner of a divided family decides to sell its property to a third party, then the water rights of the family were/are also transferred to the new owner irrespective of inheritance. It provides an example where a private *suranga* (or a well) may be treated as a community *suranga* over time, and new generations, but such cases are rare and up to present exceptional. Therefore, the set of eight design principles, shown below, often observed in successful community managed systems, reported by Ostrom (1990, p. 90) (see section 2.2), are mainly absent at the community level in the *suranga* systems, except clearly defined boundaries.

1. Clearly defined boundaries
2. Congruence
3. Collective choice arrangements
4. Regular monitoring
5. Graduated sanctions
6. Conflict resolution system
7. Minimal recognition of rights to organise
8. Nested enterprises

Moreover, private ownership provides another reason for the popularity of the *suranga* that it could be made and managed privately on a small scale, which indirectly avoided water issues among families emanating due to water scarcity, unlike shared wells and other community water sources (Crook *et al.*, 2015). Therefore, people often try to avoid water conflicts by not extending their *suranga* into neighbouring properties. However, occasionally *suranga* are found extending through farms with informal or oral authorisation from the neighbour. The small command area, lack of community involvement and water sharing (Narayanamoorthy, 2007) from *suranga* mean that there have been nearly no reports of issues arising from *suranga* and their management, which explains the lack of formal conflict resolution systems and regulations found in many other traditional irrigation systems (Agarwal and Narain, 1997; Dietz *et al.*, 2003; Narayanamoorthy, 2007; Megdiche-Kharrat *et al.*, 2020). However, a small number of water disputes among the farmers were noticed during the field survey, mainly caused by unfair water exploitation from shared water resources such as dug well, pond, or streams passing through private land. Traditionally, issues, including water disputes, were resolved by mutual agreements within the communities during local meetings. However, if no agreement could be reached, civil courts settled disputes with the first evidence, dating back to 1875 in Manila village from an agricultural map (Figure 4.13). Water disputes being taken to local civil courts are not common but are used as the final resort to find water conflicts. There are no formal conflict resolution systems associated with the system, making it unique and easy to manage, unlike other community managed TWM systems (Vincent, 1995; Agarwal and Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008; Megdiche-Kharrat *et al.*, 2020). It is debatable if the absence of a governance and conflict resolution systems increases or decreases the sustainability of the *suranga* system because redundancy of the community aspect in a small scale, individually managed *suranga* system minimises any potential conflict scenario and thus improves sustainability. On the other hand, the presence of community, governance, and social aspects in a TWM system may strengthen the system's sustainability (Ostrom, 1990; Agarwal and Narain, 1997; Mosse, 1999; Agrawal & Ostrom, 2001; Megdiche-Kharrat *et al.*, 2020).

8.4.6 Intervention or no intervention?

Presently, *suranga* are not officially recognised as a specific water resource by the government. Thus, *suranga* are not included in the Agricultural census or census of Minor Irrigation schemes of the Government of India. Therefore, neither a loan nor grant is awarded for the construction of *suranga*, nor permission is needed to construct a *suranga* by the local government. However, recent calls for external government intervention, as suggested by a study on *suranga* (Shaji *et al.*, 2020), are rejected because bureaucratic intervention and any unwanted structural changes may detract from the design simplicity and cost effectiveness (Narayanamoorthy, 2007) of the *suranga* system for low income families, as has been seen with other TWM systems in other parts of the world, for example, small scale irrigation system in the mountain region of Tajikistan (Dörre & Goibnazarov, 2018). There is a moral and ethical case for arguing that farmers are better served by retaining this simple approach to adoption that supports human agency, independence and autonomy and is opposed to succumbing to the 'glamour' and clammer for new technical responses, as also observed by Linneck *et al.* (2015), often imposed from above and with suspect motivations for implementation that may have less efficacy and be less cost efficient, especially for the already marginalised communities and BPL families in the study area. For example, there have been suspicious institutional responses from the CWRDM in the form of reports (Prasad *et al.,* 1991; Nazimuddin & Kokkal, 2002) suggesting technical interventions, such as capping *suranga* entrances (Shaji *et al.*, 2020) that appear to have little technical justification as there is not a recognisable problem with entrance collapses. These recommendations appear to be more about complicating existing simple structural and operational characteristics, generating money and creating a financial dependency amongst poor farmers, which on the face of it appears unethical and immoral and may also affect the present economic and ecological sustainability of the *suranga* system.

8.4.7 Technology transfer

Technology transfer of TWM systems has been seen in the past in arid and semi-arid regions. For example, the *qanat* spread gradually from the Middle East to the other parts of Arabia, and later to the east, with the spread of Islam, and trade primarily through the Silk Road (English, 1968; Boualem & Rabah, 2012; Mokadem *et al.*, 2018; Mahan *et al.*, 2019; Megdiche-Kharrat *et al.*, 2020). Later, during the Roman and Arabian expansions, *qanats* spread towards the west to North Africa, Spain, and Sicily (English 1968; Wulff, 1968). In America’s ancient diversion irrigation systems in South America have also been transferred or regenerated in places like the Colca valley (Treacy, 1987; Branch *et al.*, 2007). More recently, another old (10^{th} century) but extant slope offtake diversion system, the *bisse* system found in the Valais canton of Switzerland (Megdiche-Kharrat *et al.*, 2020), but a model used throughout the European Alps, was transferred to the Himalayas by Swiss Aid in the 1990s (Crook *pers.comm*.). The transfer of *suranga* technology to the villages in the study area may have happened through the conduit of oral communications. However, in two examples, *suranga* knowledge was transferred to the north of the study area more informally because of social events such as marriage, travel, and tourism. The results from this study suggest that the three vital hydrogeological characteristics of *suranga* are: highly weathered soil profile that allows fast rainfall infiltration through weathered soil layers and allows the formation of shallow depth (or perched) aquifers; high rainfall that recharges the perched aquifers; and undulating topography that allows easy excavation of these tunnels. The weathered laterites soil profiles also allow structural stability to the tunnel because of the hardening property of the exposed laterite layers. Therefore, *suranga* technology can be transferred to other parts of the world with similar climatic and geographical conditions.

8.4.8 Overall quality of life

As explained in Chapter 1, water scarcity can negatively affect the overall quality of life for individuals and communities, leading to poverty, hunger, decreased physical and mental health, decreased social and economic independence, and affecting women's education and empowerment (WaterAid, 2017, p. 7; Yadav & Lal, 2018; Kumar, 2019; UNDP, 2020, p. 65; Cai *et al.*, 2021). The *suranga*, being an economical water resource, has contributed to providing clean drinking water to low income families by increasing water availability in their homestead for their basic needs and water for irrigation in the remote villages and hillslopes without exogenous support in the 20th century. Water availability for safe drinking water and sanitation ensure good health and development (WHO, 2009). The everyday heavy water lifting burden on women and young children in the families decreased significantly, as, in the past, they would have to walk long distances to fetch water from shared water sources, while adult male members of the family would go to work in the fields. Now children could join schools rather than helping their parents to collect water for drinking and household activities, which seems to have improved the job opportunities beyond agriculture for young people and socioeconomic conditions of the families in the study area and have increased out migration and agriculture abandonment (Kumar & Krishna, 2015) resulting in loss of social knowledge of agriculture and water practices within the community. Moreover, the *suranga* helped low income farmers and farm workers by ending their reliance on the wealthy farmers and the local government for their drinking water needs, which eventually made them water independent, helped them start subsistence agriculture on their lands, and eventually raised the economy of low income families, as has happened in other TWM systems in India and worldwide. For example, the *zabo* farming system has been helping communities to generate income with the help of traditional hill agriculture and alleviate poverty in northeast India using perennial springs and bamboo pipe drip irrigation system for areca nut plantations (De, 2021). Likewise, tanks in parts of India (Agarwal & Narain, 1997; Mosse, 1999; Narayanamoorthy, 2007; Shah, 2008), *qanat*s in Middle Eastern countries (Dahmen & Kassab 2017; Mokadem *et al.*, 2018; Mahan *et al.*, 2019; Yechezkel *et al.*, 2021), the *suranga* has been indirectly instrumental in alleviating water scarcity and poverty in the study area. The water security achieved from *suranga* has allowed the families to improve their overall quality of life in the study area. Therefore, the *suranga* systems have contributed to achieving the United Nations Sustainable Development clean water and sanitation (goal 6) in the remote villages, without direct support from local government agencies. In addition to this, *suranga* have further contributed towards meeting the sustainable development goals by indirectly helping to alleviate poverty (goal 1), promoting good health (goal 3), supporting education for children (goal 4), and empowering women and gender equality (goal 5) in the study area (Fuso Nerini *et al.*, 2019; Moyer & Hedden, 2020).

In summary, results from this study support the view that the *suranga* system, in conjunction with other water traditional water harvesting strategies such as *katta*, *madaka*, and open well, has been instrumental in securing potable water for domestic and water for irrigation purposes, especially for low income groups without any outer intervention (Doddamani, 2007; Balooni *et al.*, 2010). Thus, the *suranga* systems have managed to provide potable water supplies to the marginalised communities in the study area, which shows the humanitarian aspect and is one of the goals of sustainable development (Fuso Nerini *et al.*, 2019; Moyer & Hedden, 2020), which can be important for several non-governmental water charities in south India such as the DHAN Foundation, and Arghyam, working towards eliminating fundamental water scarcity in south India. Table 8.4 attempts to summarise the key strength and weakness of the *suranga* system concerning its sustainability components. This exercise will also allow for a more nuanced understanding of sustainable development in the study area linked to socioeconomic stability, ecological integrity, and to sustain life (Rockström *et al.*, 2014; Singh *et al.*, 2021) and aids to present a visual summary of the sustainability of the *suranga* system based on sustainability indicators.

Table 8.4: A summary of strengths and weaknesses of the *suranga* system.

Sustainability components	Strengths of the *suranga* system	Weaknesses of the *suranga* system
Structural and functional	Highly adaptable design Flexible excavation approach	Laborious process Risk involved
Environmental and ecological	Self-regulated water discharge Suitable for drinking and domestic usages Creates natural habitat for a variety of flora and fauna Maintains biodiversity in a biodiversity hotspot and potentially increases biodiversity	Only successful in discrete geographical conditions Limited water yield Season variation in water yield Not sufficient suitable for large scale agriculture Vulnerable to surface pollution
Social and cultural	Privately owned and managed Highly popular in the society Solved water scarcity issues Promotes water self-dependency for low income families	No direct social and cultural association Non collaborative approach No institutions and entitlements aspects
Economic benefits	Low construction cost Low maintenance cost Available to even the marginalised families	Low earnings for the *suranga* worker

The use of overlapping temporal scales in defining sustainability had been a significant omission in past definitions of sustainability (Robinson, 2004; Kuhlman & Farrington, 2010; Holden *et al.*, 2014; Saunders & Becker, 2015; Marchese *et al.*, 2018). Thus, for example, most TWM systems may become redundant because they could not meet the high water demand of the present world (Singh *et al.,* 2021) compared to the last century (see Chapter 1).

The *suranga* system seemed to be established with sustainable principles, and as a result, grew significantly in the study area in the 20th century in a small geographical region under the parameters of a low population, low economic levels, and limited alternatives water resources. However, because of the projected high water demand caused by the increasing population and the intensification of agriculture in India by 2030 CE (see section 1.1), the *suranga* may not match the water demands in the study area. Moreover, as an alternative to the *suranga* and other TWM systems, the readily available, latest pumping based groundwater abstraction systems, such as borewell, have provided an easy alternative to match the farmers' growing water demands and governments. However, as a reminder, *suranga* discharge varied between 1.10 to 26.17 m^3/day in five different *suranga* in the study area over a year. These figures seem more credible than the higher figures suggested in a recent study (Shaji *et al.*, 2020), which reported maximum and minimum discharges between 2.2 to 691 m^3/day from a survey of 26 different *suranga,* as they seem unlikely given the average dimensions of *suranga*. However, the dug well discharge rates varied between 30 to 250 m^3/day, and wider borewells (tube wells) produced between 260 to 430 m^3/day in the neighbouring state of Tamil Nadu (Karunanidhi *et al.*, 2021b). Thus, in a present world scenario with increasing water demands, TWM systems, such as *suranga,* may not be able to cope with the high water demand at a larger scale consistent with irrigation, as has been suggested for *qanat* in Iran that need upscaling and adaptation coupled with increased collaborative practices to meet increased demand for water (Manuel *et al*., 2017; Ghorbani *et al.*, 2021), which can often be a trade-off between environmental and economic sustainability.

Furthermore, a small number of families did use well and borewell for their drinking and household usage because their *suranga* was not successful, which shows the discrete nature of *suranga*. Therefore, this study suggests that *suranga* are not a single solution for all water issues, but the *suranga* are best suited for domestic water supplies and small scale farming in specific geographical regions. There are not many largescale farmers with enormous water demands in the study area, but where they exist, borewell is favoured. Thus, the *suranga* systems may continue to be sustainable at least on a small scale in the near future, such as used for domestic and small irrigations requirements or in collaboration with other TWM systems, as it was seen with several small farmers in the study area, but upscaling of the *suranga* system is unlikely to happen as an alternative to borewells which are gradually increasing in the study area.

So far in this chapter, it has been seen that the resilience and the sustainability of a real life embedded water system, such as the *suranga*, are part of a community with complex and highly intertwined environmental and socioeconomic components, where a minor change in any of its components can significantly change the dynamics of the system. However, Figures 8.7 and 8.8 attempts to summarise the sustainability response of the *suranga* system based on sixteen relevant sustainability indicators up until the end of the 20^{th} century and until the mid-21^{st} century. The green coloured components indicate a high level of sustainability, while yellow signifies issues with sustainability, and non-coloured indicators were found to be redundant for the *suranga* system.

Figure 8.7: Sustainability wheel for the *suranga* system until the end of the 20th century.

Figure 8.8: Sustainability wheel for the *suranga* system until the mid-21st century.

Comparing, Figure 8.7 and 8.8, the institutions and entitlements and collaborative capacity indicators were missing in the *suranga* system in both the figures because *suranga* are small scale privately managed water resources. Moreover, the *suranga* system appeared sustainable in the 20th century, with only sustainability issues related to water harvesting and collection efficiency and reliability and safety indicators (Figure 8.7). However, the number of sustainability issues are likely to increase in the first half of the 21st century (Figure 8.8) because four more sustainability indicators have started to show signs of not being sustainable, which are related to water quality caused by increasing surface pollution, increasing construction costs, limited water availability for increased agriculture, and decreasing social learning. Besides these, decreasing use of *suranga* compared to the easy availability of alternative borewell technology and outward migration is also likely to decrease the popularity of the *suranga* system within the community. However, only water harvesting and collection efficiency are likely to improve between the last century and in the present phase, with the existing *suranga* because of PVC pipes and improved water storage structures motivated by the increasing water demands and climate change. Thus, overall, the present state of sustainability of the *suranga* system is deteriorating gradually.

8.5 Limitations of the study

The research process is never perfect, and lessons are learnt through inductive reasoning as things go wrong or are imperfect and the limitations are recognised. Whilst it is acknowledged that there are many minor flaws with the methodology and methods used during this research, this section concentrates purely on the more substantial issues that arose over the course of this research.

Accessing archival documents at the various state archives in India, with the notable exception of the Goa state archive, was incredibly time consuming and challenging because of the bureaucratic hurdles that had to be overcome coupled with the lack of information on archive guides, catalogues and manuals and because the original materials consulted did not always follow conventional European catalogue series, despite many of these being colonial archives. Thus, it cannot be ruled out that there is a document out there that lists or describes *suranga* from an earlier age or offers a different view or perspective than that taken here. It is hoped that as these archives become increasingly digitised, they also become more systematically catalogued, although there is always the danger that some documents will be lost forever in this process. This will also then allow replication and repeat readings and fresh interpretations of the data to check that the conclusions from this work are valid.

Another limitation of the project was created by the language barrier faced. *Kannada* and *Tulu* are widely spoken languages in the area, and a community also uses a dialect known as *Karadi* among the community members. The researcher could only speak and understand Hindi and English languages. Thus, there was a language barrier between the researcher and the locals. Therefore, a few local people, who could understand and speak basic *Hindi* or English, helped with the research as local guides to communicate with local people and farmers and through these people, it was possible to negotiate meanings; however, this process is not perfect, and errors may have been made in interpretation.

Another limitation was a relative lack of previous research studies or any direct documentation on the *Suranga* water harvesting system other than inventories produced mainly by the Centre for Water Research Development and Management (CWRDM) Kozhikode. However, this work also drew on a current *suranga* database developed for a Leverhulme Trust funded project (RPG 392) whilst the researcher worked as a research assistant on that project. This exploratory study uses data from the survey of 215 *suranga* user households, traced by a purposive snowball sampling approach. This meant that no control group of non *suranga* users was included in the survey, thus possibly introducing some bias and questions about the representativeness of this study. Any future study would benefit from a more representative and randomized survey of all farmers in the region.

A further limitation of this work is that in a traditional groundwater hydrology study, the slug test and pumping tests to monitor groundwater levels would have been practical to explore the aquifer characteristics in the study area. However, it is often difficult to access the government managed observation borewells situated in the broader region. Moreover, self-financed observation of local borewell levels could have been an option, but it would require long term monitoring by locals, but it was impossible to find and train non-experts, who would be willing to monitor the groundwater levels for a minimum of one year which is the minimum timeframe needed for this type of study. Therefore, an alternative approach was taken as a compromise in which radiocarbon dating of various subsurface water samples was used to explore the groundwater provenance. They provided valuable insight into the possible sources of groundwater but were limited in their scale and scope by the cost of processing these. Therefore, the new hypothesis about *suranga* geohydrology offered here can only be tested using the slug and pump tests.

Sampling size was another limitation of the discharge measurements used in this study. This study monitored the discharge data from five different *suranga* over a hill catchment over a year, and it was partly helped by a local student, who was trained to follow the measurement protocol previously used by the researcher. Thus, the small number of calculations also limits the generalisation of the discharge data and any possibility to calculate a meaningful annual water budget of a farmstead in the study area. Similarly, a certified local laboratory was used to process water quality tests, which also limited the number of samples and types of analysis that were used for testing because of financial reasons. Whilst there was no evidence of salinity and sodicity occurring in farm soils, it cannot be ruled out that this could be a problem for farmers in the future, so a greater range of tests to cover these parameters would have helped to identify this.

Finally, the remoteness, undulating geography, sparse distribution of farmstead in these hills limited the access to produce a comprehensive database of the *suranga* users in the study area. However, this exploratory study provides a foundation for future studies on the *suranga* system, as discussed in the next section.

8.6 Recommendations for future work

As with all studies of this type, despite best efforts to cover all bases, there are still gaps in knowledge that need to be filled. This study was timely because of increasing groundwater issues and water scarcity in India, and there was a need to document and evaluate the future of *the suranga* system because the demand for new *suranga* is decreasing. In addition, the skills of constructing *suranga* are gradually vanishing mainly because of migration and the increasing popularity of borewells.

Sanitation: This study did not focus on sanitation issues, but surface sanitation and leakage issues caused by faulty septic tanks can contaminate *suranga* water sources situated in the lower elevations. Thus, large scale water quality tests are also recommended for the water resources used for drinking and household usages to monitor the pollution level in *suranga* and other TWM systems for nitrate nitrogen concentrations and bacterial contamination in the water post and pre-monsoon seasons.

During this study, it was suggested by various informants that other *suranga* could be found in different *taluks*. Future work would look to locate the example of *suranga* technology transfers that could not be traced and verified in this study. This would then form the basis to produce a comprehensive and shared database of the *suranga* systems and their users in the region. In addition, a more comprehensive database will allow for better determination and refinement of the transferable principles of *suranga* that maybe offer sustainable water solutions to other drylands of the World. The *suranga* system can provide a low cost and flexible design approach to water alternative in underdeveloped regions.

This project has developed a brand new hypothesis about *suranga* geohydrology, to explain the source of water in a *suranga*, which needs to be tested. This study suggests that although most *suranga* seems to harvest from shallow depth aquifers, a small number may harvest water from the phreatic zone in a laterite hill. Thus, to improve understanding of the groundwater characteristics of subsurface shallow and deep aquifers in the study area, soil resistivity tests and periodic longitudinal pumping tests, and slug tests would be carried out. Moreover, it would be advantageous to repeat the radiocarbon dating tests for the same samples for temporal analysis of groundwater moment and evaluate groundwater abstraction and recharge rates in the study area, which can help develop policies for better management of groundwater resources in the study area.

In addition to these ideas, it is crucial to monitor annual discharges from a more significant number of *suranga* than was possible in this work, spread over a larger area to better understand the spatial and temporal distribution of water and identify areas of potential scarcity in the study area. These studies can significantly improve the hydrological understanding of the *suranga* and other groundwater systems in the region, which can be used to design future policies and interventions to minimise the impact of seasonal water scarcity in the region.

Finally, the *suranga* system provided a relatively new habitat, similar but different from natural caves to a diverse range of flora and fauna found in the biodiverse hotspot of the Western Ghats. Thus, future studies should identify population numbers at a species level for some of the arachnids and insects found in *suranga* and the different slimes, moulds and lichens may be rare and deserving of further investigation. Further work on the bat colonies found in *suranga* would also be beneficial, especially identifying their role in keeping the number of vectors down that carry the infectious disease for humans and animals, and their role in contaminating drinking water supplies, or enriching irrigation water supplies from *suranga*. It is likely that new species might be found in *suranga*.

Chapter 9 – Conclusion

This project used a hill irrigation analytical framework adapted from Vincent (1995), which incorporated a mixed methods methodology to study the *suranga* system found primarily in southern Karnataka and northern Kerala in the foothills of the Western Ghats and answer the research question

Aim

To investigate the resilience and sustainability of *suranga* irrigation in the Western Ghats of India.

In order to do this, five objectives were followed, which were:

1. To critically analyse the origin and history of *suranga*
2. To critically assess the spatial distribution and number of *suranga*
3. To critically evaluate the design principles, governance, and management of the *suranga* system
4. To critically assess the key hydrological and geohydrological characteristics of *suranga*
5. To critically examine the socioeconomic and political context that *suranga* operate in.

The conclusion succinctly outlines how well each of these objectives were met by outlining the key results from each objective and then makes a final judgement about the success of the project based on how well the main aim was addressed.

Objective 1

This study has proposed a new *suranga* origin theory which is counter to all earlier interpretations of their history linked to the *qanat,* which suggest that the system was born organically sometime in the early 20th century as a response to a new need for water to sustain human life in these recently peopled remote hilly environments. The development of *suranga* has followed three main phases: inception, growth and consolidation. From a piecemeal slow beginning in the early 20th century, through word of mouth, the system developed. Land fragmentation, terraced farms, and agricultural intensification further popularised *suranga* and led to growth in their use during the mid-20th century. The *suranga* technology was also transferred to two neighbouring regions situated in similar geographical and topographical regions situated on the western side of the foothills of the Western Ghats in India in the late 20th century. In the core area of DK and Kasaragod, consolidation has occurred, and the rate of new builds has slowed significantly, suggesting a level of saturation has occurred in the research area.

Objective 2

The building of a comprehensive database of all the *suranga* in the study area and the neighbouring region was only partly met because of the broad distribution of *suranga* in this highly remote and undulating geography, where access was difficult, making it impossible to cover all the areas in the provided time frame for the research. However, by combining the data from this study of 700 *suranga* owned by 215 individuals to previous work, a figure of 3000 *suranga* is arrived at, but this is still thought to be an underestimate of the actual number of *suranga*. The fieldwork experience suggests that surveying all the *suranga* in the study area may not be possible and practical without high level institutional support, such as the state and federal governments received during the agricultural and minor irrigation census in India.

Objective 3

The key design principles of the *suranga* have been found to be:

1. Simple tunnel design
2. Structural stability
3. Flexible adaptation in shape to environmental challenges
4. Simple and replicable water capture and gravitational conveyance from tunnel systems based on gallery filtration
5. Natural filtration leading to good water quality

A key characteristic of the governance and management of *suranga* was that they are small scale and predominantly private and therefore managed uniquely using different and bespoke practices for each *suranga*. The *suranga* system, therefore, did not follow the community model of management that is typical in many other TWH systems in hilly and mountainous regions, which cautions against applying a universal adoption of cooperative principles in the hill irrigation model. The *suranga* are owned and managed at the individual family level, which is suited to the micro catchment hydrology that small farm units fit into and limits the need for complex conflict resolution systems.

Objective 4

This project presented a brand new hypothesis that *suranga* mainly harvest water from perched aquifers or shallow depth aquifers, commonly formed in weathered soil profiles known as laterites. The overall high precipitation received during the monsoon recharges these aquifers annually. This study recorded *suranga* discharge in the range of 1.1 m^3/day - 26.2 m^3/day in five different *suranga* over a year. Landowners use and divert water from their *suranga* under gravity into a cascading series of ponds that store water that often gets conveyed to different fields using either open channels or an underground network of pipes using a mix of drips, sprinklers, sprays, and hose irrigation. The most significant advantages of harvesting water from minor scale aquifers through *suranga* or any other TWM systems are that water supplies are self-regulated and cannot be over abstracted. This is in marked contrast to borewell technology that can unsustainably harvest water from deeper aquifers, which takes a significant number of years to recharge until they are completely exhausted or become unsuitable because of contamination caused by over-abstraction and other anthropogenic activities. This also means, the majority of the *suranga* water supplies theoretically should not be affected by any decrease in groundwater level in the deeper aquifer through the borewell.

Objective 5

It was discovered that the research area constituted a dynamic agrarian community that had gone through various endogenous and exogenous agricultural, social, economic and political changes, which may multiply in their impact in the future. Of these, the most critical social, cultural and political endogenous and exogenous changes recorded were:

Endogenous Influences:

1. Poverty – still a significant number of families below the poverty line
2. Increased access to education and new schools in the research area - upskilling
3. Out-migration to urban areas leading to an ageing population in the research area
4. Growth of cooperatives for cash crops – making farm incomes more reliable and secure
5. Increasing influence by local government and government sponsored research institutions over the direction of farming and irrigation (borewell) – decreasing autonomy and increasing dependency
6. Improved sanitation and hygiene practices in homes supported by increased water availability

Exogenous Influences:

1. Green revolution – farm intensification, increased irrigation,
2. Introduction of borewells and pumps
3. Resilience born from the legal battles around the harm to communities caused by endosulfan resulting in a lack of trust in wider agribusiness – wide scale switch to organic practices
4. Out-migration overseas - remittances – changing farming priorities
5. Regional legal bans- betel nut production
6. Cash crops and global farm product markets – growth in the rubber plantations
7. The increasing influence of National charities and NGOs – e.g. Dhan Foundation

The socioeconomic and political context of the region where the study took place was and continues to be dynamic, presenting different push and pulls factors for local farmers in the community to continue using *suranga*. The closing section draws together the meaning of the results from the five objectives to better address the main aim of the project.

Conclusions towards the main aim of the project

This study avoided the rhetorical pitfall of branding a system either as sustainable or not sustainable because there is no endpoint to sustainability. Instead, it identified various strong and weak points of the system and compared these to available alternatives in the present time. These strong/weak points can swap between strong to weak according to the various reference frames such as time, dimensions, boundaries, and impact of the system. For example, when the population, water demands, and the size of the irrigated area were low, the *suranga* systems was the best available choice for the communities to sustain life in these remote hills. However, under present conditions, the *suranga* system still operates but may soon not be able to meet the increased water demands because of population increase and intensive agriculture, especially when farmers can choose an alternative in the form of borewell technology made viable by technological advancements and improved socioeconomic conditions. However, several low income families still rely on *suranga*, as their sole water resource, with this water preferred to other external sources because it is free flowing, high quality water suited to drinking and domestic use. This trend holds even when families also have a borewell on their property. Hence the *suranga* retain some relevance to farmers because of their flexibility and adaptiveness, which have made them resilient to changes in the past. However, as outlined above, several key endogenous and exogenous pressures may make *suranga* in the study area vulnerable to changes in the future that cause the collapse of the system unless further adaptation occurs. Ironically, the potential for technology transfer to other parts of the Indian subcontinent or, indeed, sub Saharan Africa, rather than the current catchment area, may offer a brighter future for this innovative, original, and humanitarian system.

References

Acharya, V., Halanaik, B., Ramaprasad, A., Swamy, T., Singai, C., & Syn, T. (2019). Transboundary sharing of river water: Informating the policies. *River Research and Applications*, *36*(1), 161-170. https://doi.org/10.1002/rra.3564

Adeel, Z., Schuster, B., & Bigas, H. (2008). *What makes traditional technologies tick? A review of traditional approaches for water management in drylands*. United Nations University.

Agarwal, A., & Narain, S. (1997). *Dying wisdom: Rise, fall and potential of India's traditional water harvesting systems*. Centre for Science and Environment.

Agrawal, A., & Ostrom, E. (2001). Collective action, property rights, and decentralization in resource use in India and Nepal. *Politics and Society*, *29*(4), 485-514. Retrieved 16 July 2019.

Ahi, P., & Searcy, C. (2013). A comparative literature analysis of definitions for green and sustainable supply chain management. *Journal of Cleaner Production*, *52,* 329-341. https://doi.org/10.1016/j.jclepro.2013.02.018

Ahmed, K., Khan, A., Tiwari, S., Habeeb, A., Ahi, J., & Abid, Z. et al. (2007). Impact of household hygiene and water source on the prevalence and transmission of Helicobacter pylori: A South Indian perspective. *Singapore Medical Journal*, *48*(6), 543-549. Retrieved 30 March 2021, from http://www.smj.org.sg/sites/default/files/4806/4806a9.pdf.

Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., & Mohanty, S. (2021). Managed aquifer recharge implementation criteria to achieve water sustainability. *Science of The Total Environment*, *768*, 144992. https://doi.org/10.1016/j.scitotenv.2021.144992

Aleva, G., & Creutzberg, D. (1994). *Laterites: Concepts, geology, morphology, and chemistry*. International Soil Reference and Information Center.

Al-Ghafri, A. (2012). Chapter 6 - Sultanate of Oman. In A. Yazdi & M. Khaneiki, *Qanats in its cradle: Situation of qanat (Kariz, Karez, Falaj) in the World* (1st ed., pp. 191-273). Retrieved 5 June 2019.

Alise, M., & Teddlie, C. (2010). A continuation of the paradigm wars? Prevalence rates of methodological approaches across the social/behavioral sciences. *Journal of Mixed Methods Research*, *4*(2), 103-126. https://doi.org/10.1177/1558689809360805

Alok, A. (2020). Problem of poverty in India. *International Journal of Research and Review*, *7*(1), 174-181. https://doi.org/E-ISSN: 2349-9788; P-ISSN: 2454-2237

Alokhunov, A. (2021). On the study of ancient irrigation systems In central Asia. *The American Journal of Social Science and Education Innovations*, *03*(04), 145-150. https://doi.org/10.37547/tajssei/volume03issue04-22

Andrew, S., & Halcomb, E. (2009). *Mixed methods research in the health sciences* (1st ed.). John Wiley & Sons.

Anna Bhagya Yojana. (2017). Retrieved 24 September 2017, from https://ahara.kar.nic.in/annabhagyyojana.html.

Annual Rainfall Map of India, Rainfall in India. Maps of India. (2021). Retrieved 2 March 2021, from https://www.mapsofindia.com/maps/india/annualrainfall.htm.

Aravinthasamy, P., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K., & Anand, B. (2019). Geochemical evaluation of fluoride contamination in groundwater from Shanmuganadhi River basin, South India: implication on human health. *Environmental Geochemistry and Health*, *42*(7), 1937-1963. https://doi.org/10.1007/s10653-019-00452-x

Armstrong, L., & Johnson, E. (2018). Water Intake, water balance, and the elusive daily water requirement. *Nutrients*, *10*(12), 1928. https://doi.org/10.3390/nu10121928

Arora, S., & Squier, C. (2018). Areca nut trade, globalisation and its health impact: perspectives from India and South-east Asia. *Perspectives in Public Health*, *139*(1), 44-48. https://doi.org/10.1177/1757913918785398

Arumugam, S., Ravichandran, V., Manikandan, R., & Murugan, C. (2018). Rediscovery and lectotypification of *Drypetes porteri* (Putranjivaceae: Phyllanthoideae: Drypeteae), A narrow endemic and endangered species of the Western Ghats, India. *Nelumbo*, *60*(1), 10-12. https://doi.org/10.20324/nelumbo/v60/2018/122552

Ashiq, M., Rehman, H., & Khan, N. (2020). Impact of large diameter recharge wells for reducing groundwater depletion rates in an urban area of Lahore, Pakistan. *Environmental Earth Sciences*, *79*(17). https://doi.org/10.1007/s12665-020-09144-7

Atkinson, P., & Coffey, A. (2011). Analysing documentary realities. In D. Silverman, *Qualitative research: issues of theory, method and practice* (3rd ed., pp. 77-92). Sage publications ltd. Retrieved 27 August 2017.

Attri, S., & Tyagi, A. (2010). *Climate profile of India*. New Delhi: India Meteorological Department.

Baba, A., Tsatsanifos, C., Gohary, T., Palerm, J., Khan, S., & Mahmoudian, S. et al. (2018). Developments in water dams and water harvesting systems throughout history in different civilizations. *International Journal of Hydrology, 2*(2), 150-166. https://doi.org/10.15406/ijh.2018.02.00064

Bahar, N., Noor, Z., Aris, A., & Kamaruzaman, N. (2021). An indicator framework approach on manufacturing water assessment towards sustainable water demand management. *Journal of Environmental Treatment Techniques*, *8*(3), 875-883. Retrieved 12 January 2021.

Bahinipati, C., & Viswanathan, P. (2019). Can micro-irrigation technologies resolve India's groundwater crisis? Reflections from dark-regions in Gujarat. *International Journal of The Commons*, *13*(2), 848-858. https://doi.org/10.5334/ijc.888

Bahri, H. (2009). सुरंग (Suranga). *Rajpal hindi shabdakosh* (1st ed., p. 840). Rajpal and Sons. Retrieved 2 June 2017.

Bainbridge, D. (2001). Buried clay pot irrigation: A little known but very efficient traditional method of irrigation. *Agricultural Water Management, 48*(2), 79-88. https://doi.org/10.1016/s0378-3774(00)00119-0

Balasubramanya, S., & Stifel, D. (2020). Viewpoint: Water, agriculture & poverty in an era of climate change: Why do we know so little?. *Food Policy*, *93*, 101905. https://doi.org/10.1016/j.foodpol.2020.101905

Balooni, K., Kalro, A., & Kamalamma, A. (2010). Sustainability of tunnel wells in a changing agrarian context: A case study from South India. *Agricultural Water Management*, *97*(5), 659-665. https://doi.org/10.1016/j.agwat.2009.12.006

Bansal, P., & DesJardine, M. (2014). Business sustainability: It is about time. *Strategic Organization*, *12*(1), 70-78. https://doi.org/10.1177/1476127013520265

Barker, R., Herdt, R., & Rose, B. (1985). *The rice economy of Asia*. Resources for the Future.

Basak, P., Prasad, P., & Sreedharan, K. (1997). 2.11 Western Ghats. In A. Agarwal & S. Narain, *Dying wisdom: Rise, fall and potential of India's traditional water harvesting systems* (pp. 220-223). Centre for science and environment. Retrieved 13 May 2017.

Bassi, N. (2017). Solarizing groundwater irrigation in India: a growing debate. *International Journal Of Water Resources Development, 34*(1), 132-145. https://doi.org/10.1080/07900627.2017.1329137

Basurto, X., & Ostrom, E. (2009). Beyond the tragedy of the commons. *Economia Delle Fonti Di Energia E Dell'Ambiente*, *1*, 35-60. Retrieved 16 July 2019.

Behailu, B., Pietilä, P., & Katko, T. (2016). Indigenous practices of water management for sustainable services: Case of Borna and Konso, Ethiopia. *SAGE Open*, *6*(4), 215824401668229. https://doi.org/10.1177/2158244016682292

Bentaleb, I., Caratini, C., Fontugne, M., Morzadec-Kerfoun, M., Pascal, J., & Tissot, C. (1997). Monsoon regime variations during the late Holocene in the Southwestern India. In H. Dalfes, G. Kukla & H. Weiss, *Third millennium BC climate change and old world collapse* (pp. 475-488). Springer in cooperation with NATO Scientific Affairs Division. Retrieved 20 June 2017.

Berking, J. (2018). Water management in ancient civilizations: Editorial. In J. Berking, *Water management in ancient civilizations* (1st ed., pp. 7-16). Berlin studies of the ancient world. Retrieved 30 July 2019.

Bhagawati, R., Bhagawati, K., Jini, D., Alone, R., Singh, R., & Chandra, A. et al. (2017). Review on climate change and its impact on agriculture of Arunachal Pradesh in the northeastern Himalayan region of India. *Nature Environment and Pollution Technology*, *16*(2), 535-539. https://doi.org/p-ISSN: 0972-6268, e-ISSN: 2395-3454

Bhallamudi, S., Kaviyarasan, R., Abilarasu, A., & Philip, L. (2019). Nexus between sanitation and groundwater quality: case study from a hard rock region in India. *Journal of Water, Sanitation and Hygiene For Development*, *9*(4), 703-713. https://doi.org/10.2166/washdev.2019.002

Bharucha, Z., Smith, D., & Pretty, J. (2014). All Paths Lead to Rain: Explaining why Watershed Development in India Does Not Alleviate the Experience of Water Scarcity. *The Journal of Development Studies*, *50*(9), 1209-1225. https://doi.org/10.1080/00220388.2014.928699

Bhat, N. (1998). *South Kanara (1799-1860): A study in colonial administration and regional response*. Mittal.

Bhat, N. (2001). *Judiciary and police in early colonial South Kanara, 1799-1862*. Mittal Publications.

Bhattacharya, S. (2015). Traditional water harvesting structures and sustainable water management in India: A socio-hydrological review. *International Letters of Natural Sciences*, *37*, 30-38. https://doi.org/10.18052/www.scipress.com/ilns.37.30

Biesta, G. (2010). Pragmatism and philosophical foundations of mixed methods research. In A. Tashakkori & C. Teddlie, *Sage Handbook of Mixed Methods in Social & Behavioral Research* (2nd ed., pp. 95-118). SAGE Publications, Inc. Retrieved 19 July 2017.

Boag, G. (1933). *The Madras presidency, 1881-1931*. Printed by the superintendent, Government Press.

Bogra, S., & Bakshi, B. (2020). Direct and indirect vulnerability of economic sectors to water scarcity: A hotspot analysis of the Indian economy. *Journal of Industrial Ecology*, *24*(6), 1323-1337. https://doi.org/10.1111/jiec.13022

Bonsor, H., MacDonald, A., & Davies, J. (2013). Evidence for extreme variations in the permeability of laterite from a detailed analysis of well behaviour in Nigeria. *Hydrological Processes*, *28*(10), 3563-3573. https://doi.org/10.1002/hyp.9871

Boualem, R., & Rabah, K. (2012). The foggara in the Arab world. *Geographia Technica*, *1*, 1-7. Retrieved 27 June 2019.

Bowen, G. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, *9*(2), 27-40. https://doi.org/10.3316/qrj0902027

Branch, N., Kemp, R., Silva, B., Meddens, F., Williams, A., Kendall, A., & Pomacanchari, C. (2007). Testing the sustainability and sensitivity to climatic change of terrace agricultural systems in the Peruvian Andes: a pilot study. *Journal of Archaeological Science*, *34*(1), 1-9. https://doi.org/10.1016/j.jas.2006.03.011

Branchet, B., Monfort, E., Poulet, C., & Weil, G. (2018). A triadic approach to health and dependence in aging adults: incongruence in perception. *Quality of Life Research*, *27*(11), 3047-3055. https://doi.org/10.1007/s11136-018-1950-0

Brannen, J. (1992). Combining qualitative and quantitative approaches: An overview. In J. Brannen, *Mixing methods: Qualitative and quantitative research* (pp. 3-37). Ashgate Publishing Limited. Retrieved 19 July 2017.

Braudel, F., & Mayne, R. (2005). *A history of civilizations*. Penguin Books.

Braun, V., & Clarke, V. (2012). Thematic analysis. In H. Cooper, *APA handbook of research methods in psychology: Vol. 2. research designs* (pp. 57-71). Retrieved 25 May 2021.

Brundtland Commission. (1987). *Our Common Future*. United Nations.

Bryman, A. (1988). *Quantity and quality in social research*. Unwin Hyman Ltd.

Buchanan, F. (1807). *A journey from Madras through the countries of Mysore, Canara, and Malabar, Volume 3* (pp. 1-130). The Directors of the East India Company.

Buckley, B., Anchukaitis, K., Penny, D., Fletcher, R., Cook, E., & Sano, M. et al. (2010). Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of The National Academy of Sciences*, *107*(15), 6748-6752. https://doi.org/10.1073/pnas.0910827107

Buhk, C., Schirmel, J., Rebekka, G., & Frör, O. (2019). Traditional water meadows: A sustainable management type for the future?. *Irrigation in Agroecosystems*. https://doi.org/10.5772/intechopen.79429

Bunclark, L., Carter, R., Casey, V., Day, S., & Guthrie, D. (2011). *Managing water locally: An essential dimension of community water development.*. The Institution of Civil Engineers, Oxfam GB and WaterAid.

Bureau of Indian Standards. (2012). *Indian Standard: Drinking water- Specification (Second Revision)*. New Delhi: Bureau of Indian Standards.

Cable Rains, M., Fogg, G., Harter, T., Dahlgren, R., & Williamson, R. (2006). The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California. *Hydrological Processes*, *20*(5), 1157-1175. https://doi.org/10.1002/hyp.5937

Cai, T., Verze, P., & Bjerklund Johansen, T. (2021). The quality of life definition: Where are we going?. *Uro*, *1*(1), 14-22. https://doi.org/10.3390/uro1010003

Census of 1871. (1874). *Census statement of population of 1871 in each village of the South Canara district, arranged according to area, caste, and occupation*. Madras: Printed at the Scottish Press, By Graves, Cookson and Co.

Census of 1881. (1883). *Villagewar statements of area, houses, and population for the South Canara district*. Madras: Printed at the Memorial Press.

Census of 1891. (1895). *Taluk and village statistics: South Canara district*. Madras: Printed by the Superintendent, Government Press.

Census of 1901. (1901). *Village statistics: South Canara district, Madras presidency*. Madras: Printed by the Superintendent, Government Press.

CGWB. (2012). *Groundwater information booklet: Dakshina Kannada district, Karnataka* (pp. 1-28). Bangalore: Central Ground Water Board, Ministry of Water Resources, Government of India. Retrieved from http://cgwb.gov.in/District_Profile/karnataka/DAKSHINA_KANNADA.pdf

CGWB. (2013). *Groundwater information booklet of Kasargod district, Kerala state* (pp. 1-27). Thiruvananthpuram: Central Ground Water Board, Ministry of Water Resources, Government of India. Retrieved from http://cgwb.gov.in/District_Profile/Kerala/Kasargod.pdf

Chakraborty, K., Sudhakar, S., Sarma, K., Raju, P., & Das, A. (2018). Recognizing the rapid expansion of rubber plantation – A threat to native forest in parts of northeast India. *Current Science, 114*(1), 207-2013. https://doi.org/10.18520/cs/v114/i01/207-213

Chakraborty, M., & Shukla, S. (2020). Monsoon and its Influence on Economic Activity. *Journal of Management Outlook*, *10*(1), 2-14. Retrieved 20 May 2021.

Chakravarthy, K., Badam, G., & Paranjpye, V. (2006). *Traditional water management systems of India* (1st ed.). Aryan Books International.

Chandran, A. (2020). Extent of population ageing and intergenerational support in the states of India. In M. Shankardass, *Ageing Issues and Responses in India* (1st ed., pp. 115-127). Springer. Retrieved 26 March 2021, from http://978-981-15-5189-5.

Chandrashekar, K., Sridhar, K., Rajashekhar, M., & Kaveriappa, K. (2020). Thermal springs of Dakshina Kannada. *Lake 2000 SECTION-2 Biodiversity*, *PAPER-5*. Retrieved 21 May 2021.

Chatterjee, N., Gupte, H., & Mandal, G. (2021). A qualitative study of perceptions and practices related to areca nut use among adolescents in Mumbai, India. *Nicotine & Tobacco Research*. https://doi.org/10.1093/ntr/ntab067

Chatterjee, S., & Kundu, R. (2020). Co-production or contested production? Complex arrangements of actors, infrastructure, and practices in everyday water provisioning in a small town in India. *International Journal of Urban Sustainable Development*, 1-13. https://doi.org/10.1080/19463138.2020.1852408

Chaudhry, A. (2018). Improving on-farm water use efficiency: Role of collective action in irrigation management. *Water Resources and Economics*, *22*, 4-18. https://doi.org/10.1016/j.wre.2017.06.001

Chen, D. (2018). *Pandas for everyone* (1st ed.). Pearson India Education Services.

Chitale, V., Behera, M., & Roy, P. (2014). Future of endemic flora of biodiversity hotspots in India. *PLOS ONE*, *9*(12), e115264. https://doi.org/10.1371/journal.pone.0115264

Chitale, V., Behera, M., & Roy, P. (2015). Global biodiversity hotspots in India: Significant yet under studied. *Current Science*, *108*(2), 149.

Chitale, V., Behera, M., & Roy, P. (2020). Congruence of endemism among four global biodiversity hotspots in India. *Current Science*, *118*(1), 9.

Chriki, S., & Hocquette, J. (2020). The myth of cultured meat: A review. *Frontiers in Nutrition*, *7*, 1-9. https://doi.org/10.3389/fnut.2020.00007

Clasen, T., McLaughlin, C., Boisson, S., Nayaar, N., Desai, D., Gupta, R., & Shah, N. (2008). Microbiological Effectiveness and Cost of Disinfecting Water by Boiling in Semi-urban India. *The American Journal of Tropical Medicine and Hygiene*, *79*(3), 407-413. https://doi.org/10.4269/ajtmh.2008.79.407

Closas, A., & Rap, E. (2017). Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, *104*, 33-37. https://doi.org/10.1016/j.enpol.2017.01.035

Cohen, S., Demeritt, D., Robinson, J., & Rothman, D. (1998). Climate change and sustainable development: towards dialogue. *Global Environmental Change*, *8*(4), 341-371. https://doi.org/10.1016/s0959-3780(98)00017-x

Collier, M., Nedović-Budić, Z., Aerts, J., Connop, S., Foley, D., & Foley, K. et al. (2013). Transitioning to resilience and sustainability in urban communities. *Cities*, *32*, S21-S28. https://doi.org/10.1016/j.cities.2013.03.010

Coral, C., & Bokelmann, W. (2017). The role of analytical frameworks for systemic research design, explained in the analysis of drivers and dynamics of historic land-use changes. *Systems*, *5*(1), 20. https://doi.org/10.3390/systems5010020

Creative Commons, D. (2019). *File:Hampi aug09 243.jpg - Wikimedia Commons*. Commons.wikimedia.org. Retrieved 12 July 2019, from https://commons.wikimedia.org/wiki/File:Hampi_aug09_243.jpg.

Creswell, J. (2013). *Qualitative inquiry and research design: Choosing among five approaches* (3rd ed.). SAGE Publications.

Creswell, J. (2015). *A concise introduction to mixed methods research* (p. California). SAGE.

Crook, D. (2001). The historical impacts of hydroelectric power development on traditional mountain irrigation in the Valais, Switzerland. *Mountain Research and Development*, *21*(1), 46-53. https://doi.org/10.1659/0276-4741(2001)021[0046:thiohp]2.0.co;2

Crook, D., & Elvin, M. (2013). Bureaucratic control of irrigation and labour in late-imperial China: The uses of administrative cartography in the Miju catchment, Yunnan. *Water History*, *5*(3), 287-305. https://doi.org/10.1007/s12685-013-0091-1

Crook, D., & Jones, A. (1999). Design principles from traditional mountain irrigation systems (Bisses) in the Valais, Switzerland. *Mountain Research and Development*, *19*(2), 79-99. https://doi.org/10.2307/3674250

Crook, D., Tripathi, S., & Jones, R. (2013). The sustainability of suranga irrigation in South Karnataka and Northern Kerala, India. Mardin; 1st World Irrigation Forum. Retrieved 11 December 2020.

Crook, D., Tripathi, S., & Jones, R. (2015). An investigation into the age and origin of Suranga in the foothills of the Western Ghats of India. *Water History, 7*(3), 253-270. https://doi.org/10.1007/s12685-015-0125-y

Crook, D., Tripathi, S., & Jones, R. (2016). Chapter 24: Traditional methods of groundwater abstraction and recharge along the windward side of the foothills of the Western Ghats of India. In A. Angelakis, E. Chiotis, S. Eslamian & H. Weingartner, *Underground aqueducts handbook* (pp. 415-424). CRC Press. Retrieved 2 June 2017.

Crook, D., Tripathi, S., & Jones, R. (2020). Traditional design principles of a groundwater irrigation system in the foothills of the Western Ghats of southwest India. *Mountain Research and Development*, *40*(3). https://doi.org/10.1659/mrd-journal-d-19-00065.1

CSE. (1998). *Waterworks India: Four engineers and a manager* [Video]. New Delhi; Centre for Science and Environment.

Cullet, P. (2018). Model Groundwater (Sustainable Management) Bill, 2017: A new paradigm for groundwater regulation. *Indian Law Review*, *2*(3), 263-276. https://doi.org/10.1080/24730580.2019.1565567

Dahmen, A., & Kassab, T. (2017). Studying the origin of the foggara in the Western Algerian Sahara: an overview for the advanced search. *Water Science and Technology: Water Supply*, *17*(5), 1268-1277. https://doi.org/10.2166/ws.2017.022

Damle, C. (1989). Land reforms legislation in Karnataka: Myth of success. *Economic and Political Weekly*, *24*(33), 1896-1906. Retrieved 16 March 2021, from https://www.jstor.org/stable/4395235.

Davidson, K., Nguyen, T., Beilin, R., & Briggs, J. (2019). The emerging addition of resilience as a component of sustainability in urban policy. *Cities*, *92*, 1-9. https://doi.org/10.1016/j.cities.2019.03.012

De, L. (2021). Traditional knowledge practices of North East India for sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry*, *10*(1), 549-556. Retrieved 11 March 2021.

Deepa, J., & Gnanaseelan, C. (2021). The decadal sea level variability observed in the Indian Ocean tide gauge records and its association with global climate modes. *Global and Planetary Change*, *198*, 103427. https://doi.org/10.1016/j.gloplacha.2021.103427

deMenocal, P. (2001). Cultural responses to climate change during the late Holocene. *Science*, *292*(5517), 667-673. https://doi.org/10.1126/science.1059827

Deng, C., Zhang, G., Liu, Y., Nie, X., Li, Z., Liu, J., & Zhu, D. (2021). Advantages and disadvantages of terracing: A comprehensive review. *International Soil and Water Conservation Research*. https://doi.org/10.1016/j.iswcr.2021.03.002

Department of Agriculture, Madras. (1925). *Report on the work of the coconut stations in the Kasaragod taluk of South Kanara district for 1924-25*. Madras: The Superintendent, Government Press.

Department of Agriculture. (2015). *All India report on agriculture census 2010-11*. New Delhi: Ministry of Agriculture & Farmers Welfare. Retrieved from http://agcensus.nic.in/document/ac1011/reports/air2010-11complete.pdf

Derissen, S., Quaas, M., & Baumgärtner, S. (2011). The relationship between resilience and sustainability of ecological-economic systems. *Ecological Economics*, *70*(6), 1121-1128. https://doi.org/10.1016/j.ecolecon.2011.01.003

Dietz, T., Ostrom, E., & Stern, P. (2003). The struggle to govern the commons. *Science*, *302*, 1907-1912. Retrieved 17 July 2019.

Dillinger, J. (2017). The divining rod: Origins, explanations and uses in the thirteenth to eighteenth centuries. In L. Kallestrup & R. Toivo, *Contesting orthodoxy in medieval and early modern Europe. Palgrave historical studies in witchcraft and magic* (1st ed., pp. 127-144). Palgrave Macmillan. Retrieved 22 October 2019.

Dixit, Y., Hodell, D., & Petrie, C. (2014a). Abrupt weakening of the summer monsoon in northwest India 4100 yr ago. *Geology*, *42*(4), 339-342. https://doi.org/10.1130/g35236.1

Dixit, Y., Hodell, D., Sinha, R., & Petrie, C. (2014b). Abrupt weakening of the Indian summer monsoon at 8.2 kyr B.P. *Earth and Planetary Science Letters*, *391*, 16-23. https://doi.org/10.1016/j.epsl.2014.01.026

Doddamani, R. (2007). Tapping water through tunnels: The Malnad way. In S. Iyengar, *Waternāma: A collection of traditional practices for water conservation and management in Karnataka* (pp. 69-74). Communication for Development and Learning. Retrieved 3 June 2017.

Doordarshan. (2008). *Water warriors* [Video]. New Delhi; Public Service Broadcasting Trust, India.

Dörre, A., & Goibnazarov, C. (2018). Small-scale irrigation self-governance in a mountain region of Tajikistan. *Mountain Research and Development*, *38*(2), 104-113. https://doi.org/10.1659/mrd-journal-d-17-00085.1

Drysdale, R., Zanchetta, G., Hellstrom, J., Maas, R., Fallick, A., & Pickett, M. et al. (2006). Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. *Geology*, *34*(2), 101-104. https://doi.org/10.1130/g22103.1

Dutt, R. (1902). *The economic history of India: Under early British rule from the rise of the British power in 1757 to the accession of queen Victoria in 1837, Volume 1*. Kegan Paul, Trench, Trübner.

Dutta, K., & Dan, A. (2020). Artificial groundwater recharge: its prospect in West Bengal. *International Journal of All Research Writings*, *1*(11). Retrieved 23 May 2021.

DWI. (2017). *What are the drinking water standards?*. London: Drinking Water Inspectorate.

Dzhengiz, T. (2020). A literature review of inter-organizational sustainability learning. *Sustainability*, *12*(12), 4876. https://doi.org/10.3390/su12124876

Eggleton, R., & Taylor, G. (1999). Some selected thoughts on laterite. In G. Taylor & C. Pain, *New approaches to an old continent* (pp. 209-226). Co-operative Research Centre for Landscape Evolution & Mineral Exploration, Perth. Retrieved 28 April 2017.

Ein Mor, D., & Ron, Z. (2016). ʿAin Joweizeh: An iron age royal rock-cut spring system in the Naḥal Refa'im valley, near Jerusalem1. *Tel Aviv*, *43*(2), 127-146. https://doi.org/10.1080/03344355.2016.1215531

Elvin, M., & Crook, D. (2003). An argument from silence? The implications of Xu Xiake's description of the Miju river in 1639. In *: Yunnan University Research Centre for Chinese Economic History and Yunnan University Department of History (eds) Li Ting jiaoshou jiushi huayan jinian wenji (Collected essays for the ninetieth birthday of Professor Li Ting)* (pp. 150-160). Yunnan University Press. Retrieved 16 March 2021.

English, P. (1968). The origin and spread of qanats in the old world. *American Philosophical Society*, *112*(3), 170-181. Retrieved 5 July 2019.

Fabricius, C., & Collins, S. (2007). Community-based natural resource management: governing the commons. *Water Policy*, *9*, 83-97. https://doi.org/10.2166/wp.2007.132

Fagan, B. (2010). *The great warming: Climate change and the rise and fall of civilizations*. Bloomsbury Press.

Fahimnia, B., & Jabbarzadeh, A. (2016). Marrying supply chain sustainability and resilience: A match made in heaven. *Transportation Research Part E*, *91*, 306-324. https://doi.org/10.1016/j.tre.2016.02.007

Fan, C., Allison, R., & Jones, M. (1994). The effects of tropical weathering on the characteristics of argillaceous rocks. In D. Robinson & R. Williams, *Rock* *weathering and landform evolution* (pp. 339-354). John Wiley & Sons Ltd. Retrieved 29 April 2017.

Fang, Y., & Ying, B. (2016). Spatial distribution of mountainous regions and classifications of economic development in China. *Journal of Mountain Science, 13*(6), 1120-1138. https://doi.org/10.1007/s11629-015-3714-4

FAO & WWC. (2015). *Towards a water and food secure future*. Rome, Marseille: FAO & WWC.

Fattahi, M. (2015). OSL dating of the Miam Qanat (KĀRIZ) system in NE Iran. *Journal of Archaeological Science*, *59*, 54-63. https://doi.org/10.1016/j.jas.2015.04.006

Feilzer, M. (2009). Doing mixed methods research pragmatically: Implications for the rediscovery of pragmatism as a research paradigm. *Journal of Mixed Methods Research*, *4*(1), 6-16. https://doi.org/10.1177/1558689809349691

Ferrand, E., & Cecunjanin, F. (2014). Potential of rainwater harvesting in a thirsty world: A survey of ancient and traditional rainwater harvesting applications. *Geography Compass*, *8*(6), 395-413. https://doi.org/10.1111/gec3.12135

Fischer, A., Hope, R., Manandhar, A., Hoque, S., Foster, T., & Hakim, A. et al. (2020). Risky responsibilities for rural drinking water institutions: The case of unregulated self-supply in Bangladesh. *Global Environmental Change*, *65*, 102152. https://doi.org/10.1016/j.gloenvcha.2020.102152

Fisher, M. (2018). *An environmental history of India: From earliest times to the twenty-first century* (1st ed.). Cambridge University Press.

Flecker, M. (2001). A ninth-century AD Arab or Indian shipwreck in Indonesia: First evidence for direct trade with China. *World Archaeology*, *32*(3), 335-354. https://doi.org/10.1080/00438240120048662

Flores-Román, D., Alcalá-Martínez, J., González-Velázquez, A., & Gama-Castro, J. (1996). Duripans in subtropical and temperate subhumid climate in the trans-Mexico volcanic belt. *Revista Mexicana De Ciencias Geológicas*, *13*(2), 228-239. Retrieved 19 May 2017.

Fontaine, L., & Siddle, D. (2000). Mobility, kinship and commerce in the Alps, 1500-1800. In D. Siddle, *Migration, mobility and modernization* (pp. 47-69). Liverpool University Press. Retrieved 20 May 2021.

Freund, A. (2009). Oral history as process-generated data. *Historical Social Research*, *34*(1), 22-48. Retrieved 16 May 2021, from https://www.jstor.org/stable/20762332.

Freund, A. (2014). “Confessing Animals”: Toward a Longue Durée History of the Oral History Interview. *The Oral History Review*, *41*(1), 1-26. https://doi.org/10.1093/ohr/ohu005

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., & Howells, M. et al. (2019). Connecting climate action with other Sustainable Development Goals. *Nature Sustainability*, *2*(8), 674-680. https://doi.org/10.1038/s41893-019-0334-y

Gabella, J., & Strijker, D. (2018). Sustainability or resilience? A case study in the semi-arid Pampean region of Argentina. *Resilience*, *7*(1), 1-20. https://doi.org/10.1080/21693293.2018.1446298

Gadgil, S. (2003). The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, *31*(1), 429-467. https://doi.org/10.1146/annurev.earth.31.100901.141251

Gadgil, S. (2006). The Indian monsoon: 1. Variations in space and time. *Resonance*, *11*(8), 8-21. https://doi.org/10.1007/bf02855775

Gadgil, S. (2007). The Indian monsoon: 3. Physics of the monsoon. *Resonance*, *12*(5), 4-20. https://doi.org/10.1007/s12045-007-0045-y

Gaikwad, K. (2010). Patronage and support: Socio-cultural role of Kanheri caves in the evolving interactions. *Ancient Asia*, *2*, 113-117. https://doi.org/http://doi.org/10.5334/aa.10208

García, N., Fernández, J., & Fitz, C. (2020). Environmental scenario analysis on natural and social-ecological systems: A review of methods, approaches and applications. *Sustainability*, *12*(18), 7542. https://doi.org/10.3390/su12187542

Gautam, D., Thapa, B., & Prajapati, R. (2017). Indigenous water management system in Nepal: Cultural dimensions of water distribution, cascaded reuse and harvesting in Bhaktapur City. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-017-9964-2

Gerber, J., Nahrath, S., Reynard, E., & Thomi, L. (2008). The role of common pool resource institutions in the implementation of Swiss natural resource management policy. *International Journal of The Commons*, *2*(2), 222-247. https://doi.org/10.18352/ijc.44

Gerrard, A. (1990). *Mountain environments: An examination of the physical geography of mountains*. Belhaven Press.

Ghanbarpour, M., Ahmadi, E., & Gholami, S. (2007). Evaluation of different traditional water management systems in semi-arid regions (case study from Iran). In N. Lamaddalena, C. Bogliotti, M. Todorovic & A. Scardigno, *Water saving in*

Mediterranean agriculture and future research needs [Vol. 3] (pp. 133-139). CIHEAM. Retrieved 11 March 2021.

Ghorbani, M., Eskandari-Damaneh, H., Cotton, M., Ghoochani, O., & Borji, M. (2021). Harnessing indigenous knowledge for climate change-resilient water management – lessons from an ethnographic case study in Iran. *Climate and Development*, 1-14. https://doi.org/10.1080/17565529.2020.1841601

Ghosh, S., Guchhait, S., & Hu, X. (2015). Characterization and evolution of primary and secondary laterites in northwestern Bengal Basin, West Bengal, India. *Journal of Palaeogeography*, *4*(2), 203-230. https://doi.org/10.3724/sp.j.1261.2015.00074

Giosan, L., Clift, P., Macklin, M., Fuller, D., Constantinescu, S., & Durcan, J. et al. (2012). Fluvial landscapes of the Harappan civilization. *Proceedings of The National Academy of Sciences (PNAS)*, *109*(26), E1688-E1694. https://doi.org/10.1073/pnas.1112743109

Gleick, P. (1996). Basic water requirements for human activities: Meeting basic needs. *Water International*, *21*, 83-92. Retrieved 23 April 2021.

Gleick, P. (2010). Roadmap for sustainable water resources in southwestern North America. *Proceedings of The National Academy of Sciences*, *107*(50), 21300-21305. https://doi.org/10.1073/pnas.1005473107

GOI. (2018). *Composite water management index: A tool for water management.*. New Delhi: Niti Aayog.

Gokhale, S. (1968). *Epigraphia Indica (1967-68)*, *37*, 1-3. Retrieved 11 June 2017.

Gokhale, S. (1991). *Kanheri inscriptions*. Deccan College.

Gokhale, S. (2006). The inscriptional evidence of ancient water management systems with special reference to western India. In K. Chakravarthy, G. Badam & V. Paranjpye, *Traditional water management systems of India* (pp. 19-23). Aryan Books International. Retrieved 11 June 2017.

Gopalakrishnan, C. (1973). The doctrine of prior appropriation and its impact on water development. *American Journal of Economics and Sociology*, *32*(1), 61-72. https://doi.org/10.1111/j.1536-7150.1973.tb02180.x

Gorard, S. (2010). Research design, as independent of methods. In A. Tashakkori & C. Teddlie, *Sage handbook of mixed methods in social & behavioral research* (2nd ed., pp. 237-251). SAGE Publications, Inc. Retrieved 19 July 2017.

Government of India. (2012). *Census 2011: Provisional population totals, India data sheet*. New Delhi: Office of the Registrar General and Census Commissioner.

Government of Karnataka. (2021). *Social welfare department*. www.kar.nic.in. Retrieved 16 March 2021, from https://www.scsptsp.kar.nic.in/SchemByType.html.

Graham, N., Hejazi, M., Chen, M., Davies, E., Edmonds, J., & Kim, S. et al. (2020). Humans drive future water scarcity changes across all shared socioeconomic pathways. *Environmental Research Letters*, *15*(1), 014007. https://doi.org/10.1088/1748-9326/ab639b

Gray, D. (2014). *Doing research in the real world* (3rd ed.). SAGE Publications Ltd.

Greenacre, M. (2007). *Correspondence analysis in practice* (2nd ed., pp. 137-144). Chapman and Hall/CRC.

Greenacre, M., & Blasius, J. (2006). *Multiple correspondence analysis and related methods*. Chapman & Hall/CRC.

GSI. (1981). *Geological and mineral map of Karnataka and Goa (Scale 1:500,000)*. Hyderabad: Geological Survey of India.

GSI. (1993). *Geological map of India*. Hyderabad: Map Printing Division, Geological Survey of India.

GSI. (1995). *Geological and mineral map of Kerala (Scale 1:500,000)*. Hyderabad: The Map Printing Division, Geological Survey of India.

GSI. (2005). *Geology and mineral resources of the states of India: Part IX-Kerala*. Hyderabad: Southern Region, Geological Survey of India.

GSI. (2006). *Geology and mineral resources of the states of India: Part VII- Karnataka & Goa*. Bangalore: Geological Survey of India.

GSI. (2014). *Geological and mineral map of Kerala*. Hyderabad: Map Production Division, Geological Survey of India.

Guba, E., & Lincoln, Y. (1994). Competing paradigms in qualitative research. In N. Denzin & Y. Lincoln, *Handbook of qualitative research* (pp. 105-117). SAGE Publications. Retrieved 19 July 2017.

Gunn, A. (2010). *A student guide to climate and weather: Cyclones, hurricanes, and tornadoes, Vol 3*. Greenwood/ABC-CLIO.

Halemane, H. (2007). Suranga: A sustainable water resource. In *National Seminar on Water & Culture*. Hampi. Retrieved 2 June 2017.

Haq, S. (2017). Groundwater Recharging. In S. Haq, *Harvesting Rainwater from Buildings* (pp. 153-172). Springer, Cham. Retrieved 23 May 2021, from https://doi.org/10.1007/978-3-319-46362-9_9.

Hara, T. (2020). *An essay on the principle of sustainable population*. Springer.

Hardin, G. (1968). The tragedy of commons. *Science*, *New Series 162*(3859), 1243-1248. Retrieved 22 June 2019.

Hassan, F. (1997). Nile floods and political disorder in early Egypt. In H. Dalfes, G. Kukla & H. Weiss, *Third millennium BC climate change and old world collapse* (pp. 1-23). Springer in cooperation with NATO Scientific Affairs Division. Retrieved 20 June 2017.

Hastie, T., Tibshirani, R., & Friedman, J. (2009). *The Elements of Statistical Learning* (2nd ed.). Springer.

Haug, G., Günther, D., Peterson, L., Sigman, D., Hughen, K., & Aeschlimann, B. (2003). Climate and the collapse of Maya civilization. *Science*, *299*(5613), 1731-1735. https://doi.org/10.1126/science.1080444

Hellström, D., Jeppsson, U., & Kärrman, E. (2000). A framework for systems analysis of sustainable urban water management. *Environmental Impact Assessment Review*, *20*(3), 311-321. https://doi.org/10.1016/s0195-9255(00)00043-3

Hering, J., Maag, S., & Schnoor, J. (2016). A call for synthesis of water research to achieve the sustainable development goals by 2030. *Environmental Science & Technology*, *50*(12), 6122-6123. https://doi.org/10.1021/acs.est.6b02598

Herrera-Herrera, A., Leierer, L., Jambrina-Enríquez, M., Connolly, R., & Mallol, C. (2020). Evaluating different methods for calculating the Carbon Preference Index (CPI): Implications for palaeoecological and archaeological research. *Organic Geochemistry*, *146*, 104056. https://doi.org/10.1016/j.orggeochem.2020.104056

Hiscock, K., & Bense, V. (2014). *Hydrogeology: Principles and Practice* (2nd ed.). Wiley Blackwell.

Hjellbrekke, J. (2019). *Multiple correspondence analysis for the social sciences* (1st ed.). Routledge.

Hodell, D., Curtis, J., & Brenner, M. (1995). Possible role of climate in the collapse of classic Maya civilization. *Nature*, *375*(6530), 391-394. https://doi.org/10.1038/375391a0

Hoekstra, A. (2012). The hidden water resource use behind meat and dairy. *Animal Frontiers*, *2*(2), 3-8. https://doi.org/10.2527/af.2012-0038

Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our common future revisited. *Global Environmental Change*, *26*, 130-139. https://doi.org/10.1016/j.gloenvcha.2014.04.006

Holling, C. (1973). Resilience and stability of ecological systems. *Annual Review of Ecological Systems*, *4*, 1-23. Retrieved 8 December 2020.

Holling, C., & Gunderson, L. (2002). *Panarchy: Understanding transformations in human and natural systems*. Island Press.

Hultzsch, E. (1969). Inscriptions of Asoka. *Corpus inscriptionum indicarum, 1*. Retrieved 11 June 2017.

Hunter, W. (1887). *The imperial gazetteer of India Vol 14* (2nd ed.). Trübner & Co.

Hunter, W. (1908). *The imperial gazetteer of India Vol XIV*. The Clarendon Press.

Hunter, W., Cotton, J., Burn, R., & Meyer, W. (1907). *Imperial gazetteer of India. Vol 18* (p. 250). Clarendon Press.

Hussain, I. (2007). Direct and indirect benefits and potential disbenefits of irrigation: evidence and lessons. *Irrigation and Drainage*, *56*(2-3), 179-194. https://doi.org/10.1002/ird.301

Huston, A., Gaskin, S., Moriarty, P., & Watsisi, M. (2021). More sustainable systems through consolidation? The changing landscape of rural drinking water service delivery in Uganda. *Water Alternatives*, *14*(1), 248-270. Retrieved 16 March 2021.

Hutchings, P. (2018). Community management or coproduction? The role of state and citizens in rural water service delivery in India. *Water Alternatives*, *11*(2), 357-374. Retrieved 16 March 2021.

Ilias, M. (2007). Mappila Muslims and the cultural content of trading Arab diaspora on the Malabar coast. *Asian Journal of Social Science*, *35*(4-5), 434-456. https://doi.org/10.1163/156853107x240288

India Population. Worldometers.info. (2021). Retrieved 12 January 2021, from https://www.worldometers.info/world-population/india-population/.

IPCC. (2007). *Climate change 2007: Synthesis report*. Geneva: IPCC.

Iyengar, S. (2007). *Waternama: A collection of traditional practices for water conservation and management in Karnataka* (1st ed.). Communication for Development and Learning.

Jain, S., Agarwal, P., & Singh, V. (2007). *Hydrology and water resources of India*. Springer.

Jaiswal, K., & Banerjee, R. (1930). *Epigraphia Indica (1929-30), 20,* 71-80. Retrieved 11 June 2017.

James, G., Witten, D., Hastie, T., & Tibshirani, R. (2013). *An introduction to statistical learning*. Springer.

Jamkhedkar, A. (1992). The age of the Vakatakas. In A. Shastri, *Discovery of Vakataka temples at Ramtek* (pp. 156-164). Harman Publishing House. Retrieved 11 June 2017.

Jansen, M. (1989). Water supply and sewage disposal at Mohenjo-Daro. *World Archaeology*, *21*(2), 177-192. https://doi.org/10.1080/00438243.1989.9980100

Jayaprabha, K., & Suresh, K. (2016). Endosulfan contamination in water : A review on to an efficient method for its removal. *Journal of Chemistry and Chemical Sciences*, *6*(2), 182-191. Retrieved 11 December 2020.

Jessee, E. (2011). The Limits of Oral History: Ethics and Methodology Amid Highly Politicized Research Settings. *Oral History Review*, *38*(2), 287-307. https://doi.org/10.1093/ohr/ohr098

John, J., Bindu, G., Srimuruganandam, B., Wadhwa, A., & Rajan, P. (2020). Land use/land cover and land surface temperature analysis in Wayanad district, India, using satellite imagery. *Annals of GIS*, *26*(4), 343-360. https://doi.org/10.1080/19475683.2020.1733662

Johnson, R., & Onwuegbuzie, A. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, *33*(7), 14-26. https://doi.org/10.3102/0013189x033007014

Joppen, C. (1907). *A historical atlas of India for the use of high-schools, colleges, and private students* (pp. 16-26). Longman Green and Co.

Jose, M., & Padmanabhan, M. (2015). Dynamics of agricultural land use change in Kerala: a policy and social-ecological perspective. *International Journal of Agricultural Sustainability*, *14*(3), 307-324. https://doi.org/10.1080/14735903.2015.1107338

Joseph, N., Ryu, D., Malano, H., George, B., & Sudheer, K. (2020). Investigation into sustainable water use in India using combined large-scale earth system-based modelling and census-based statistical data. *Journal of Hydrology*, *587*, 124930. https://doi.org/10.1016/j.jhydrol.2020.124930

Juran, L., & MacDonald, M. (2014). An assessment of boiling as a method of household water treatment in South India. *Journal of Water and Health*, *12*(4), 791-802. https://doi.org/10.2166/wh.2014.010

Kale, M., Chavan, M., Pardeshi, S., Joshi, C., Verma, P., & Roy, P. et al. (2016). Land-use and land-cover change in Western Ghats of India. *Environmental Monitoring and Assessment*, *188*(7). https://doi.org/10.1007/s10661-016-5369-1

Kale, V. (2014). Geomorphic history and landscapes of India. In V. Kale, *Landscape and landforms of India* (pp. 25-37). Springer. Retrieved 19 June 2017.

Kangle, R. (1963). *Kautilya's Arthashastra*. University of Bombay.

Kapos, V., Rhind, J., Edwards, M., Price, M., & Ravilious, C. (2000). Developing a map of the world's mountain forest. In M. Price & N. Butts, *Forest in sustainable mountain development: A state of knowledge report for 2000* (pp. 4-18). Commonwealth Agricultural Bureau (CAB) International. Retrieved 7 October 2017.

Karanth, K. (1933). *Picturesque south Kanara*. Basel Mission Book and Tract Depository.

Karnawat, M., Trivedi, S., Nagar, R., & Nagar, D. (2020). Role of monsoon in Indian agriculture. *Biotica Research Today*, *2*(10), 1019-1021. Retrieved 20 May 2021.

Karunanidhi, D., Aravinthasamy, P., Deepali, M., Subramani, T., & Shankar, K. (2021a). Groundwater pollution and human health risks in an industrialized region of Southern India: Impacts of the COVID-19 lockdown and the monsoon seasonal cycles. *Archives of Environmental Contamination and Toxicology*, *80*(1), 259-276. https://doi.org/10.1007/s00244-020-00797-w

Karunanidhi, D., Aravinthasamy, P., Subramani, T., & Kumar, M. (2021b). Human health risks associated with multipath exposure of groundwater nitrate and environmental friendly actions for quality improvement and sustainable management: A case study from Texvalley (Tiruppur region) of India. *Chemosphere*, *265*, 129083. https://doi.org/10.1016/j.chemosphere.2020.129083

Katyaini, S., Barua, A., & Duarte, R. (2020). Science-policy interface on water scarcity in India: Giving 'visibility' to unsustainable virtual water flows (1996–2014). *Journal of Cleaner Production*, *275*, 124059. https://doi.org/10.1016/j.jclepro.2020.124059

Kenoyer, J. (1991). The Indus valley tradition of Pakistan and western India. *Journal of World Prehistory*, *5*(4), 331-385. https://doi.org/10.1007/bf00978474

Khadra, W., & Stuyfzand, P. (2019). Problems and promise of managed recharge in karstified aquifers: the example of Lebanon. *Water International*, *45*(1), 23-38. https://doi.org/10.1080/02508060.2019.1682910

Khuman, S., Vinod, P., Bharat, G., Kumar, Y., & Chakraborty, P. (2020). Spatial distribution and compositional profiles of organochlorine pesticides in the surface soil from the agricultural, coastal and backwater transects along the south-west coast of India. *Chemosphere*, *254*, 126699. https://doi.org/10.1016/j.chemosphere.2020.126699

Knez, I., & Eliasson, I. (2017). Relationships between personal and collective place identity and well-being in mountain communities. *Frontiers in Psychology*, *8*, 1-12. https://doi.org/10.3389/fpsyg.2017.00079

Kodandapani, N., & Parks, S. (2019). Effects of drought on wildfires in forest landscapes of the Western Ghats, India. *International Journal of Wildland Fire*, *28*(6), 431-444. https://doi.org/10.1071/wf18188

Kohler, T., & Maselli, D. (2012). *Mountains and climate change: From understanding to action* (3rd ed.). Geographica Bernensia with the support of the Swiss Agency for Development and Cooperation (SDC), and an international team of contributors.

Koilparambil, A., & Kamath, S. (2015). Treatment of effluent generated from raw rubber sheet production by biomethanation: A laboratory study. *Mahatma Gandhi Institute of Rural Energy and Development Journal*, *2*(1), 1-8. https://doi.org/ISSN 2393 -9605

Kokkal, K., & Aswathy, M. (2009). Traditional water resources in Kerala. In *Proceedings of Kerala Environment Congress 2009: Water resources of Kerala* (pp. 47-62). Thiruvananthapuram; Centre for Environment and Development. Retrieved 16 March 2021.

Kolvankar, A. (2019). A history and assessment of transboundary water disputes of India. *International Journal of Trend in Research and Development*, *6*(6), 279-284. Retrieved 25 March 2021, from http://www.ijtrd.com/papers/IJTRD21888.pdf.

Kreutzmann, H. (2011). Scarcity within opulence: Water management in the Karakoram Mountains revisited. *Journal of Mountain Science*, *8*(4), 525-534. https://doi.org/10.1007/s11629-011-2213-5

Kripalani, R., Kulkarni, A., Sabade, S., & Khandekar, M. (2003). Indian monsoon variability in a global warming scenario. *Natural Hazards*, *29*(2), 189-206. https://doi.org/10.1023/a:1023695326825

Krishnan, R., & Dhara, C. (2020). Executive summary. In R. Krishnan, J. Sanjay, C. Gnanaseelan, M. Mujumdar, A. Kulkarni & S. Chakraborty, *Assessment of climate change over the Indian region* (p. xiii-xvii). Springer Open. Retrieved 27 April 2021.

Kuhlman, T., & Farrington, J. (2010). What is sustainability?. *Sustainability*, *2*, 3436-3448. https://doi.org/10.3390/su2113436

Kuhn, T. (1962). *The structure of scientific revolutions*. University of Chicago Press.

Kumar, G., Adhikary, P., & Dash, C. (2020). Spatial extent, formation process, reclaimability classification system and restoration strategies of gully and ravine lands in India. In P. Shit, H. Pourghasemi & G. Bhunia, *Gully erosion studies from India and surrounding regions* (pp. 1-20). Springer. Retrieved 9 May 2021.

Kumar, P., & Krishna. (2015). Disengagement of rural youth in agriculture with reference to Puttur taluk. *Deeksha Bi-Annual Journal of Social Work*, *13*(1), 24-39. https://doi.org/ISSN - 2250 - 3919

Kumar, R. (2019). Emerging challenges of water scarcity in India: The way ahead. *International Journal of Innovative Studies in Sociology and Humanities*, *4*(4), 6-28. Retrieved 12 March 2021.

Kuper, M., Ameur, F., & Hammani, A. (2017). Unraveling the enduring paradox of increased pressure on groundwater through efficient drip irrigation. *Drip Irrigation For Agriculture*, 85-104. https://doi.org/10.4324/9781315537146-6

Kurwadkar, S. (2019). Occurrence and distribution of organic and inorganic pollutants in groundwater. *Water Environment Research*, *91*(10), 1001-1008. https://doi.org/10.1002/wer.1166

Kurwadkar, S., Kanel, S., & Nakarmi, A. (2020). Groundwater pollution: Occurrence, detection, and remediation of organic and inorganic pollutants. *Water Environment Research*, *92*(10), 1659-1668. https://doi.org/10.1002/wer.1415

Langsholt, E. (1992). A water balance study in lateritic terrain. *Hydrological Processes*, *6*(1), 11-27. https://doi.org/10.1002/hyp.3360060103

Lankford, B. (2012). Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. *Agricultural Water Management*, *108*, 27-38. https://doi.org/10.1016/j.agwat.2011.08.010

Lankford, B., Closas, A., Dalton, J., López Gunn, E., Hess, T., & Knox, J. et al. (2020). A scale-based framework to understand the promises, pitfalls and paradoxes of irrigation efficiency to meet major water challenges. *Global Environmental Change*, *65*, 102182. https://doi.org/10.1016/j.gloenvcha.2020.102182

Lasage, R., & Verburg, P. (2015). Evaluation of small scale water harvesting techniques for semi-arid environments. *Journal of Arid Environments*, *118*, 48-57. https://doi.org/10.1016/j.jaridenv.2015.02.019

Le Fort, P. (1975). Himalayas: The collided rang. Present knowledge of the continental arc. *American Journal of Science, 275*(A), 1-44.

Le Roux, B., & Rouanet, H. (2005). *Geometric data analysis* (1st ed.). Springer Netherlands.

Leibundgut, C. (2004). Historical meadow irrigation in Europe—a basis for agricultural development. In *UNESCO/IAI-1S/IWHA symposium*. Rome; IHAS Publications. Retrieved 8 December 2020.

Leridon, H. (2020). World population outlook: Explosion or implosion?. *Population & Societies*, *573*(1), 1-4. https://doi.org/10.3917/popsoc.573.0001

Lightfoot, D. (2012). Chapter 5 - Iraq. In A. Yazdi & M. Khaneiki, *Qanats in its cradle: Situation of qanat (Kariz, Karez, Falaj) in the World* (1st ed., pp. 149-189). Retrieved 5 June 2019.

Linneck, S., Parker, A., Smeets, P., Cruddas, P., & Jeffrey, P. (2015). Social and economic factors influencing the 'choice' of water supply in rural Karnataka, India. In *38th WEDC International Conference*. Loughborough University, UK; Loughborough University. Retrieved 22 May 2021.

Lone, S., Bhat, S., Hamid, A., Bhat, F., & Kumar, A. (2020). Quality assessment of springs for drinking water in the Himalaya of South Kashmir, India. *Environmental Science and Pollution Research*, *28*(2), 2279-2300. https://doi.org/10.1007/s11356-020-10513-9

Lucero, L., Gunn, J., & Scarborough, V. (2011). Climate change and classic Maya water management. *Water*, *3*(4), 479-494. https://doi.org/10.3390/w3020479

Mahan, A., Khorramrouei, R., & Nasiri, A. (2019). Restoring the qanats as a traditional water transfer system: A sustainable approach. *International Journal of Architecture and Urban Development*, *9*(1), 35-42. Retrieved 25 June 2019.

Mahendra, N., Chowdary, J., Darshana, P., Sunitha, P., Parekh, A., & Gnanaseelan, C. (2021). Interdecadal modulation of interannual ENSO-Indian summer monsoon rainfall teleconnections in observations and CMIP6 models: Regional patterns. *International Journal of Climatology*, *41*(4), 2528-2552. https://doi.org/10.1002/joc.6973

Majumdar, D. (2014). *Irrigation water management: Principles and practice* (2nd ed.). Prentice-Hall Of India Learning Private Limited.

Malhotra, S. (2017). Horticultural crops and climate change: A review. *Indian Journal of Agricultural Sciences*, *87*(1), 12-22. Retrieved 1 May 2021.

Manuel, M., Lightfoot, D., & Fattahi, M. (2017). The sustainability of ancient water control techniques in Iran: an overview. *Water History*, *10*(1), 13-30. https://doi.org/10.1007/s12685-017-0200-7

Marchese, C. (2015). Biodiversity hotspots: A shortcut for a more complicated concept. *Global Ecology and Conservation*, *3*, 297-309. https://doi.org/10.1016/j.gecco.2014.12.008

Marchese, D., Reynolds, E., Bates, M., Morgan, H., Clark, S., & Linkov, I. (2018). Resilience and sustainability: Similarities and differences in environmental management applications. *Science of The Total Environment, 613-614*, 1275-1283. https://doi.org/10.1016/j.scitotenv.2017.09.086

Marian, C. (2019). Literature on inheritance: A summary of what can be learnt. *Journal of Interdisciplinary History of Ideas, 15*. Retrieved 23 May 2021, from http://journals.openedition.org/jihi/449.

Marwick, A. (1994). Chapter 2: Primary sources: Handle with care. In M. Drake, R. Finnegan & J. Eustace, *Studying family and community history: Volume 4, sources and methods for family and community historians: A handbook*. Cambridge University Press. Retrieved 3 April 2021.

Masroor, M., Rehman, S., Avtar, R., Sahana, M., Ahmed, R., & Sajjad, H. (2020). Exploring climate variability and its impact on drought occurrence: Evidence from Godavari Middle sub-basin, India. *Weather and Climate Extremes, 30*, 100277. https://doi.org/10.1016/j.wace.2020.100277

Mate, M. (1969). Building in ancient India. *World Archaeology, 1*(2), 236-246. https://doi.org/10.1080/00438243.1969.9979442

Mate, M. (2006). Water management in ancient and medieval India. In K. Chakravarty, G. Badam & V. Paranjpye, *Traditional water management systems of India* (pp. 24-33). Aryan Books International. Retrieved 11 June 2017.

Mathew, R. (2009). *No end to Endosulfan tragedy*. The Hindu. Retrieved 11 December 2020, from https://www.thehindu.com/news/cities/Thiruvananthapuram/No-end-to-Endosulfan-tragedy/article16888527.ece.

Maurya, S., Singh, P., Ohri, A., & Singh, R. (2020). Identification of indicators for sustainable urban water development planning. *Ecological Indicators, 108*, 105691. https://doi.org/10.1016/j.ecolind.2019.105691

McFarlane, M. (1976). *Laterite and landscape*. Academic Press.

McGuinness, S., O’Toole, J., Barker, S., Forbes, A., Boving, T., & Giriyan, A. et al. (2020). Household water storage management, hygiene practices, and associated drinking water quality in rural India. *Environmental Science & Technology*, *54*(8), 4963-4973. https://doi.org/10.1021/acs.est.9b04818

Megdiche-Kharrat, F., Zheng, X., Moussa, M., Famin, Z., & Angelakis, A. (2020). Historic hydraulic works: paradigms of traditional good water governance, integrity and sustainability. *Water Supply*, *20*(7), 2484-2498. https://doi.org/10.2166/ws.2020.146

Meinzen-Dick, R., Raju, K., & Gulati, A. (2002). What affects organization and collective action for managing resources? Evidence from canal irrigation systems in India. *World Development*, *30*(4), 649-666. https://doi.org/10.1016/s0305-750x(01)00130-9

Mekonnen, M., & Hoekstra, A. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*(2), e1500323. https://doi.org/10.1126/sciadv.1500323

Menon, A., Nair, R., B., P., Sai, S., & Vishnudasan, D. (2020). Climate change triggered floods and its effect on soil profile of Kerala. *16Th International Conference On Concentrator Photovoltaic Systems (CPV-16)*. https://doi.org/10.1063/5.0030308

Meybeck, M., Green, P., & Vörösmarty, C. (2001). A new typology for mountains and other relief classes. *Mountain Research and Development*, *21*(1), 34-45. https://doi.org/10.1659/0276-4741(2001)021[0034:antfma]2.0.co;2

Middleton, G. (2012). Nothing lasts forever: Environmental discourses on the collapse of past societies. *Journal of Archaeological Research*, *20*(3), 257-307. https://doi.org/10.1007/s10814-011-9054-1

Miley, S. (1875). *Canara past and present*. Addison and Co.

Mini, M., & Razeena, P. (2013). Socio-ecological importance of midland laterite hillocks of Kasaragod district of Kerala, south India. *Ecology, Environment and Conservation Paper*, *19*(4), 1005-1011. Retrieved 22 May 2021.

Mishra, A. (1993). *Aaj bhi khare hai talab (Hindi)*. Gandhi Peace Foundation.

Mishra, A. (2012). The ancient ingenuity of water harvesting systems. *Journal of The Development and Research Organisation For Nature, Arts and Heritage*, *9*(1), 83-89. Retrieved 29 June 2017, from http://www.dronah.org/wp-content/uploads/2017/03/context-15.pdf.

Mishra, A., Ghosh, S., Nanda, P., & Kumar, A. (2011). Assessing the impact of rehabilitation and irrigation management transfer in minor irrigation projects in Orissa, India: A case study. *Irrigation and Drainage*, *60*(1), 42-56. https://doi.org/10.1002/ird.540

Mishra, J. (2017). *Burhanpur – A medieval water oasis*. Virsat-e-hind foundation. Retrieved 11 December 2020, from https://blogvirasatehind.wordpress.com/2017/07/10/burhanpur-a-medieval-water-oasis/.

Misra, A. (2014). Climate change and challenges of water and food security. *International Journal of Sustainable Built Environment*, *3*(1), 153-165. https://doi.org/10.1016/j.ijsbe.2014.04.006

Mokadem, N., Redhaounia, B., Besser, H., Ayadi, Y., Khelifi, F., & Hamad, A. et al. (2018). Impact of climate change on groundwater and the extinction of ancient “Foggara” and springs systems in arid lands in North Africa: a case study in Gafsa basin (Central of Tunisia). *Euro-Mediterranean Journal For Environmental Integration*, *3*(28), 1-14. https://doi.org/10.1007/s41207-018-0070-0

Molotoks, A., Smith, P., & Dawson, T. (2020). Impacts of land use, population, and climate change on global food security. *Food and Energy Security*. https://doi.org/10.1002/fes3.261

Moratelli, R., & Calisher, C. (2015). Bats and zoonotic viruses: can we confidently link bats with emerging deadly viruses?. *Memórias Do Instituto Oswaldo Cruz*, *110*(1), 1-22. https://doi.org/10.1590/0074-02760150048

Morgan, D. (2007). Paradigms lost and pragmatism regained: Methodological implications of combining qualitative and quantitative methods. *Journal of Mixed Methods Research*, *1*, 48-76. https://doi.org/10.1177/2345678906292462

Mosse, D. (1999). Colonial and contemporary ideologies of ‘Community Management’: The case of tank irrigation development in south India. *Modern Asian Studies*, *33*(2), 303-338. https://doi.org/10.1017/s0026749x99003285

Moyer, J., & Hedden, S. (2020). Are we on the right path to achieve the sustainable development goals?. *World Development*, *127*, 104749. https://doi.org/10.1016/j.worlddev.2019.104749

Mujumdar, P., & Jain, S. (2018). *Hydrology in ancient India: Some fascinating facets*. Presentation, Geophysical Research Abstracts Vol. 20, General Assembly 2018.

Mukherjee, I., & Singh, U. (2018). Groundwater fluoride contamination, probable release, and containment mechanisms: a review on Indian context. *Environmental Geochemistry and Health*, *40*(6), 2259-2301. https://doi.org/10.1007/s10653-018-0096-x

Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: a review. *Regional Environmental Change*, *19*(5), 1311-1326. https://doi.org/10.1007/s10113-019-01484-w

Müller, F. (1965). *Rigveda (3:3:45 & 7:49:2)*. Chaukhmbha Series (Reprint).

Munoz-Najar Galvez, S., Heiberger, R., & McFarland, D. (2019). Paradigm wars revisited: A cartography of graduate research in the field of education (1980–

2010). *American Educational Research Journal*, *57*(2), 612-652. https://doi.org/10.3102/0002831219860511

Muppidi, S., Namburu, S., & Kone, V. (2020). A study on ground water problems, artificial recharge techniques in Musunuru. *Materials Today: Proceedings*, *33,* 353-359. https://doi.org/10.1016/j.matpr.2020.04.136

Murtagh, F., & Legendre, P. (2014). Ward's hierarchical agglomerative clustering method: Which algorithms implement Ward's criterion?. *Journal of Classification*, *31*(3), 274-295. https://doi.org/10.1007/s00357-014-9161-z

Nagaraj, N., Chandrakanth, M., & Gurumurthy. (1994). Borewell failure in drought prone areas of southern India: A case study. *Indian Journal of Agricultural Economics*, *49*(1). Retrieved 16 March 2021.

Nagrah, A., Chaudhry, A., & Giordano, M. (2016). Collective action in decentralized irrigation systems: Evidence from Pakistan. *World Development*, *84,* 282-298. https://doi.org/10.1016/j.worlddev.2016.02.003

Narayanamoorthy, A. (2007). Tank irrigation in India: a time series analysis. *Water Policy*, *9*(2), 193-216. https://doi.org/10.2166/wp.2006.063

Nasiri, F., & Mafakheri, M. (2015). Qanat water supply systems: a revisit of sustainability perspectives. *Environmental Systems Research*, *4*(13), 1-13. https://doi.org/10.1186/s40068-015-0039-9

Nastasi, B., Hitchcock, J., & Brown, L. (2010). An inclusive framework for conceptualizing mixed methods design typologies. In A. Tashakkori & C. Teddlie, *Sage handbook of mixed methods in social & behavioral research* (2nd ed., pp. 305-338). SAGE Publications, Inc. Retrieved 19 July 2017.

Nawale, V., Malpe, D., Marghade, D., & Yenkie, R. (2021). Non-carcinogenic health risk assessment with source identification of nitrate and fluoride polluted groundwater of Wardha sub-basin, central India. *Ecotoxicology and Environmental Safety*, *208*, 111548. https://doi.org/10.1016/j.ecoenv.2020.111548

Naz, F., & Subramanian, S. (2010). : Water management across space and time in India, ZEF Working Paper Series, No. 61. Bonn; University of Bonn, Center for Development Research (ZEF). Retrieved 20 May 2021.

Nazimuddin, M., & Kokkal, K. (2002). *Studies on development of surangams as a nonconventional water resource in the Kanhangad block panchayat, Kasargod District, Kerala*. Kozhikode: Centre for Water Resources Development and Management.

Neethu, V., & Miriam, R. (2018). A geographic study on the role of physiography in the incidence of illnesses related to Endosulphan in Kasaragod district, Kerala, India. *International Journal of Scientific Research and Reviews*, *7*(4), 1812-1829. Retrieved 11 December 2020.

Ollier, C. (1988). Deep weathering, groundwater and climate. *Geografiska Annaler. Series A, Physical Geography*, *70*(4), 285-290. https://doi.org/10.2307/521260

Ollier, C., & Galloway, R. (1990). The laterite profile, ferricrete and unconformity. *CATENA*, *17*(2), 97-109. https://doi.org/10.1016/0341-8162(90)90001-t

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press.

Otero, I., Darbellay, F., Reynard, E., Hetényi, G., Perga, M., & Rüegg, J. et al. (2020). Designing Inter- and transdisciplinary research on mountains: What place for the unexpected?. *Mountain Research and Development*, *40*(4), D10-D20. https://doi.org/10.1659/mrd-journal-d-20-00036.1

Padre, S. (2002). *Rain water harvesting*. Alter Media.

Padre, S. (2006a). *India Together: Don't dig down*. Indiatogether.org. Retrieved 24 November 2020, from http://www.indiatogether.org/addabore-environment.

Padre, S. (2006b). *Surangas : Manmade caves to tap underground*. Indiatogether.org. Retrieved 24 November 2020, from http://www.indiatogether.org/articles/suranga-environment--2/print.

Padre, S. (2008a). *India Together: A 'Gurukula' for surangas*. Indiatogether.org. Retrieved 24 November 2020, from http://www.indiatogether.org/suranga-environment.

Padre, S. (2008b). *India Together: One-man-army greens barren land*. Indiatogether.org. Retrieved 24 November 2020, from http://www.indiatogether.org/mahanaik-agriculture.

Padre, S. (2009). *India Together: The unique water tunnel of Sheni*. Indiatogether.org. Retrieved 24 November 2020, from http://www.indiatogether.org/suranga-environment--3.

Palerm-Viqueira, J. (2004). Filtrating galleries or qanats in México: Introduction and typology of techniques. *Agricultura, Sociedad Y Desarrollo*, *Julio-Diciembre*, 133-145. Retrieved 28 February 2021.

Panagariya, A., & More, V. (2020). Decline in poverty in India: Real or an artifact of a low poverty line?. *Indian Public Policy Review*, *2*(2), 13-24. https://doi.org/JEL: D63, I32

Panda, B., & Sarkar, S. (2020). Environmental impact of rubber plantation: Ecological vs. economical perspectives. *Asian Jr. of Microbiol. Biotech. Env. Sc.*, *22*(4), 657-661. Retrieved 22 May 2021.

Panigrahi, A., & Pattnaik, S. (2019). A review on consequences of pollution of some indian major rivers and their remedial measures. *International Journal of Research & Review*, *6*(7), 373-383. Retrieved 20 May 2021, from http://www.ijrrjournal.com.

Pant, N., & Verma, R. (2010). *Tanks in eastern India: A study in exploration*. Hyderabad: IWMI-TATA Water Policy Research Program and Centre for Development Studies.

Papke, R., Bhattacharyya, I., Hatsukami, D., Moe, I., & Glatman, S. (2019). Betel nut (areca) and smokeless tobacco use in Myanmar. *Substance Use & Misuse*, *55*(9), 1385-1394. https://doi.org/10.1080/10826084.2019.1624774

Parducci, L., Matetovici, I., Fontana, S., Bennett, K., Suyama, Y., & Haile, J. et al. (2013). Molecular- and pollen-based vegetation analysis in lake sediments from central Scandinavia. *Molecular Ecology*, *22*(13), 3511-3524. https://doi.org/10.1111/mec.12298

Parthasarathy, R. (2000). Participatory Irrigation Management programme in Gujarat: Institutional and financial issues. *Economic and Political Weekly*, *35*(35/36), 3147-3154. Retrieved 20 December 2020, from https://www.jstor.org/stable/4409680.

Patel, P., Saha, D., & Shah, T. (2020). Sustainability of groundwater through community-driven distributed recharge: An analysis of arguments for water scarce regions of semi-arid India. *Journal of Hydrology: Regional Studies*, *29*, 100680. https://doi.org/10.1016/j.ejrh.2020.100680

Pathak, R. (2007). सुरंग (Suranga). *Aadarsh hindi shabdkosh* (1st ed.). Bhargav Book Depot. Retrieved 2 June 2017.

Peiser, B. (2003). Climate change and civilizational collapse. In K. Okonski, *Adapt or die: The science, politics and economics of climate change* (pp. 191-204). Profile Books. Retrieved 9 May 2021.

Perry, K. (1998). Basics of frost and freeze protection for horticultural crops. *Horttechnology*, *8*(1), 10-15. https://doi.org/10.21273/horttech.8.1.10

Pfeiffer, L., & Lin, C. (2014). Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management*, *67*(2), 189-208. https://doi.org/10.1016/j.jeem.2013.12.002

Phadtare, N. (2000). Sharp Decrease in Summer Monsoon Strength 4000–3500 cal yr B.P. in the Central Higher Himalaya of India Based on Pollen Evidence from

Alpine Peat. *Quaternary Research*, *53*(01), 122-129. https://doi.org/10.1006/qres.1999.2108

Pimentel, D., & Pimentel, M. (2003). Sustainability of meat-based and plant-based diets and the environment. *The American Journal of Clinical Nutrition*, *78*(3), 660S-663S. https://doi.org/10.1093/ajcn/78.3.660s

Pletcher, K. (2011). *The geography of India*. Britannica Educational Pub. in association with Rosen Education Services.

Plowright, R., Becker, D., Crowley, D., Washburne, A., Huang, T., & Nameer, P. et al. (2019). Prioritizing surveillance of Nipah virus in India. *PLOS Neglected Tropical Diseases*, *13*(6), 1-17. https://doi.org/10.1371/journal.pntd.0007393

Poonia, V., Jha, S., & Goyal, M. (2021). Copula based analysis of meteorological, hydrological and agricultural drought characteristics across Indian river basins. *International Journal of Climatology*, 1-16. https://doi.org/10.1002/joc.7091

Prasad, P., Jayakumar, N., & Basak, P. (1991). *Surangams of Kasargod: An unconventional water harvesting mechanism*. Kozhikode: Centre for Water Resources Development and Management.

Prior, L. (2011). Using documents in social research. In D. Silverman, *Qualitative research: Issues of theory, method and practice* (3rd ed.). SAGE. Retrieved 31 August 2017.

Raghavendra, K., Arvind, K., Anushree, G., & Grace, T. (2020). Biodiversity of butterflies in endosulfan-affected areas of Kerala, India. *The Journal of Basic and Applied Zoology*, *81*(1), 1-7. https://doi.org/10.1186/s41936-020-00192-w

Raghuwanshi, S. (2006). Conservation of traditional water supply of Bhruanpur town. In K. Chakravarty, G. Badam & V. Paranjpye, *Traditional water management systems of India* (pp. 133-135). Aryan Books International. Retrieved 11 June 2017.

Rajan, A., & Shah, T. (2020). Impact of Irrigation on India’s Dairy Economy. *Agriculture*, *10*(53), 5-13. https://doi.org/10.3390/agriculture10030053

Rajesha, M. (2017). Anna-bhaghya yojana scheme of Karnataka state: An analysis. *Global Journal For Research Analysis*, *6*(4), 416-417. Retrieved 28 September 2019.

Rakhecha, P. (2016). Assessment of water resources and seasonal prediction of rainfall in India. *Proceedings of The International Association of Hydrological Sciences*, *374*, 151-157. https://doi.org/10.5194/piahs-374-151-2016

Ramachandra, T. (2017). Unplanned urbanisation and imminent water scarcity in Bengaluru [Blog]. Retrieved 30 July 2019, from http://ananth.org/unplanned-urbanisation-imminent-water-scarcity-bengaluru/.

Rao, K., Kulkarni, A., Patwardhan, S., Kumar, B., & Kumar, T. (2020). Future changes in precipitation extremes during northeast monsoon over south peninsular India. *Theoretical and Applied Climatology*, *142*(1-2), 205-217. https://doi.org/10.1007/s00704-020-03308-y

Ratnasari, D. (2019). The importance of cross-cultural understanding in foreign language teaching in the asian context. *Bahasa Dan Seni: Jurnal Bahasa, Sastra, Seni, Dan Pengajarannya*, *46*(2), 124-131. https://doi.org/10.17977/um015v46i22018p124

Rautela, P. (2000). *Water resources in the Himalayas: Harvesting, tradition and change* (1st ed.). Concept Pub. Co.

Rawat, A., & Sah, R. (2009). Traditional knowledge of water management in Kumaon Himalaya. *Indian Journal of Traditional Knowledge*, *8*(2), 249-254. Retrieved 26 July 2017.

Razeena, P., & Mini, M. (2016). Physico chemical properties of water from different water sources of midland laterite hill ecosystem of Kasaragod district of Kerala, India. *Asian Journal of Microbiology, Biotechnology and Environmental Sciences*, *18*(3), 651-654. Retrieved 22 May 2021.

Reddy, C., Jha, C., & Dadhwal, V. (2016). Assessment and monitoring of long-term forest cover changes (1920–2013) in Western Ghats biodiversity hotspot. *Journal of Earth System Science*, *125*(1), 103-114. https://doi.org/10.1007/s12040-015-0645-y

Reid, P., Hari, R., Beaugrand, G., Livingstone, D., Marty, C., & Straile, D. et al. (2015). Global impacts of the 1980s regime shift. *Global Change Biology*, *22*(2), 682-703. https://doi.org/10.1111/gcb.13106

Reynard, E., Bonriposi, M., Graefe, O., Homewood, C., Huss, M., & Kauzlaric, M. et al. (2014). Interdisciplinary assessment of complex regional water systems and their future evolution: how socioeconomic drivers can matter more than climate. *Wiley Interdisciplinary Reviews: Water*, *1*(4), 413-426. https://doi.org/10.1002/wat2.1032

Richer, S., & Gearey, B. (2017). The medicine tree: Unsettling palaeoecological perceptions of past environments and human activity. *Journal of Social Archaeology*, *17*(3), 239-262. https://doi.org/10.1177/1469605317731013

Robinson, J. (2004). Squaring the circle? Some thoughts on the idea of sustainable development. *Ecological Economics*, *48*(4), 369-384. https://doi.org/10.1016/j.ecolecon.2003.10.017

Robson, C., & McCartan, K. (2015). *Real world research* (4th ed.). John Wiley & Sons.

Rockström, J., Barron, J., Enfors, E., Falkenmark, M., Folke, C., & Gordon, L. et al. (2014). *Water resilience for human prosperity*. Cambridge University Press.

Ron, Z. (1985). Development and management of irrigation systems in mountain regions of the Holy Land. *Transactions of The Institute of British Geographers*, *10*(2), 149-169. Retrieved 28 February 2021, from https://www.jstor.org/stable/621820.

Rose, A. (2011). Resilience and sustainability in the face of disasters. *Environmental Innovation and Societal Transitions*, *1*(1), 96-100. https://doi.org/10.1016/j.eist.2011.04.003

Roser, M., Ritchie, H., & Ortiz-Ospina, E. (2019). *World population growth*. OurWorldInData.org. Retrieved 4 October 2019, from https://ourworldindata.org/world-population-growth.

Saha, D., & Agrawal, A. (2005). Determination of specific yield using a water balance approach – case study of Torla Odha watershed in the Deccan Trap province, Maharastra State, India. *Hydrogeology Journal*, *14*, 625-635. https://doi.org/10.1007/s10040-005-0471-4

Saleth, R. (2011). Water scarcity and climatic change in India: the need for water demand and supply management. *Hydrological Sciences Journal*, *56*(4), 671-686. https://doi.org/10.1080/02626667.2011.572074

Salve, P. (2017). *63 million Indians do not have access to clean drinking water*. Hindustan Times. Retrieved 7 August 2019, from https://www.hindustantimes.com/india-news/6-3-crore-indians-do-not-have-access-to-clean-drinking-water/story-dWIEyP962FnM8Mturbc52N.html.

Saranya, P., Krishnakumar, A., Kumar, S., & Anoop Krishnan, K. (2020). Isotopic study on the effect of reservoirs and drought on water cycle dynamics in the tropical Periyar basin draining the slopes of Western Ghats. *Journal of Hydrology*, *581*, 124421. https://doi.org/10.1016/j.jhydrol.2019.124421

Sarath, K., Narayan, A., & Shaji, E. (2021). Petrology and geochemistry of mafic, ultramafic and granitoid rocks of Swarga area within the Mercara shear zone, southern India. *Journal of Geology & Earth Sciences*, *1*(6), 1-23. Retrieved 28 April 2021.

Sarath, K., Shaji, E., Deepchand, V., Gurudeth, V., & Subeesh Chandran, C. (2020). Subsurface erosion by soil piping: A case study from Adoor-Pandi Area, Kasaragod, Kerala, India. In *Proceedings of the 4th Disaster, Risk and Vulnerability Conference* (pp. 294-300). Kottayam; School of environmental Sciences, Mahatma Gandhi University, Kerala. Retrieved 21 May 2021.

Sarkar, D., Sarkar, S., Manna, R., & Das, B. (2020). Microplastic pollution : Threat to Indian river system. *Everyman's Science*, *LIV*(6), 376-382. Retrieved 20 May 2021.

Sarvalingam, A., & Rajendran, A. (2016). Rare, endangered and threatened (RET) climbers of Southern Western Ghats, India. *Revista Chilena De Historia Natural*, *89*(1), 1-5. https://doi.org/10.1186/s40693-016-0058-6

Saunders, W., & Becker, J. (2015). A discussion of resilience and sustainability: Land use planning recovery from the Canterbury earthquake sequence, New Zealand. *International Journal of Disaster Risk Reduction*, *14*, 73-81. https://doi.org/10.1016/j.ijdrr.2015.01.013

Scarborough, V. (1998). Ecology and ritual: Water management and the Maya. *Latin American Antiquity*, *9*(2), 135-159. https://doi.org/10.2307/971991

Scarborough, V., Dunning, N., Tankersley, K., Carr, C., Weaver, E., & Grazioso, L. et al. (2012). Water and sustainable land use at the ancient tropical city of Tikal, Guatemala. *Proceedings of The National Academy of Sciences (PNAS)*, *109*(31), 12408-12413. https://doi.org/10.1073/pnas.1202881109

Schellmann, W. (2017). *An introduction to laterite: Products and processes of intensive rock weathering*. www.laterite.de. Retrieved 28 April 2017, from http://www.laterite.de/.

Schelwald-van der Kley, L., & Reijerkerk, L. (2009). *Water a way of life: Sustainable water management in a cultural context*. CRC Press/Balkema.

Schneider, F., Bonriposi, M., Graefe, O., Herweg, K., Homewood, C., & Huss, M. et al. (2015). Assessing the sustainability of water governance systems: the sustainability wheel. *Journal of Environmental Planning and Management*, *58*(9), 1577-1600. https://doi.org/10.1080/09640568.2014.938804

Schoonenboom, J., & Johnson, R. (2017). How to construct a mixed methods research design. *Kzfss Kölner Zeitschrift Für Soziologie Und Sozialpsychologie*, *69*(S2), 107-131. https://doi.org/10.1007/s11577-017-0454-1

Schwandt, T. (1998). Constructivist, interpretivist approaches to human inquiry. In N. Denzin & S. Lincoln, *The landscape of qualitative research: Theories and issues* (pp. 221-259). Sage Publications. Retrieved 4 January 2021.

Scott, A., & Coustalin, G. (1995). The evolution of water rights. *Natural Resources Journal*, *821*, 821-979. Retrieved 17 March 2021, from https://digitalrepository.unm.edu/nrj/vol35/iss4/4.

Shah, E. (2008). Telling otherwise: A historical anthropology of tank irrigation technology in south India. *Technology and Culture*, *49*(3), 652-674. https://doi.org/10.1353/tech.0.0054

Shaji, E., Santosh, M., Sarath, K., Prakash, P., Deepchand, V., & Divya, B. (2021). Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. *Geoscience Frontiers*, *12*(3), 101079. https://doi.org/10.1016/j.gsf.2020.08.015

Shaji, E., Sarath, K., Prakash, P., Abraham, A., Deepchand, V., Kunhambu, V., & Pradeepkumar, A. (2020). Tunnel wells, the traditional water harvesting structures of Kasaragod, Kerala: Re-visited. *Current Science*, *118*(6), 983-987. Retrieved 15 March 2021.

Shanmugasundaram, J., Gunnell, Y., Hessl, A., & Lee, E. (2017). Societal response to monsoon variability in Medieval South India: Lessons from the past for adapting to climate change. *The Anthropocene Review*, 205301961769534. https://doi.org/10.1177/2053019617695343

Sheeja, R., Joseph, S., Jaya, D., & Baiju, R. (2011). Land use and land cover changes over a century (1914–2007) in the Neyyar River Basin, Kerala: a remote sensing and GIS approach. *International Journal of Digital Earth*, *4*(3), 258-270. https://doi.org/10.1080/17538947.2010.493959

Shetty, G. (2018). Progress of anna bhagya yojana in Hungund taluk of Karnataka state. *International Journal of Current Research in Life Sciences*, *7*(5), 2083-2088. Retrieved 26 May 2021.

Shrestha, S., & Dahal, K. (2019). Comparison of operational cost between deep tubewell irrigation and borewell irrigation system in Parasan, Kanchanpur district, Nepal. *American Scientific Research Journal For Engineering, Technology, and Sciences*, *52*(1), 21-27. Retrieved 9 May 2021.

Shukla, S., & Saxena, A. (2020). Appraisal of groundwater quality with human health risk assessment in parts of Indo-Gangetic alluvial plain, North India. *Archives of Environmental Contamination and Toxicology*, *80*(1), 55-73. https://doi.org/10.1007/s00244-020-00771-6

Siebrecht, N. (2020). Sustainable agriculture and its implementation gap—Overcoming obstacles to implementation. *Sustainability*, *12*(9), 3853. https://doi.org/10.3390/su12093853

Silverman, D. (2011). *Qualitative research: Issues of theory, method and practice* (3rd ed.). SAGE.

Singh, C., Osbahr, H., & Dorward, P. (2018). The implications of rural perceptions of water scarcity on differential adaptation behaviour in Rajasthan, India. *Regional Environmental Change*, *18*(8), 2417-2432. https://doi.org/10.1007/s10113-018-1358-y

Singh, G., Rishi, M., Herojeet, R., Kaur, L., & Sharma, K. (2019). Evaluation of groundwater quality and human health risks from fluoride and nitrate in semi-arid region of northern India. *Environmental Geochemistry and Health*, *42*(7), 1833-1862. https://doi.org/10.1007/s10653-019-00449-6

Singh, P., Dey, P., Jain, S., & Mujumdar, P. (2020). Hydrology and water resources management in ancient India. *Hydrology and Earth System Sciences*, *24*(10), 4691-4707. https://doi.org/10.5194/hess-24-4691-2020

Singh, R., Mruthyunjaya, M., & Srivastava, P. (2021). Traditional water management in India. *Agricultural Water Management*, 19-28. https://doi.org/10.1016/b978-0-12-812362-1.00002-3

Singh, S., Gupta, A., Dutt, S., Bhaumik, A., & Anderson, D. (2020). Abrupt shifts in the Indian summer monsoon during the last three millennia. *Quaternary International*, *558*, 59-65. https://doi.org/10.1016/j.quaint.2020.08.033

Skalski, P., Neuendorf, K., & Cajigas, J. (2017). Content analysis in the interactive media age. In K. Neuendorf, *The content analysis guidebook* (2nd ed., pp. 201-403). SAGE. Retrieved 22 August 2017.

Sowthanya, C., & Shanmugam, T. (2019). An analysis of efficiency of drip irrigation technology in reducing water use. *International Journal of Agricultural Science and Research (IJASR)*, *9*(6), 69-76. Retrieved 23 May 2021.

Srinivasulu, B., Srinivasulu, C., & Kaur, H. (2015). Echolocation calls of four species of leaf-nosed bats (genus Hipposideros) from central peninsular India. *Current Science, 108*(6), 1055-1057. https://www.jstor.org/stable/24905425.

Staubwasser, M., Sirocko, F., Grootes, P., & Segl, M. (2003). Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. *Geophysical Research Letters*, *30*(8), 1425. https://doi.org/10.1029/2002gl016822

Steffen, W., Sanderson, A., Tyson, P., Jäger, J., Matson, P., & Moore III, B. et al. (2004). *Global change and the Earth system: A planet under pressure* (1st ed.). Springer.

Stiros, S. (2006). Accurate measurements with primitive instruments: the “paradox” in the qanat design. *Journal of Archaeological Science*, *33*(8), 1058-1064. https://doi.org/10.1016/j.jas.2005.11.013

Strauch, A., & Almedom, A. (2011). Traditional water resource management and water quality in rural Tanzania. *Human Ecology*, *39*(1), 93-106. https://doi.org/10.1007/s10745-011-9376-0

Subba Rao, N., Sunitha, B., Adimalla, N., & Chaudhary, M. (2019). Quality criteria for groundwater use from a rural part of Wanaparthy District, Telangana State, India, through ionic spatial distribution (ISD), entropy water quality index (EWQI) and principal component analysis (PCA). *Environmental Geochemistry and Health*, *42*(2), 579-599. https://doi.org/10.1007/s10653-019-00393-5

Surendran, S., Gadgil, S., Francis, P., & Rajeevan, M. (2015). Prediction of Indian rainfall during the summer monsoon season on the basis of links with equatorial Pacific and Indian Ocean climate indices. *Environmental Research Letters*, *10*(9), 094004. https://doi.org/10.1088/1748-9326/10/9/094004

Suri, K. (2018). Understanding historical, cultural and religious frameworks of mountain communities and disasters in Nubra valley of Ladakh. *International Journal of Disaster Risk Reduction*, *31*, 504-513. https://doi.org/10.1016/j.ijdrr.2018.06.004

Suseelan, A. (2008). Investigating the relation of a sustainable vernacular technique to settlement pattern. In J. Feyen, K. Shannon & M. Neville, *Water and urban development paradigms: Towards an integration of engineering, design and management approaches* (pp. 473-478). CRC Press. Retrieved 2 June 2017.

Sutcliffe, J., Shaw, J., & Brown, E. (2011). Historical water resources in South Asia: the hydrological background. *Hydrological Sciences Journal*, *56*(5), 775-788. https://doi.org/10.1080/02626667.2011.587425

Swart, R., Robinson, J., & Cohen, S. (2003). Climate change and sustainable development: expanding the options. *Climate Policy*, *3S1*, S19-S40. https://doi.org/10.1016/j.clipol.2003.10.010

Tableau Desktop. (2020). Tableau Desktop [Windows 10].

Tashakkori, A., & Teddlie, C. (2010). Epilogue: Current developments and emerging trends in integrated research methodology. In A. Tashakkori & C. Teddlie, *Sage handbook of mixed methods in social & behavioral research* (2nd ed., pp. 803-826). SAGE Publications, Inc. Retrieved 19 July 2017.

Thanal. (2009). *India’s endosulfan disaster: A review of the health impacts and status of remediation* (pp. 3-6). Thiruvananthapuram: Thanal.

The Hindu. (2018). *Man trapped in tunnel dies in Kasaragod*. The Hindu. Retrieved 11 December 2020, from https://www.thehindu.com/news/national/kerala/man-trapped-in-suranga-dies/article25637802.ece.

The News Minute. (2020). *Man trapped in Kerala water tunnel for over 5 hours passes away*. The News Minute. Retrieved 11 December 2020, from https://www.thenewsminute.com/article/man-trapped-kerala-water-tunnel-over-5-hours-passes-away-127145.

The Telegraph. (2012). *Water at the end of the tunnel*. Telegraphindia.com. Retrieved 24 March 2021, from https://www.telegraphindia.com/science-tech/water-at-the-end-of-the-tunnel/cid/455598.

Thimmaiah, G., & Aziz, A. (1983). The political economy of land reforms in Karnataka, A south Indian state. *Asian Survey*, *23*(7), 810-829. Retrieved 16 March 2021, from https://www.jstor.org/stable/2644290.

Thomas, G. (2013). *How to do your research project: A guide for students in education and applied social sciences* (2nd ed.). SAGE Publications Ltd.

Thompson, P., & Bornat, J. (2017). *The voice of the past: Oral history* (4th ed.). Oxford University Press.

Thorén, H. (2014). Resilience as a unifying concept. *International Studies in The Philosophy of Science*, *28*(3), 303-324. https://doi.org/10.1080/02698595.2014.953343

Thorén, H., & Olsson, L. (2017). Is resilience a normative concept?. *Resilience: International Policies, Practices and Discourses*, *6*(2), 112-128. https://doi.org/10.1080/21693293.2017.1406842

Treacy, J. (1987). Building and rebuilding agricultural terraces in the Colca valley of Peru. *Yearbook (Conference of Latin Americanist Geographers), 13*, 51-57. Retrieved 25 May 2021.

Tripathi, A., & Mishra, A. (2017). Knowledge and passive adaptation to climate change: An example from Indian farmers. *Climate Risk Management*, *16*, 195-207. https://doi.org/10.1016/j.crm.2016.11.002

Tripathi, S. (2009). *A case study of surangas (adit systems): A traditional water management system practised in India* (MSc dissertation). University of Hertfordshire.

Ünal, M., Can, O., Can, B., & Poyraz, K. (2018). The effect of Bat guano applied to the soil in different forms and doses on some plant nutrient contents. *Communications in Soil Science and Plant Analysis*, *49*(6), 708-716. https://doi.org/10.1080/00103624.2018.1434540

UNDP. (2020). *The next frontier: Human development and the Anthropocene*. New York: The United Nations Development Programme.

United Nations. (2021). *The human right to water and sanitation*. Un.org. Retrieved 23 April 2021, from https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf.

Unnikrishnan, H., Sen, S., & Nagendra, H. (2017). Traditional water bodies and urban resilience: A historical perspective from Bengaluru, India. *Water History*. https://doi.org/10.1007/s12685-017-0199-9

van Oldenborgh, G., Philip, S., Kew, S., van Weele, M., Uhe, P., & Otto, F. et al. (2018). Extreme heat in India and anthropogenic climate change. *Natural Hazards and Earth System Sciences, 18*(1), 365-381. https://doi.org/10.5194/nhess-18-365-2018

Varis, O., Kummu, M., & Salmivaara, A. (2012). Ten major rivers in monsoon Asia-Pacific: An assessment of vulnerability. *Applied Geography*, *32*(2), 441-454. https://doi.org/10.1016/j.apgeog.2011.05.003

Veeranna, J., & Jeet, P. (2020). Groundwater recharges technology for water resource management: A case study. *Groundwater*. https://doi.org/10.5772/intechopen.93946

Vij, S., Moors, E., Kujawa-Roeleveld, K., Lindeboom, R., Singh, T., & de Kreuk, M. (2021). From pea soup to water factories: wastewater paradigms in India and the Netherlands. *Environmental Science & Policy*, *115*, 16-25. https://doi.org/10.1016/j.envsci.2020.09.015

Vijay, A., Sivan, S., Mudbhatkal, A., & Mahesha, A. (2021). Long-term climate variability and drought characteristics in tropical region of India. *Journal of Hydrologic Engineering*, *26*(4), 05021003. https://doi.org/10.1061/(asce)he.1943-5584.0002070

Vincent, L. (1995). *Hill irrigation: Water and development in mountain agriculture*. Intermediate Technology Publications on behalf of the Overseas Development Institute.

Viswanath, S., Lubina, P., Subbanna, S., & Sandhya, M. (2018). Traditional agroforestry systems and practices: A Review. *Advanced Agricultural Research & Technology Journal, II*(1), 18-29. Retrieved 20 November 2019.

Vitelli, R. (2017). *How universal Is body language?*. Psychology Today. Retrieved 9 May 2021, from https://www.psychologytoday.com/gb/blog/media-spotlight/201704/how-universal-is-body-language.

Vogt, E., & Golde, P. (1958). Some aspects of the folklore of water witching in the United States. *The Journal of American Folklore*, *71*(282), 519-531. Retrieved 22 October 2019.

Wacharapluesadee, S., Sintunawa, C., Kaewpom, T., Khongnomnan, K., Olival, K., & Epstein, J. et al. (2013). Group C betacoronavirus in Bat guano fertilizer, Thailand. *Emerging Infectious Diseases*, *19*(8). https://doi.org/10.3201/eid1908.130119

Wahurwagh, A., & Dongre, A. (2015). Burhanpur cultural landscape conservation: Inspiring quality for sustainable regeneration. *Sustainability*, *7*(1), 932-946. https://doi.org/10.3390/su7010932

Walker, B. (2020). Resilience: what it is and is not. *Ecology and Society*, *25*(2), 11. https://doi.org/10.5751/es-11647-250211

Walker, B., & Salt, D. (2012). *Resilience practice*. Island Press.

Walker, B., Holling, C., Carpenter, S., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, *9*(2:5). Retrieved 8 December 2020, from https://www.ecologyandsociety.org/vol9/iss2/art5/.

Walsh, M. (2001). *Research made real: A guide for students*. Nelson Thornes.

Wang, B., & Ding, Q. (2006). Changes in global monsoon precipitation over the past 56 years. *Geophysical Research Letters, 33*(6). https://doi.org/10.1029/2005gl025347

Wang, B., Biasutti, M., Byrne, M., Castro, C., Chang, C., & Cook, K. et al. (2021). Monsoons climate change assessment. *Bulletin of The American Meteorological Society*, *102*(1), E1-E19. https://doi.org/10.1175/bams-d-19-0335.1

WaterAid. (2017). *Wild water: The state of the world's water 2017*. WaterAid.

WCRP. www.wcrp-climate.org. (2017). Retrieved 21 June 2017, from https://www.wcrp-climate.org/documents/monsoon_factsheet.pdf.

Wei, W., Chen, D., Wang, L., Daryanto, S., Chen, L., & Yu, Y. et al. (2016). Global synthesis of the classifications, distributions, benefits and issues of terracing. *Earth-Science Reviews*, *159*, 388-403. https://doi.org/10.1016/j.earscirev.2016.06.010

Weiss, H., Courty, M., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., & Curnow, A. (1993). The Genesis and Collapse of Third Millennium North Mesopotamian Civilization. *Science*, *261*(5124), 995-1004. https://doi.org/10.1126/science.261.5124.995

Welc, F., & Marks, L. (2014). Climate change at the end of the Old Kingdom in Egypt around 4200 BP: New geoarchaeological evidence. *Quaternary International*, *324*, 124-133. https://doi.org/10.1016/j.quaint.2013.07.035

WHO. (2009). *Summary and policy implications Vision 2030 : The resilience of water supply and sanitation in the face of climate change*. WHO.

Whyte, I. (2013). *A dictionary of environmental history*. IB Tauris.

Widgren, M., Maggs, T., Plikk, A., Risberg, J., Schoeman, M., & Westerberg, L. (2016). Precolonial agricultural terracing in Bokoni, South Africa: Typology and an exploratory excavation. *Journal of African Archaeology*, *14*(1), 33-53. https://doi.org/10.3213/2191-5784-10281

Wiek, A., & Larson, K. (2012). Water, people, and sustainability: A systems framework for analyzing and assessing water governance regimes. *Water Resources Management*, *26*(11), 3153-3171. https://doi.org/10.1007/s11269-012-0065-6

Wilkinson, T. (1997). Environmental fluctuations, agricultural production and collapse: A view from bronze age upper Mesopotamia. In H. Dalfes, G. Kukla & H. Weiss, *Third millennium BC climate change and old world collapse* (pp. 67-106). Springer in cooperation with NATO Scientific Affairs Division. Retrieved 20 June 2017.

Wilson, G. (2018). “Constructive tensions” in resilience research: Critical reflections from a human geography perspective. *The Geographical Journal*, *184*, 89-99. https://doi.org/10.1111/geoj.12232

Wilson, G., Schermer, M., & Stotten, R. (2018). The resilience and vulnerability of remote mountain communities: The case of Vent, Austrian Alps. *Land Use Policy*, *71*, 372-383. https://doi.org/10.1016/j.landusepol.2017.12.022

Wisser, D., Frolking, S., Douglas, E., Fekete, B., Schumann, A., & Vörösmarty, C. (2010). The significance of local water resources captured in small reservoirs for crop production – A global-scale analysis. *Journal of Hydrology*, *384*(3-4), 264-275. https://doi.org/10.1016/j.jhydrol.2009.07.032

World Bank. (2020). *World Bank Climate Change Knowledge Portal*. Climateknowledgeportal.worldbank.org. Retrieved 26 November 2020, from https://climateknowledgeportal.worldbank.org/country/india.

Wulff, H. (1968). The qanats of Iran. *Scientific American*, *218*(4), 94-105. https://doi.org/10.1038/scientificamerican0468-94

Wurster, C., Munksgaard, N., Zwart, C., & Bird, M. (2015). The biogeochemistry of insectivorous cave guano: a case study from insular Southeast

Asia. *Biogeochemistry*, *124*(1-3), 163-175. https://doi.org/10.1007/s10533-015-0089-0

XLSTAT. (2020). XLSTAT statistical and data analysis solution [Windows 10]. Addinsoft.

Xu, A., Yang, L., Yang, W., & Chen, H. (2020). Water conservancy projects enhanced local resilience to floods and droughts over the past 300 years at the Erhai Lake basin, Southwest China. *Environmental Research Letters*, *15*(12), 125009. https://doi.org/10.1088/1748-9326/abc588

Yadav, S., & Lal, R. (2018). Vulnerability of women to climate change in arid and semi-arid regions: The case of India and South Asia. *Journal of Arid Environments, 149*, 4-17. Retrieved 29 April 2021.

Yannopoulos, S., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A., & Angelakis, A. (2015). Evolution of water lifting devices (Pumps) over the centuries worldwide. *Water*, *7*(12), 5031-5060. https://doi.org/10.3390/w7095031

Yates, S. (2004). *Doing social science research*. Sage Publications in association with the Open University.

Yazdi, A., & Khaneiki, M. (2012). Chapter 1 - Forward. In A. Yazdi & M. Khaneiki, *Qanats in its cradle: Situation of qanat (Kariz, Karez, Falaj) in the World* (1st ed., pp. 7-20). Retrieved 5 June 2019.

Yechezkel, A., & Frumkin, A. (2016). Chapter 10: Spring tunnels (Niqba') the Jerusalem hills perspective, Israel. In A. Angelakis, E. Chiotis, S. Eslamian & H. Weingartner, *Underground aqueducts handbook* (pp. 151-172). CRC Press. Retrieved 2 June 2017.

Yechezkel, A., Frumkin, A., & Tzionit, S. (2021). Ancient spring tunnels of Jerusalem, Israel: Physical, spatial, and human aspects. *Environmental Archaeology,* 1-19. https://doi.org/10.1080/14614103.2021.1888613

Zhisheng, A., Guoxiong, W., Jianping, L., Youbin, S., Yimin, L., & Weijian, Z. et al. (2015). Global Monsoon Dynamics and Climate Change. *Annual Review of Earth and Planetary Sciences*, *43*(1), 29-77. https://doi.org/10.1146/annurev-earth-060313-054623

Zhou, T., Yu, R., Li, H., & Wang, B. (2008). Ocean forcing to changes in global monsoon precipitation over the recent half-century. *Journal of Climate*, *21*(15), 3833-3852. https://doi.org/10.1175/2008jcli2067.1

Appendices

Appendix A: TWM systems in India[1]

	Name	Location (India)	Water source	Main Structure	Associate structure	Ownership Management
1	Zing	Ladakh	Glaciers	Tank	Open channel	Community
2	Kuls	Spiti valley, (Himachal Pradesh) Jammu region (Jammu and Kashmir)	Glaciers, streams	Channels	Tanks	Community
3	Naula	Uttarakhand	Stream, spring	Steppond Stepwell		Community, Private
4	Khatri	Hamirpur, Kangra, Madi (Himachal Pradesh)	Rainwater	Well carved in hard rock		Community, Private, Government-owned
5	Kuhl	Himachal Pradesh	Streams			Community
6	Zabo or Ruza	Phek (Nagaland)	Rainwater From a hill top	Tanks at terraces	Channel	
7	Cheo-ozihi	Angami village, Kwigema, (Nagaland)	River	Bamboo channels	Channel	Community
8	Eri	Tamilnadu	Rivers, Rainwater	Large tanks	Channel	Community
9	Oorani	Tamilnadu	Rainwater	Pond		
10	Dongs	Nalbari, Baksa (Assam)	River, Floodwater	Diversion channels of rivers	Earthen dams on low streams, ponds	Community
11	Ahar-Pyne	South Bihar	Floodwater, river	Payne: flood water diversion channel, Ahar: a water tank		
12	Ohad	Vidarbha	Streams	Series of Phad on a stream		
13	Gonchi	Anantapur (Andhra Pradesh)				
14	Bamboo drip irrigation	Khasi, Jaintia hills (Meghalaya)	Stream Spring	Conduits		
15	Apatani	Ziro (Arunachal Pradesh)	Springs Streams Groundwater	Small connected ponds at a	Channel	

[1] Adapted from Agarwal & Narain, 1997

				terraced field		
16	Virdas	Rann of Kutch (Gujarat)	Rainwater harvesting, subsurface flow in depressions	Small shallow wells		Community
17	Keni	Waynad (Kerala)	Subsurface flow, Rainwater In depressions	Small shallow wells		Community
18	Katas Mundas Bandhas	Ancient Gonds Kingdom (Orissa, Madhya Pradesh, Chhattisgarh, and Maharashtra)		Tank	Channels	
19	*Suranga*	Kasaragod (Kerala) Dakshin Kannada (Karnataka) North Goa	Subsurface rainwater	Adit system	Pond, and dug well	Private
20	Korambu, chira	Kasaragod, Thrissur (Kerala)	Streams	Temporary wooden check dam	Channels	Community
21	Katta	Dakshin Kannada (Karnataka)	River Streams Springs	Temporary check dam	Channels	Community
22	Dung or Jampoi	Jalpaiguri (West Bengal)		Channels		
23	Cheruvu	Chitoor, Cuddapah districts (Andhra Pradesh)	Rainwater runoff	Tank	Canal Flood weir	Community
24	Inundation Channel	Bengal	Floodwater	Canal	Tanks, Lakes	Community
25	Kohli tanks	Bhandara (Maharashtra)		Tank	Channels	Community
26	Bhandara	Maharashtra	River	Check dams	Channels	Community Individual
27	Phad	North-west Maharashtra				Community
28	Kere	Karnataka	River Stream *Suranga* Katta	Tank	Channels	Community Individual
29	Madaka	Dakshin Kanada, Kasaragod	Rainwater	Tank	Channels	Community
30	Ramtek model	Ramtek (Maharashtra)	Rainwater	Tank	Channels	Community

Appendix B: The documents consulted at various archives

Year	Archive location	Title
1807	Online archives	A journey from Madras through the Countries of Mysore, Canara, and Malabar by Francis Buchanan Vol 1 London
1807	Online archives	A journey from Madras through the Countries of Mysore, Canara, and Malabar by Francis Buchanan Vol 2 London
1807	Online archives	A journey from Madras through the Countries of Mysore, Canara, and Malabar by Francis Buchanan Vol 3 London
1821	Online archives	A visit to Madras: Being a sketch of the local and characteristic peculiarities in the year 1811
1844	The British Library, London	Report on The Medical Topography and Statistics of The Provinces of Malabar and Canara. Madras: Printed by R.W.Thorpe, at the Vepery Mission Press. 1844.
1853	Personal archives	Manila village land document
1855	Archives and historical research, Chennai	Gazetteer of South India 1855
1858	Online archives	A dictionary, Canarese and English, by the Rev. W. Reeve, Revised, corrected and abridged, by Daniel Sanderson, Bangalore
1861	Archives and historical research, Chennai	Settlement Report of South Canara
1864	Archives and historical research, Chennai	Report on the settlement of the land revenue of the provinces under the Madras Presidency for 1862-1963
1866	Archives and historical research, Chennai	The Imperial Gazetteer of India
1866	Personal archives	Peruvai village, Murva land contract
1869	Archives and historical research, Chennai	Proceedings of the Board of Revenue for the month of November 1875 Vol XI Madras
1870	The British Library, London	Report on Pisciculture in South Canara by H S Thomas. London:
1870	Personal archives	Land tenancy agreement, Peruvai village
1871	Archives and historical research, Chennai	Census of India
1874	The British Library, London	Census Statement of Population of 1871 in each village of the South Canara District. By Graves, Cookson and Co. IOR/V/15/11
1875	Archives and historical research, Chennai	Proceedings of the Board of Revenue for the month of February 1869 Vol II Madras

1875	The British Library, London	Canara Past and Present by Samuel Miley. Madras: Addison and Co., 18, Mount Road, 1875
1883	The British Library, London	Census of 1881. Villagewar Statements of Area, Houses, and Population for the South Canara District. Madras: Printed at the Memorial Press. IOR/v/15/27
1884	Archives and historical research, Chennai	Report on the settlement of the land revenue of the provinces under the Madras Presidency for 1882-1883
1893	Archives and historical research, Chennai	Census of India 1891 Volume XIII, Madras
1893	Archives and historical research, Chennai	Census of India 1891 by H A Stuart Volume XIV, Madras
1894	Archives and historical research, Chennai	Madras District Manuals, South Canara Manual Vol I by Harold A Stuart
1895	Archives and historical research, Chennai	Report of the administration of the Madras Presidency during the year 1894-95, Madras
1895	Archives and historical research, Chennai	Madras District Manuals, South Canara Manual Vol II by J Strurrock
1895	The British Library, London	Census of 1891. Taluk and Village Statistics. South Canara District. Madras: Printed by the Superintendent, Government Press. IOR/V/15/43
1895	Personal archives	Murva farm map
1901	The British Library, London	Census of 1901. Village Statistics. South Canara District, Madras Presidency. Madras: Printed by the Superintendent, Government Press. IOR/V/15/76
1902	Online archives	The Economic History of India under early British Rule by Romesh Dutt Vol 1 London
1904	Online archives	The Economic History of India in the Victorian age by Romesh Dutt Vol 2 London
1905	Archives and historical research, Chennai	Report on the settlement of the land revenue of the provinces under the Madras Presidency for 1903-1904
1905	The British Library, London	Madras District Gazetteers. South Canara. Volume II. Statistical Appendix for South Canara District. Printed by the Superintendent, Government Press. 1905. BA self No: IOR/V/27/66/52
1905	Personal archives	First land settlement record Manila village, Survey Map no 169,
1908	Archives and historical research, Chennai	Imperial Gazetteer of India, Provincial Series, Madras II 1908
1908	Archives and historical research, Chennai	The Imperial Gazetteer of India 1908 Vol IX
1912	Archives and historical research, Chennai	Census of India 1911 VOl XII Madras Part II

1913	Online archives	The Madras Presidency with Mysore, Coorg and the associated states by Edgar Thurston, Cambridge
1915	Archives and historical research, Chennai	Southern India: History, People, Commerce, and Industrial Resources by Somerset Playne
1915	Archives and historical research, Chennai	Report on the settlement of the land revenue of the provinces under the Madras Presidency for 1913-1914
1915	The British Library, London	Madras District Gazetteers. South Canara. Volume II. BA self No: IOR/V/27/66/53
1918	The British Library, London	Annual report of the four agricultural research stations. IVOR/V/24/1480
1918	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk for 1917-1918. By H C Sampson. Madras, Government Press, 1918
1919	The British Library, London	An Essay on the development of industries in South Canara. By M. Shankaranaraina Rao. Mangalore: Mangalore Trading Association's Sharada Press. 1919
1921	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1920-21. By M Govind Kidavu. Madras, Government Press, 1921
1922	Archives and historical research, Chennai	Census of India 1921 VOl XIII Madras Part III by G T Boag
1922	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1921-22. By M Govind Kidavu. Madras, Government Press, 1922
1923	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1922-23. By M Govind Kidavu. Madras, Government Press, 1923
1924	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1923-24.By M Govind Kidavu. Madras, Government Press, 1924
1925	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1924-25. By M Govind Kidavu. Madras, Government Press, 1925
1926	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1925-26. By M Govind Kidavu. Madras, Government Press, 1926
1927	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1926-27. By M Govind Kidavu. Madras, Government Press, 1927.
1928	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1927-28. By M Govind Kidavu. Madras, Government Press, 1928.
1929	The British Library, London	Report on the work of the Coconut stations in the Kasaragod Taluk of South Canara District for 1928-29. By M Govind Kidavu. Madras, Government Press, 1929.
1931	The British Library, London	Annual Report of the four agricultural research stations in the Kasaragod taluk of South Canara District for the year 1929-30. By Saadatullah Khan, Madras, Government Press, 1931.

1932	Archives and historical research, Chennai	Census of India 1931 Volume XIV Madras State Part II
1933	The British Library, London	Picturesque South Canara. By K S Karanth. Basel Mission Book and Tract Depository, Mangalore, S. K. P/T1202 1933
1933	Online archives	Boag, G.T. (1933). The Madras Presidency 1881-1931. Madras: Government Press
1934	The British Library, London	The Scenery of South Canara by T B Krishnaswami. Printed by F H Rauleder, Basel Mission Press Mangalore S. K. Brit. India T1113
1938	Archives and historical research, Chennai	Fortnightly report 1938
1938	The British Library, London	Madras District Gazetteers, Statistical Appendix, together with a supplement to the two District Manuals for South Canara District. By K N Krishnaswami Ayyar. Madras: Superintendent Government Press. 1938
1940	Online archives	Some south Indian Villages: A resurvey by P J Thomas and K C Ramakrishnan, University of Madras
1942	Archives and historical research, Chennai	Census of India 1941
1942	Archives and historical research, Chennai	Fortnightly report 1938
1950	The British Library, London	Karantha, K. V. (1950). Prosperity for villages. Madras: Harsha Printery & Publications.
1952	Archives and historical research, Chennai	Census of India, Final Population Totals 1961 Census
1956	Archives and historical research, Chennai	Abstract of 1951 Census tables for Madras State
1962	Archives and historical research, Chennai	Census of India, Final Population Totals 1951 Census
1964	Karnataka State Archives, Bengaluru	Revision settlement report of Puttur zone- South Canara district, The government press Bangalore
1964	Personal archives	Land records
1969	The British Library, London	Antiquities of South Canara. Dr P Gururaja Bhatt, 1969. Prabhakara Press Limited: Udipi. T 25058
1972	Archives and historical research, Chennai	Census Centenary 1972 Pocket book of population statistics
1973	Archives and historical research, Chennai	Gazetteer of India, Karnataka State, South Canara District
1983	Archives and historical research, Chennai	Karnataka State Gazetteer Part I and II, Gazetteer of India

1985	Archives and historical research, Chennai	Gazetteer of India, Karnataka State, Uttara Kannada Manual 1985
1990	The British Library, London	Basel Mission Industries in Malabar and South Canara 1834 – 1914: A study of its social and economic Impact. By Jaiprakash Raghaviah . Gian Publishing House: New Delhi. 1990
1997	Archives and historical research, Chennai	The Encyclopaedic District Gazetteers of India S C Bhatt
1997	Personal archives	Manila village map
1998	The British Library, London	South Canara (1799-1860): A study in colonial administration and Regional response by N S Bhat (1998)

Appendix C: The population of South Canara[2] (1871-2011 CE)

Year of census	Total Population	Area of South Canara (square km)	Density (person per square km)
1871	918,362	10,106.13	91
1881	959,514	10,106.13	95
1891	1,056,081	10,106.13	104
1901	1,134,713	10,106.13	112
1911	1,195,227	10,414.34	115
1921	1,247,368	10,414.34	120
1931	1,372,241	10,414.34	132
1941	1,522,016	10,476.50	145
1951	1,748,991	10,473.91	167
1961[3]	1,563,837	8,414.87	186
1971	2,077,238	8,414.87	247
1981[4]	---	8,414.87	---
1991	---	8,414.87	---
2001[5]	1,897,730	4,559.00	416
2011	2,083,625	4,559.00	457

[2] Source: Various census data (Census of 1871, 1874; Census of 1881, 1883; Census of 1891, 1895; Census of 1901, 1901; Government of India, 2012)

[3] Kasaragod sub-district was carved out from South Kanara and added into Kannur District (Kerala State) on 1st November 1956 . South Kanara, which as a part of Madras State was now attached to Mysore State.

[4] Census record could not be found or 1981, and 1991 census.

[5] Udupi district was carved out from South Kanara on 15 August 1997.

Appendix D: Risk assessment

FACULTY OF HEALTH AND HUMAN SCIENCES
RISK ASSESSMENT

Ref No:	# 144.
Date:	23 AUG 2012
Review Date:	23 AUG 2013

ACTIVITY INFORMATION	
Name of Assessor/ Contact details	Name: Sudhir Tripathi Email address: s.tripathi2@herts.ac.uk Ext no: 1025
Title of Activity	An investigation into the sustainability of *suranga* technology in south Karnataka and north Kerala states of India.
Location of Activity	Manila Village, Dakshin Kannada, Karnataka, India. Most of the samples will be tested in fields and in a local laboratory as well. No samples/chemicals are planned to import to the UK.
Description of Activity	A case study of *suranga* (men made water tunnel) by observation and interviewing adult farmers, nongovernmental and governmental organisations. Further, water and soil samples to be collected for testing various parameters.
Personnel Involved	Sudhir Tripathi

TYPES OF HAZARD LIKELY TO BE ENCOUNTERED		
☐ Animal Allergens ☑ **Biological Agents (see COSHH)** ☑ **Chemical Compounds (see CoSHH)** ☐ Compressed/liquefied gases ☑ **Computers** ☐ Electricity ☑ **Falling Objects** ☐ Farm Machinery ☐ Fire ☐ Glassware Handling	☐ Hand Tools ☐ Ionising Radiation ☐ Office Equipment ☐ Laboratory Equipment ☐ Ladders ☐ Manual Handling ☐ Non-ionising Radiation ☐ Hot or cold extremes ☐ Repetitive Handling ☐ Severe Weather	☐ Sharps ☑ **Slips/trips/falls** ☐ Stress ☑ **Travel** ☐ Vacuum systems ☐ Pressure systems ☐ Vehicles ☐ Violence, physical or verbal abuse ☐ Workshop Machinery
The above is not an exhaustive list – all other hazards should be listed here. Adit Collapse Dehydration and Sunstroke Suffocation inside adit Venomous snakes Travelling to and within India		

FACULTY OF HEALTH AND HUMAN SCIENCES
RISK ASSESSMENT

Traffic accident
Tropical diseases
Biological Hazard

HAZARD ASSESSMENT						
Severity of Consequences	Factor	Risk Classification				
No or minor injury/ health disorder Minor Damage or Loss Insignificant Environmental Impact Group 1 Biological agents	1	Trivial (1)	Trivial (2)	Trivial (3)	Trivial (4)	Tolerable (5)
Injury or Health Disorder – resulting in absence up to 3 days Moderate Damage or Loss Moderate Environmental Impact Group 2 Biological agents	2	Trivial (2)	Trivial (4)	Tolerable (6)	Tolerable (8)	Moderate (10)
Injury or Health Disorder – resulting in absence over 3 days Substantial Damage or Loss Serious Environmental Impact Group 3 Biological agents	3	Trivial (3)	Tolerable (6)	Moderate (9)	Moderate (12)	Substantial (15)
Long Term Injury or Sickness – resulting in permanent incapacity Extensive Damage or Loss Major Long Term Environmental Impact	4	Trivial (4)	Tolerable (8)	Moderate (12)	Substanti al (16)	Intolerable (20)
Death Serious Structural Damage Environmental Catastrophe Group 4 Biological agents	5	Tolerable (5)	Moderate (10)	Substantial (15)	Intolerable (20)	Intolerable (25)
Note on Risk Classification: 1-4 Trivial 5-7 Tolerable 8-12 Moderate 13-16 Substantial >20 Intolerable	→ Likelihood	1 Almost Impossible	2 Unlikely – possible exposure every 1-3 years	3 Harm is possible	4 Harm is likely to occur	5 Harm will occur or is very likely to occur.

University of Hertfordshire UH

FACULTY OF HEALTH AND HUMAN SCIENCES
RISK ASSESSMENT

ASSESSMENT OF RISK CLASSIFICATION			
Hazard	Likelihood Score	Severity Score	Risk Classification
Biological Agents (see COSHH)	2	2	Trivial (4)
Chemical Comounds (CoSHH)	2	1	Trivial (2)
Computer breakdown	2	2	Trivial (4)
Falling objects	2	2	Trivial (4)
Slips/Trips/Falls	2	3	Tolerable (6)
Travel	2	3	Tolerable (6)
Adit Collapse	2	2	Trivial (4)
Dehydration and Sunstroke	1	3	Trivial (3)
Suffocation inside adit	1	5	Tolerable (5)
Venomous snakes	2	3	Tolerable (6)
Traffic accident	2	3	Tolerable (6)
Tropical diseases	2	2	Trivial (4)
Biological Hazard	2	3	Tolerable (6)

EFFECT OF RISK CLASSIFICATION	
Risk Classification	Action
Trivial	No further action required. Activity can begin.
Tolerable	No additional controls required. Current controls must be maintained and monitored.
Moderate	Reduce risks if cost effective. Implement new controls over an agreed period.
Substantial	Activity cannot begin without major risk reduction.
Intolerable	Activity must not begin.

RISK CONTROL MEASURES
Is the local code of practice or local rules adequate to control the risks identified? Yes/No If no, list all additional measures required.

University of Hertfordshire UH

FACULTY OF HEALTH AND HUMAN SCIENCES RISK ASSESSMENT

Additional Measures:

Adit Collapse: Use of a helmet and glasses is recommended. Must be accompanied with the owner of *suranga* and only enter into safe and reliable *suranga*. In case of doubt about the stability of a *suranga* never enter into the *suranga*. Working alone must be avoided. Carrying a mobile phone and a whistle/alarm is always recommended.

Dehydration and Sunstroke: Drink and carry water to fields. Moreover, use of sun screen and insect repellent during field and use of insect repellent during night time.

Suffocation inside adit: Remove to fresh air immediately if feel suffocated inside a *suranga*. Never allow more than three people inside a *suranga* at a time. Never use, fire lamps inside a suranga.

Venomous snakes: Always wear safety shoes, safety clothes inside a *suranga*. Always use a light/torch in dark.

Traffic accident and Travelling to and within India: Avoid using open and unsafe vehicles. Use reliable travel companies and travel insurance is recommended.

Tropical diseases: Practice good hygiene and seek local doctor's advice in case of doubt.

Biological Hazard: Practice good hygiene, i.e washing of hands and use of anti-bacterial washes.

HEALTH SURVEILLANCE ISSUES	
Persons at Special Risk	N.A.
Health Surveillance Measures (including symptoms and signs of exposure)	In contact with chemicals • Irritation in eyes, nose or skin • suffocation Symptoms of dehydration : • feeling thirsty and lightheaded • having dark coloured, strong-smelling urine • passing urine less often than usual The symptoms of heatstroke can include: • mental confusion • rapid shallow breathing (hyperventilation)

	• loss of consciousness
Exclusions	

SIGNATURES				
	Staff/PhD student/MSc student/Undergraduate	Name (Print)	Signature	Date
Assessor	Staff (Research Assistant)	Sudhir Tripathi	सुधीर चन्द्र त्रिपाठी	18 Aug 2012
Supervisor (if Assessor is a student)				
Local Health and Safety Advisor	STAFF	ANDREW HARMAN	A Harman	23 AUG 2012

Appendix E: *Suranga* survey questionnaire

1. ಯಾವ ವರ್ಷದಲ್ಲಿ ಸುರ೦ಗವನ್ನು ರಚಿಸಲಾಯಿತುWhen this *suranga* was excavated (year):
2. ಸುರ೦ಗವನ್ನು ರಚಿಸಿದವರು?(owner/contracted *suranga* diggers)
3. ಸುರ೦ಗ ಮತ್ತು ಟ್ಯಾ೦ಕ್ ರಚಿಸಲು ತೆಗೆದುಕೊ೦ಡ ಅವಧಿ Time taken to finish construction of *suranga* and tank:
4. ಸುರ೦ಗ ರಚಿಸಿದ ನ೦ತರದ ನೀರಿನ ಪ್ರಮಾಣ : ಕಡಿಮೆ ಜಾಸ್ತಿ ಸ್ಥಿರ Water supply increasing(I), decreasing (d) or constant (d) since excavated:
5. ಆಕಾರ (ಆಯತRectangular/ಗು೦ಬಝ್ Dome shaped):
6. ಸುರ೦ಗದ ಉದ್ದ Length of *suranga*:
7. ಸುರ೦ಗದಲ್ಲಿ ಕವಲುಗಳಿವೆಯೆ?Is *suranga* straight or branched?
8. ಎಶ್ ಕವಲುಗಳಿವೆ? If branched, how many branches:
9. ಸುರ೦ಗದ ಹಾದಿ ಸುಗಮವಾಗಿದೆಯೇ?Is *suranga* accessible?
10. ಸುರ೦ಗದ ಒಳಗೆ ಗಾಳಿಯ ಆವಶ್ಯಕತೆಗಾಗಿ ಮೇಲ್ಭಾಗದಿ೦ದ ಕಿ೦ಡಿಗಳನ್ನು ಕೊರೆದಿದ್ದೀರಾ?Any airshafts in the *suranga*:
11. ಸುರ೦ಗ ರಚಿಸಿದ ಜಾಗ Location of *suranga*:

a)Elevated ಗುಡ್ಡಕ್ಕೆ ಅಡ್ಡವಾಗಿ	
b)Bottom of dug well ಬಾವಿಯ ಒಳಗೆ	
c)Beside a pond ಕೆರೆಯ ಬದಿ	
d)Others ಇತರ	

12. ಸುರ೦ಗ ನಿರ್ವಹಣೆ ಮಾಡಲ್ಪಡುತ್ತದೆಯೋ? ಅಥವಾ ನಿರ್ಲಕ್ಷಿಸಲ್ಪಟ್ಟಿದೆಯೆ?Is *suranga* maintained or abandoned:
13. ನಿರ್ಲಕ್ಷಿಸಲ್ಪಟ್ಟ ಕಾರಣ If abandoned, the reason for abandonment:
14. ನಿರ್ಲಕ್ಷಿಸಲ್ಪಟ್ಟ ಸುರ೦ಗದಿ೦ದ ಈಗಲೂ ನೀರು ಸಿಗುತ್ತಿದೆಯೇ ?Does the abandoned *suranga* still produce water?
15. ನೀರು ಸಿಗುತ್ತಿದ್ದಲ್ಲಿ ಇಡೀ ವರ್ಷ ಸಿಗುತ್ತದೋ ಅಥವಾ ಕೆಲವು ತಿ೦ಗಳು ಸಿಗುತ್ತದೋ? If it produces water, is it seasonal or perennial:

16. ಸ್ವಂತ ಬಂಡವಾಳದಿಂದ ಸುರಂಗ ನಿರ್ಮಿಸಿದ್ದೀರೋ ಅಥವಾ ಸರಕಾರ/ಬ್ಯಾಂಕ್ ನಿಂದ ಸಾಲ/ಸಹಾಯ ಧನ ಪಡೆದಿರುತ್ತೀರೊ? Self financed (S) or Loan from government/Banks (G/B):

17. ಸುರಂಗದಲ್ಲಿ ನೀರು ಬರುವುದು ನಿಂತಿದೆಯೇ? ಬತ್ತಿ ಹೋಗಿರುವುದು ಯಾವಾಗ?If the *suranga* is dry, when was last time it produced water;

Appendix F: Geohydrology of laterites

Laterite became popular among engineers and researchers in the nineteenth and twentieth centuries after it was first mentioned by Buchanan (1807) during his journey from Madras presidency to the west coast of India, Malabar and Canara. The material reported by Buchanan (1807) was ferruginous, with dispersed Fe-oxides, vesicular, unstratified, porous, and with yellow ochres because of high iron content (Gidigasu, 1976), overlying granite, and very soft, which could be cut with big iron knives and it hardened on exposure to air (Eggleton & Taylor, 1999). Laterite blocks excavated and cut from a laterite soil profile have historically been a prime source of building material in Asian countries. The widely-found laterites on the western coast of India were mainly used as bricks for building material in south India, which can still be seen in historical monuments. Laterites are primarily found in Asia, Africa, Australia, and South America (Gidigasu, 1976).

Laterites are highly weathered pedogenic surface deposits in tropics and subtropics, rich in iron, aluminium, and silicate clay minerals but low in alkalies (McFarlane, 1976; Bonsor *et al.*, 2013). The laterites are formed mainly in the tropics and subtropics by a prolonged period of intensive chemical weathering of igneous and metamorphic rocks from water in the subsurface and physical weathering because of rain and wind on the surface (Fan *et al*., 1994). The laterites have varying proportions of iron and aluminium oxides, with quartz and other minerals. The colour of laterites, which ranges from red to yellowish-brown, depends on iron oxide and clay concertation. For example, reddish-brown laterite becomes harder on exposure to air because of the high content of iron that is oxidised on exposure to air, while yellowish laterite is soft because of higher clay content. The laterites with higher iron and aluminium contents are harder than the laterites with higher clay contents, and the proportion of various contents is governed by the type of parent rock and degree of weathering (Schellmann, 2015).

The main confusion with the use of laterite as a term was that initially, some researchers used the term laterite for any red, yellowish-brown, ferruginous profile, which was similar in appearance to the laterite described by the Buchannan (1807). The soil profile nebulously described by Buchanan (1807) was a profile composed of various soil types.

Their content proportions varied mainly according to weathering, the type of parent rock, and the climate over a prolonged period, in the absence of internationally standardised terminology, classification, and nomenclature to identify laterites (Gidigasu, 1976; Eggleton & Taylor, 1999). This variation in the type of laterites worldwide created ambiguity and confusion because of difference in basic interpretation (Schellmann, 2015). Thus, a more specific nomenclature of weathered rocks was required to replace the generic and ambiguous term laterite, therefore, over time, geologists, soil scientists, mineralogists, geographers, geomorphologists, mining and construction engineers examined, analysed and reported laterites with a wider respective point of interests, and it created a diverse pool of knowledge about the physical and chemical properties of laterite (Eggleton & Taylor, 1999; Schellmann, 2015).

In Earth sciences studies, specific terms such as ferruginous, ferricrete, saprolite, and duricrust have been used increasingly to replace the term laterite (Eggleton & Taylor, 1999). However, on the other hand, the term laterite was still used by some researchers because it covered all layers in a weathered profile. Thus, use of the term laterite continued to be used for the informal and broad description of a partially or entirely weathered profile, which may consist of all or some of the layers of a weathered profile (Eggleton & Taylor, 1999; Schellmann, 2015). As a result, some researchers preferred to use the single term laterite, while other researcher interpreted laterite diversely. Such a divided use of terminology/language used by the researchers was ambiguous for the new researchers, so the researchers were forced to follow one of the two sides, even after a number of efforts to create a standard or unanimous definition, the confusions with the laterites still exists (Gidigasu, 1976; Eggleton & Taylor, 1999; Schellmann, 2015).

The process of soil weathering starts with the infiltration of surface water from the earth surface to the subsurface into joints and veins in the deep subsurface (Ollier & Clayton, 1984, p. 109). It results in increased permeability in layers near to the surface because the rock is decomposed, and the number and size of pore spaces, cracks, and joints have increased because of leeched material (Fetter, 2001). As a result, weathered profiles allow rapid infiltration of rainwater and high percolation into the deep layers (Langsholt, 1992), which further chemically weathers the rock and minerals by hydrolysis (Ollier, 1988), so infiltration and chemical weathering become a cyclic process.

Water is a key component in chemical weathering; it has various roles: the primary reactant in a chemical process, a solvent in which a reaction occurs, transporting agent, and controlling oxidation and reduction conditions (Ollier & Clayton, 1984, p. 109). Ollier (1988) has divided deep weathering profiles into two categories, an upper zone that is oxidised, reddish, unsaturated, and a lower zone that is pale white to greenish in colour and is saturated with groundwater. The top level of the saturated zone is known as the water table (Jones, 1997). It fluctuates seasonally because of weather, groundwater recharge and abstraction (Ollier, 1988). The flexible water table may mark a boundary between the upper and lower zones.

Oxidation is the central weathering process of the unsaturated zone, with the effect of external chemicals carbon dioxide, organic matters and acids, chelating agents, while in the saturated zone, the external chemicals are quickly consumed during the weathering process that involves hydration and hydrolysis (Ollier,1988). Groundwater is nearly immobile in deeper parts of the saturated zone, so weathering products are moved slowly upwards to the discharge zone; hence the rate of weathering is slower in this zone compared to upper layers but does not stop completely (*ibid.*). A common assumption is that the tropical climate is conducive to weathering (Gidigasu, 1976; Eggleton & Taylor, 1999). Ollier (1988) argues that climate is not a necessary factor for deep weathering in the present-day conditions, but the presence of groundwater is key for deep weathering, as deep weathering can happen because of hydrolysis of silicate minerals below the water table as deep as 3000m. Deep weathering is entirely independent of surface temperatures unless the water is frozen. The surface temperature does not have any fluctuating effect on subsurface temperature after an approximate depth of 10-20 m as the temperature below this level remains constant relative to changing the temperature climate (Ollier,1988). Weathering, however, takes place deep below the constant temperature zone, so weathering process in this region has no effect of a change in surface temperature until the groundwater is not frozen or can move (Ollier, 1988).

Moreover, if the water is frozen, the surface temperature with the ice can reach as deep as permafrost, which can be as deep as hundreds of metres. In this case, weathering may occur in deep groundwater, even in not tropical conditions (Ollier, 1988). Still, weathering product will not be removed to the unsaturated zone because there is no external drainage. Ollier (1988), however, does not entirely rule out that much deep weathering of the Mesozoic or early Cenozoic age occurred during a tropical wet climate. The majority of kaolinite (clay) profiles seems to be of the Eocene age when the climate was globally warm and wet (Ollier, 1988; 288). That idea may have given way to the wide assumption of deep weathering and tropical climate. Still, deep weathering and kaolin can form in cold climates as well. However, Ollier (1988) suggests that deep weathering is independent of surface climate, but tropical weather (mainly high precipitation and dry seasons) ensures seasonal fluctuation in the water table, conducive to deep weathering. Therefore, it seems that the weathering process and the chemical composition, and the morphological characteristics of the weathered product dependent on various factors, including parent rock, clay minerals in the soil, climatic conditions, and topography of the area (Gidigasu, 1976; Sharma & Rajamani, 2000, 2001).

Water discharged to springs and seepage because of the lateral moment of water in the top part of the saturated zone, groundwater table, contains weathering products, which are discharged to a new location and become the cause of weathering new place (Ollier, 1988). Weathering products (chemicals in solution) from the deeper, weathered, saturated zone is moved upwards to the discharge zone (water table) by the ionic diffusion (Ollier, 1988) and fluctuations in the water table. In weathering process, the silicates minerals are removed from the parent rock because of the presence of acid reaction, oxygenated conditions, and simply because of hydrolysis below the water table (Ollier, 1988; Sharma & Rajamani, 2000). Hydrogen ions are created in the unsaturated zone (above the water table) because of carbonic acid, cation exchange, and nitrogen reactions at the plant roots and decaying organic material (Ollier, 1988).

$$MeSiO + H^+ > Me^+ + HSiO \quad (1)$$

$$MeAlSiO + H^+ > HAl\,SiO + Al\,(OH)_3 + Si\,(OH)_4 \quad (2)$$

Me = any metallic ion

A hydrogen ion replaces the cation from the silicate minerals on the surface of the parent rock, see equation (1), and displaced cations (Me^+) are washed away. In a second step, the hydrogen moved from the surface to the inside of the crystal structure and again removed cations. This process of weathering the crystal structure continues until all the silicate mineral are converted to clay minerals and other products. In equation (2), clay mineral (HAl SiO), aluminium, and silicon hydroxides are produced because of reaction (or weathering process), because of significant variations in the formulae of the silicate minerals found in soil, the equation (1) and (2) are not stoichiometrically balanced but represent the basic process of weathering.

In the saturated zone (below the water table), a similar nature reaction is done by water molecule during hydrolysis, equation (3), clay mineral is produced, and production of hydroxyl ion means alkaline nature, unlike acidic conditions above the water table.

$$MeAlSiO + H_2O > Me^+ + HAlSiO + Al(OH)_3 + OH^- \quad (3)$$

As the above reaction occurs in a saturated zone below the water table, the ions get concentrated in this zone as these cannot be leached out to the upper zones easily. While near the water table, ion concentration is low as ions are washed away by the moving groundwater. So ions from the deeper weathering surface start diffusing upwards to the moving water surface to maintain a chemical gradient (Ollier,1988).

The iron ions behave differently to other cations during this moment; as iron ions are migrated upwards and reach the water table, they get oxidised and removed from the water and get precipitated in the form of iron oxides (Ollier,1988), which is known as ferricrete. Ferricrete can form in different times and ways, by residual accumulation, lateral migration (Eggleton & Taylor, 1999) upwards motion of iron from the deep soil through diffusion (Ollier & Galloway, 1990). Moreover, ferricrete can form over the years from past to present and future (Eggleton & Taylor, 1999). Mann and Ollier (1985) [cited in Ollier,1988] suggest that the diffusion rate of iron cations is fast enough to accumulate one metre of ferricrete in 10000 years.

In summary, the weathering process below and above the water table takes place slightly differently. There are acid and oxidising conditions in the unsaturated zone when hydrogen ion reacts with silicate minerals. In contrast, alkaline conditions prevail in the saturated zone, and hydrolysis is the primary reaction (Ollier,1988). In both reactions, the idea is to replace cations with hydrogen ions (see Table F1).

Table F1: Some essential chemical reactions

(Ollier & Clayton, 1984, pp. 31-51).

Chemical reaction	**Explanation**
Oxidation	Minerals are in contact with air, and usually, oxides are formed, and in the presence of water, hydroxides are formed
Reduction	Opposite of oxidation, and removal of oxygen, usually takes places in waterlogged anaerobic conditions
Hydrolysis	A chemical reaction between mineral and water, as a result usually silicate minerals are decomposed
Carbonation	The reaction of carbonate or bicarbonate ions with minerals
Hydration	In this process, water is added to the mineral, for example, clay mineral formation

Weathering of rocks is the chemical and physical alteration of its components by the water, temperature, pressure, and microbiological activities in the earth's subsurface to achieve an equilibrium with the infiltrated surface water, temperature, and pressure conditions (Fan *et al.*, 1994). The chemical weathering takes place from the chemical reactions of minerals with air and water in the deep subsurface, and the mineralogical composition of a rock is transformed, while physical weathering takes place near the surface and is mainly associated with the disintegration of the rock (Ollier & Clayton, 1984, p. 31; Ollier, 1988). Weathering is a fundamental geomorphic process in the tropics, and the products of this weathering play a major role in modelling landscapes (McFarlane, 1976).

A weathered rock in deep subsurface may have the same volume same as its parent rock, but the density of the weathered product is decreased because of leeched out material from it into the solution, or in other words, a weathered rock is more porous than the parent rock (Ollier, 1988). In addition, increased porosity of argillaceous materials in the rocks result in increased water holding capacity (Fan *et al.*, 1994) because water is stored in the joints in the rocks and spaces between the grain. Therefore, the size and distribution of these spaces play a critical role in weathering (Ollier & Clayton, 1984, p. 109).

Oxidation and reduction in the subsurface lead to intense weathering of rock and results in increased clays contents, iron and aluminium oxides, which form ferricrete, claypan, and duripan (Flores-Román *et al.*, 1996). The leeched material, which is mostly fine silica, moves downwards and accumulates into low-permeable, residual clay layers, or various thickness ranging between 0.6-0.1 metres are found in the weathered subsurface (Cable Rains *et al.,* 2006). In the deep chemical weathering of granite, quartz remains unaltered, but feldspars are often converted into various clays minerals (Ollier & Clayton, 1984, p. 85). A variety of clay minerals are produced by the weathering of granite rock under tropical and sub-tropical conditions, but kaolinite clay is the main product of such chemical weathering (Gerrard, 1994).

The type of clay formation by weathering depends upon the type of parent rock (Ollier & Clayton, 1984, p. 75). The clay layer initially absorbs infiltrated water because clay has high overall porosity, the movement of absorbed water in clay is slow, but its permeability is very low. Therefore, once all possible pore spaces are saturated with water, water movement is nearly ceased in the clay layer, and waterlogged conditions are formed (Flores-Román *et al.*, 1996). The water-logged clay layer results in a barrier that deaccelerates any further vertical percolation into deep groundwater aquifers (Ollier & Clayton, 1984).

This low permeable clayey layer is often termed as a claypan, and the percolated water moving vertically downwards through unsaturated zone is perched on this claypan (Cable Rains *et al.*, 2006), and a perched aquifer is formed at shallow depths just above the main water table (unconfined aquifer) (Ollier & Clayton, 1984; Fetter, 2001). In addition to claypan, perched water conditions are caused by impermeable hard layers known as duripan composed of the deposits of oxides of aluminium and iron under the laterite profile (Flores-Román *et al.*, 1996; Whyte, 2013).

The soil profiles generally assumed uniform in their characteristics, can be highly heterogeneous in physical, chemical, and biological characteristics laterally and vertically

(Kookana & Naidu, 1998). Therefore, weathering does not take place in a homogenous way. As a result, the perched aquifers can be heterogeneously distributed over a laterite profile. Thus, the subsurface movement of water is difficult to be explained with a single, exclusive universal hypothesis.

Ollier & Galloway (1990) have argued that the laterite profile of western coasts in south India is actually primarily saprolite (weakly weathered), not laterite (highly weathered) as suggested by Buchanan (1807). The soil profile consists of inconsistently distributed Ferricrete overlying saprolite. Olier & Galloway (1990) further claim that the laterite brick material that hardens when exposed to air, first mentioned by Buchanan (1807), is saprolite and is not as hard as exposed laterite. In researcher's opinion, Buchanan's term laterite represents a broad range of weathered profile, while Ollier & Galloway (1990) divide the laterite profile into two distinct categories, firstly highly weathered laterite, scientifically known as ferricrete. Exposed ferricrete takes the form of the hardest duricrust and is highly permeable, for example, the exposed surface of *Possdigumpe* hill in Kasaragod. Secondly, partial or weakly weathered profile, scientifically known as saprolite. There is a lack of clear distinction between them both in terms of use and nature. Therefore, laterites/laterite are still a safe term to blanket some broad spectra of weathered soil and weathered rock profile among the stakeholders and the physical science researchers, except a handful of laterite experts.

Laterite in the study area is harder because of the high concentration of iron oxides laterite than the laterites of the Deccan Plateau formed by the weathering of basalt. However, more accurate scientific names are used to address different characteristics layers of soils and rocks in a laterite profile. Laterite and a laterite profile both express different meanings. The former represents a laterite soil, or a laterite rock, or a combination of both for different professionals, while the latter may be applied to a broad range of weathered soil profiles. A basic lateritic profile with distinct layers has been shown in Figure F1.

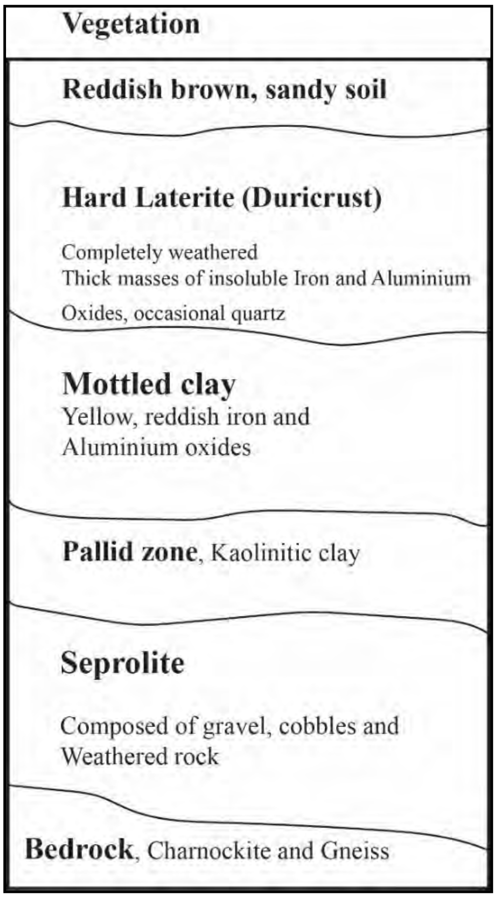


Figure F1: Various layers in a laterite soil profile
(Adopted from Ollier, 1988; Langsholt, 1992;
Eggleton & Taylor, 1999; Bonsor *et al.*, 2013).

As shown in Figure G1, a basic lateritic profile is usually made of the following layers.

a) Top layer with or without soil cover,
b) Iron and aluminium-rich layers are often exposed to the surface, usually known as ferricrete or duricrust,
c) Discretely diffused Iron-oxyhydroxides, known as mottle zone or mottled horizon
d) Clay-rich zone, but low in Iron-oxyhydroxides, known as a pallid zone, or bleached zone, or as the plasmic horizon
e) Lightly weathered saprolite
f) Unaltered parent rock, or bedrock

There is a yellow-brown top surface, pallid zone (saprolite), mottled zone layers when acidic rocks are intensively weathered. This is the further breakdown of the ‘weathered rock profile’ or a ‘laterite profile’ (saprolite), a mottled zone and dark brown laterite on top, which is often described. These laterites harden after drying, which usually allows their application as brick stones. Reduction in the subsurface leads to the intense weathering of rock results in increased clay contents, iron and aluminium oxides, which form ferricrete, claypan, and duripan (Flores-Román *et al.*, 1996). The leeched fine silica moves downwards and accumulates into low-permeable, residual clay layers, or various thickness ranging between 0.6-0.1 metres are found in the weathered subsurface (Cable Rains *et al.,* 2006). The deep chemical weathering of granite, quartz remains unaltered, but feldspars are often converted into various clays minerals (Ollier & Clayton, 1984, p. 85). The weathering of granite rock produces various clay minerals under tropical and sub-tropical conditions, but kaolinite clay is the main product of such chemical weathering (Gerrard, 1994).

The type of clay formation by weathering depends on the parent rock type (Ollier & Clayton, 1984, p. 75). The clay layer initially absorbs infiltrated water because clay has high overall porosity, the movement of absorbed water in clay is prolonged, but its permeability is very low. Therefore, once all possible pore spaces are saturated with water, and water movement is nearly ceased in the clay layer, and waterlogged conditions are formed (Flores-Román *et al.*, 1996). The water-logged clay layer results in a barrier that deaccelerates any further vertical percolation into deep groundwater aquifers (Ollier & Clayton, 1984).

This low permeable clayey layer is often termed a claypan. The percolated water moving vertically downwards through the unsaturated zone is perched on this claypan (Cable Rains *et al.,* 2006), and a perched aquifer is formed at shallow depths just above the main water table (unconfined aquifer) (Ollier & Clayton, 1984; Fetter, 2001). In addition to claypan, perched water conditions are caused by impermeable hard layers known as duripan composed of the deposits of oxides of aluminium and iron under the laterite profile (Flores-Román *et al*., 1996; Whyte, 2013).

The soil profiles generally assumed uniform in their characteristics, can be highly heterogeneous in physical, chemical, and biological characteristics laterally and vertically (Kookana & Naidu, 1998). Therefore, weathering does not take place in a homogenous way. As a result, the perched aquifers can be heterogeneously distributed over a laterite profile. Thus, water's subsurface movement is challenging to explain with a single, exclusive universal hypothesis.

Shallow groundwater aquifers are found nearest to the earth’s surface and are bound by unsaturated zone in the surface above and by aquitards and deeper aquifers below (Townley, 1998, p. 3). Therefore, like low permeable rocks, thick clay layers deep buried in the subsurface also behave like aquitard. Suppose clay layers are found at shallow depths in laterite profiles. In that case, clay layers act as an aquiclude and form perched aquifers conditions. Therefore, series of clay layers (with other rocks with a diverse spectrum of permeability) can form series of localised perched aquifers and aquifers at various depths in a laterite profile (Ollier & Clayton, 1984, p. 110).

Once the perched aquifer has reached its full water holding capacity, the excess water from the perched aquifer starts to overflow, and this water moves laterally over the aquiclude layers to reach the unconfined aquifers situated lower below in the subsurface (Ollier & Clayton, 1984; Flores-Román *et al.*, 1996; Cable Rains *et al.,* 2006), or if the claypan layer is exposed to the surface then the perched water is discharged at the intersection of perching layers to the surface in the form of ephemeral or seasonal springs, streams, and swales (Hanes, & Stromberg, 1998; Bonsor *et al.*, 2013). The area's topography usually governs the location of recharge and discharge points; for example, the discharge zones are generally found in the valleys near to the surface water bodies and the recharge zone are traditionally situated at higher lands (Townley, 1998, p. 4).

The role of Perched aquifers in springs and streams has been recognised, but relatively fewer studies have been undertaken on the hydrological relation between the perched aquifer and seasonal streams in the weathered profiles (Cable Rains *et al.,* 2006). The second (or supporting) reason for forming the localised aquifer can be attributed to the low overall porosity of the rock and the presence of water holding joints and cracks (Ollier

& Clayton, 1984, p. 110). As a result, groundwater may not be available at constant depths in the subsurface because the water flows in interconnected or not connected spaces (cracks, joints). Such a phenomenon, however, takes places mainly in karstic limestone (Ollier & Clayton, 1984, pp. 110-111) but cannot be denied in the case study area. Though, hilly terrain can be another factor for depth variation of groundwater.

Shallow groundwater systems in weathered profiles are a prime source of drinking water, from shallow dug wells, springs, *suranga*, and other traditional water harvesting systems in Africa and Asia, because of their proximity to the surface than the more in-depth groundwater systems (Townley, 1998; Bonsor *et al.*, 2013). Compared to the published research information about the origin and development of laterite, relatively less information has been published about weathered profiles' hydrogeology and aquifer properties (Langsholt, 1992; Bonsor *et al.*, 2013). Laterite plays a crucial role in the hydrogeology of the area they cover because the permeability of the laterite regulates the amount of percolation into the groundwater and recharge to the lower layers and bedrock (Bonsor *et al.*, 2013) and runoff that be contingent on the gradient of the hill.

Appendix G: Socioeconomic survey questionnaire

Interview briefing

This independent UK-based project investigates the use of *suranga* and tries to discover where and how this technology is used and the date when it was first introduced to your village. It would be appreciated if you could take the time to answer some questions on these topics whilst we record and take technical measurements for an inventory of *suranga* that we are trying to create. If you are not happy with answering a question, we can move onto the next one. It should take no longer than 15 minutes to conduct. Your identity will remain anonymous, and the data treated as confidential. We seek to reassure you that this project is not connected to the local water authorities or governors in any way. However, suppose these data can help influence policy to offer subsidies for *suranga* construction and maintenance in the future. In that case, we are seeking your verbal consent to use these data for these purposes.

Socioeconomic survey questionnaire

1. ದಿನಾಂಕ Date:
2. ಯಜಮಾನನ ಹೆಸರು ಮತ್ತು ದಿನಾಂಕ Owner’s name and age:
3. ಕುಟುಂಬದವರ ಸಂಖ್ಯೆ Total members in the house:
4. ಮನೆ House No. :
5. ಗ್ರಾಮ Village:
6. ಪಂಚಾಯತ್ Panchayat:
7. ರಾಜ್ಯ: ಕರ್ನಾಟಕ / ಕೇರಳ State:
8. ಆದಾಯದ ಮೂಲ:Source of the main income
9. ಇನ್ನಿತರ ಆದಾಯ : Secondary source of income:
10. ಸಾಕುಪ್ರಾಣಿಗಳ ವಿವರ Livestock do you have?

	ಸಂಖ್ಯೆ Number
a)ದನ Cow	
b)ಕೋಳಿ Chicken	
c) ಆಡು Goats	
d)ಇತರೆ Others	

Agricultural Questions

11. ಒಟ್ಟು ಜಮೀನು How much land do you own?
12. ಕೃಶಿ ಮಾಡುವ ಜಮೀನು How much land is cultivated?
13. ಒಟ್ಟು ಜಮೀನು ಮತ್ತು ಕೃಶಿ ಮಾಡುವ ಜಮೀನಿಗೆ ವ್ಯತ್ಯಾಸವಿದೆಯೇ? ಕಾರಣ What is the cause (If there is any difference between the land owned and the land cultivated?):
14. ಬೆಳೆಯುವ ಬೆಳೆಗಳು What crops do you grow?
15. ಬಳಸುವ ಗೊಬ್ಬರಗಳು Which kind of fertilisers do you use?:

	ಶೇಕಡಾ(%) total use (%)
a)ರಾಸಾಯನಿಕ ಗೊಬ್ಬರ Chemical fertilisers	
b) ಸಾವಯವ ಗೊಬ್ಬರ Animal manure	
c)ಇತರ Others	

16. ಲಭ್ಯವಿರುವ ನೀರಿನ ಮೂಲಗಳು What are the available sources of water:

	ಒಟ್ಟು ಸಂಖ್ಯೆ Total number	ಕುಡಿಯಲು ಮತ್ತು ಮನೆ ಬಳಕೆ Drinking, Household activities (D)	ಕೃಶಿ Agriculture (A)
a) ಬಾವಿ Well			
b)ಬೋರುವೆಲ್ Borewell			
c)ಸುರಂಗ *suranga*			
d)ನಳ್ಳಿ ನೀರು Pipe line supply			
e) ಇತರ Others			

17. ಬೇಸಗೆಯಲ್ಲಿ ನಿಮಗೆ ನೀರಿನ ಕೊರತೆ ಇದೆಯೇ Are your water requirements met during the dry season?

18. ಕೃಷಿಗೆ ನೀರನ್ನು ಬಳಸುವ ವಿಧಾನ How do you irrigate crops:

a) ತೋಡು Canal	
b) ಪ್ರವಾಹ Flood	
c) ಡ್ರಿಪ್+ ಸ್ಪ್ರಿಂಕ್ಲರ್ Drip + Sprinkler	
d) ಕೈ ಚಾಲಿತ Manual	

19. ನೀವು ಕೃಷಿಗೆ ಉಪಯೋಗಿಸುವ ಕರೆಂಟ್/ಪೆಟ್ರೊಲ್/ಡೀಸೆಲ್ ಮಶೀನ್ What electric/petrol/diesel machines do you use for irrigated agriculture:

20. ನೀವು ಉಪಯೋಗಿಸುವ ನೀರಿನ ಮೂಲಗಳನ್ನು ಅವುಗಳ ಲಭ್ಯತೆಗೆ ಅನುಗುಣವಾಗಿ ಪಟ್ಟಿ ಮಾಡಿ Please rank your water supplies in order of most importance (1 as most important) to meeting your families water needs (*suranga*/ borewell/ well)

	ಪ್ರಾಮುಖ್ಯತೆ Priority
a) ಬಾವಿ Well	
b)ಬೋರುವೆಲ್ Borewell	
c)ಸುರಂಗ *Suranga*	
d) ನಳ್ಳಿ ನೀರು	
e) ಇತರ Others	

21. ನೀರಿನ ಮೂಲಗಳಲ್ಲಿ ಏನಾದರು ತೊಂದರೆಗಳಿವೆಯೇ Are there any issues with your water supplies/sources?

22. ಮುಂಬರುವ ದಿನಗಳಲ್ಲಿ ಸುರಂಗ ತೋಡುವ ಯೋಜನೆ ಇದೆಯೇ Are you planning to dig a new *suranga* in the coming days? If No, go to the next question?

23. ಮುಂಬರುವ ದಿನಗಳಲ್ಲಿ ಯಾವ ನೀರಿನ ಮೂಲಗಳನ್ನು ಮಾಡುವ ಯೋಜನೆ ಇದೆ? ಕಾರಣ ? (ಬೋರ್ ವೆಲ್/ ಬಾವಿ) What water sources are you planning to get in the coming days and why (i.e., borewell, well):
24. ಮುಂದಿನ ದಿನಗಳಲ್ಲಿ ಕೃಷಿಯನ್ನು ನಿಲ್ಲಿಸುವ ಯೋಜನೆಗಳು ಇದೆಯೇ? ಕಾರಣ? Do you have any plans to move out of agriculture in the future? If yes, why?

Questions for in-depth interviews

25. ನೀವು ಸುರಂಗವನ್ನು ತೋಡಿದ ಕಾರಣ Why do/did you dig a *Suranga*?
26. ಮೊದಲ ಬಾರಿಗೆ ನಿಮಗೆ ಸುರಂಗದ ಮಾಹಿತಿ ತಿಳಿದದ್ದು ಹೇಗೆ ಮತ್ತು ಯಾವಾಗ When and how did you come to know about *suranga* for the first time?
27. ಸುರಂಗ ತೋಡಿದರೆ ನೀರು ಸಿಗಬಹುದೆಂಬ ಮಾಹಿತಿ ಸಿಕ್ಕಿದ್ದು ಹೇಗೆ How do you identify where to find water for *suranga*?
28. ನೀವಿರುವ ಪರಿಸರದಲ್ಲಿ ಸಾರ್ವಜನಿಕ ಉಪಯೋಗದ ಸುರಂಗಗಳು ಮತ್ತು ನೀರಿನ ಟ್ಯಾಂಕ್ ಗಳು ಇವೆಯೇ? ಇದ್ದರೆ ಅದರ ನಿರ್ವಹಣೆ ಹೇಗೆ? Are there any community-managed *suranga* and tanks in the vicinity? How is access to this water controlled?
29. ನೀವಿರುವ ಪರಿಸರದಲ್ಲಿ ಸಾರ್ವಜನಿಕ ಉಪಯೋಗದ ಟ್ಯಾಂಕ್ ಗಳು ಇವೆಯೇ Are there any community managed water tanks?
30. ನಿಮ್ಮ ಸುರಂಗದ ನೀರನ್ನು ನೀವು ಬೇರೆಯವರ ಜೊತೆ ಹಂಚಿಕೊಳ್ಳುತ್ತೀರಾ?Do you share the water from this *suranga* with neighbours/relative:
31. ನೀವು ತೋಡಿದ ಸುರಂಗವು ಬೇರೆಯವರ ಜಾಗವನ್ನು ಆಕ್ರಮಿಸಿದೆಯೇ?. Does this *suranga* extend into your neighbour's fields:
32. ಸುರಂಗದಲ್ಲಿ ನೀರಿನ ಪ್ರಮಾಣ ಕಡಿಮೆಯಾಗಲು ಕಾರಣವಾಗುವ ಅಂಶಗಳು ಯಾವುವು?What are the factors that decrease water quantity in *suranga* (local understanding):

33. ಸುರಂಗದಲ್ಲಿ ನೀರಿನ ಪ್ರಮಾಣ ಜಾಸ್ತಿಯಾಗಲು ನಾವು ಯಾವ ವಿಧಾನಗಳನ್ನು ಅನುಸರಿಸಬಹುದು?What can be done to improve water quantity in *suranga* (local knowledge):

34. ಸುರಂಗಗಳ ಬಗ್ಗೆ ನಿಮ್ಮಲ್ಲಿ ಏನಾದರು ದಾಖಲೆ/ಮಾಹಿತಿಗಳಿವೆಯೇ? Do you have any story/incident related to *suranga*?

Questions for government water officials and water journalists

1. How acute is water scarcity in your region?
2. Is this predominantly an agricultural problem?
3. Are there any problems with water quality in your region – please list
4. Are there any official inventories of *suranga* and borewells in the Western Ghats?
5. What if any subsidies are available for *suranga* and borewell construction, maintenance and operation? Please list and provide details of these subsidies.
6. If none, are there any plans to introduce subsidies – if yes, when, what for and to what level?
7. Do you see any compromise between the adoption of these two different forms of water abstraction?
8. Are there legally recognised and protectable water rights associated with *suranga* and borewell sources?
9. If yes, are these attached to land in any way?
10. Do these water rights have any monetary value, and are they transferable in any way?
11. Do you perceive land fragmentation to be a problem in the region?
12. If yes, how does this problem manifest itself concerning different water sources?
13. If yes, are there any plans to consolidate or redistribute land holdings in the future?
14. How would this be achieved with respect to water resources?

Appendix H: A summary of the socioeconomic survey data

Broad Category	Variable	Categories	Frequencies	%
Surname	Surname	Bhat	88	40.93
		Naik	48	22.33
		Missing	23	10.70
		Mulya	7	3.26
		Desai	5	2.33
		Nayak	5	2.33
		Mera	3	1.40
		Pujari	3	1.40
		Shastri	3	1.40
		Haji	2	0.93
		Prasad	2	0.93
		Shetty	2	0.93
		Amma	1	0.47
		Baira	1	0.47
		Bairi	1	0.47
		Devkar	1	0.47
		Desouza	1	0.47
		Ganesh	1	0.47
		Joisa	1	0.47
		Kaman	1	0.47
		Kannadgudi	1	0.47
		Korde	1	0.47
		Kumar	1	0.47
		Kutti (Kunya)	1	0.47
		Manyani	1	0.47
		Montero	1	0.47
		Naji	1	0.47
		Nayar	1	0.47
		Parera	1	0.47
		Patali	1	0.47
		Patil	1	0.47
		Rama	1	0.47
		Ray	1	0.47
		School	1	0.47
		Shaktibhushan	1	0.47
		Swami	1	0.47
Location	Village	Manila	79	36.74
		Enmakaje	64	29.77

		Peruvai	16	7.44
		Karvapadi	12	5.58
		Bayar	11	5.12
		Padre	10	4.65
		Priyol	9	4.19
		Kanyana	4	1.86
		Kepu	4	1.86
		Alike	2	0.93
		Paddvanuru	2	0.93
		Hiremane	1	0.47
		Maire	1	0.47
	District	Dakshin Kannada	119	55.35
		Kasaragod	86	40.00
		North Goa	9	4.19
		Shimoga	1	0.47
Occupation	Main Occupation	Farmer	124	57.67
		Labourer	70	32.56
		Employment skilled	8	3.72
		No information	8	3.72
		Self-employed	5	2.33
	Secondary Occupation (Yes/No)	No	148	68.84
		Yes	59	27.44
		No information	8	3.72
	Secondary Occupation (type)	No	148	68.84
		Farmer	27	12.56
		Employment skilled	18	8.37
		Self-employed	12	5.58
		No information	8	3.72
		Labourer	2	0.93
	Family Status	Above poverty line	128	59.53
		Below poverty line	87	40.47
Livestock	Cows	Yes	132	61.40
		No information	60	27.91
		No	23	10.70
	Chickens	No	128	59.53
		No information	60	27.91
		Yes	27	12.56
	Goats	No	152	70.70
		No information	60	27.91
		Yes	3	1.40
	Farmers' Category	Marginal	63	29.30
		Small	58	26.98
		Small Medium	47	21.86
		Medium	26	12.09

		No information	13	6.05
		Large	5	2.33
		Landless	3	1.40
Crops	Arecanut	Yes	150	69.77
		No information	52	24.19
		No	13	6.05
	Coconut	Yes	151	70.23
		No information	52	24.19
		No	12	5.58
	Cocoa	No	145	67.44
		No information	52	24.19
		Yes	18	8.37
	Pepper	No	88	40.93
		Yes	75	34.88
		No information	52	24.19
	Banana	Yes	86	40.00
		No	77	35.81
		No information	52	24.19
	Cashew	No	134	62.33
		No information	52	24.19
		Yes	29	13.49
	Paddy	No	145	67.44
		No information	52	24.19
		Yes	18	8.37
	Rubber	No	140	65.12
		No information	52	24.19
		Yes	23	10.70
	Nutmeg	No	161	74.88
		No information	52	24.19
		Yes	2	0.93
	Clove	No	162	75.35
		No information	52	24.19
		Yes	1	0.47
	Sericulture	No	162	75.35
		No information	52	24.19
		Yes	1	0.47
	Medicinal Plants	No	162	75.35
		No information	52	24.19
		Yes	1	0.47
	Pineapple	No	161	74.88
		No information	52	24.19
		Yes	2	0.93
	Organic Fertilisers	Yes	151	70.23
		No information	62	28.84

		No	2	0.93
	Chemical Fertilisers	No	127	59.07
		No information	61	28.37
		Yes	27	12.56
Water Resources	*Suranga*	Yes	215	100.00
	Borewell	No	171	79.53
		Yes	35	16.28
		No information	9	4.19
	Well	No	190	88.37
		Yes	16	7.44
		No information	9	4.19
	Dug well /Open well	Yes	152	70.70
		No	54	25.12
		No information	9	4.19
	Spring	No	195	90.70
		Yes	11	5.12
		No information	9	4.19
	Government pipe supply	No	203	94.42
		No information	9	4.19
		Yes	3	1.40
	Future water plans	No plans	130	60.47
		No information	38	17.67
		Suranga	25	11.63
		Dug well/open well	10	4.65
		Borewell	8	3.72
		Well	2	0.93
		Katta	1	0.47
		No funds	1	0.47
	Water sharing	No	155	72.09
		No information	30	13.95
		Yes	30	13.95
Suranga age	Oldest *suranga*	Between 1951-2000	128	59.53
		No information	37	17.21
		Between 1900-1950	35	16.28
		Post-2001	9	4.19
		No idea	6	2.79
	Latest *suranga*	Between 1951-2000	143	66.51
		No information	37	17.21
		Post-2001	22	10.23
		Between 1900-1950	7	3.26
		No idea	6	2.79
Drinking Household	*Suranga*	Yes	190	88.37
		No	15	6.98
		No information	10	4.65

	Dug well /Open well	No	155	72.09
		Yes	50	23.26
		No information	10	4.65
	Well	No	192	89.30
		Yes	13	6.05
		No information	10	4.65
	Borewell	No	200	93.02
		No information	10	4.65
		Yes	5	2.33
	Spring	No	204	94.88
		No information	10	4.65
		Yes	1	0.47
	Government pipe supply	No	203	94.42
		No information	10	4.65
		Yes	2	0.93
Summer Irrigation Source	*Suranga*	No	100	46.51
		Yes	90	41.86
		No information	25	11.63
	Dug well /Open well	Yes	104	48.37
		No	86	40.00
		No information	25	11.63
	Well	No	189	87.91
		No information	25	11.63
		Yes	1	0.47
	Kere	No	187	86.98
		No information	25	11.63
		Yes	3	1.40
	Borewell	No	163	75.81
		Yes	27	12.56
		No information	25	11.63
	Spring	No	185	86.05
		No information	25	11.63
		Yes	5	2.33
	River	No	178	82.79
		No information	25	11.63
		Yes	12	5.58
	Katta	No	188	87.44
		No information	25	11.63
		Yes	2	0.93
Irrigation method	Drips and foggers	No	146	67.91
		Yes	46	21.40
		No information	23	10.70
	Sprinklers	No	125	58.14
		Yes	67	31.16

		No information	23	10.70
	Channel	No	187	86.98
		No information	23	10.70
		Yes	5	2.33
	Manual /Hosepipe	No	142	66.05
		Yes	50	23.26
		No information	23	10.70
	Rainfed /No irrigation	No	181	84.19
		No information	23	10.70
		Yes	11	5.12
Water pump	Electric water pump	Yes	112	52.09
		No information	71	33.02
		No	32	14.88
	Diesel/Petrol /Kerosene pump	No	153	71.16
		No information	53	24.65
		Yes	9	4.19

Appendix I: Interview transcripts, three examples

Example 1

(MGB 5APR14)

My name is ******.

Daddapadi, Murva, Delantmajalu, Kumunje, Pretimar, Pakalkunja were the main hamlets in the olden Manila village.

The areas having ample flowing water and flat land paddy used to be grown, and these were the most popular choices for community inhabitation, and cultivation was done in only those areas.

Todu [Seasonal streams] and Katta [temporary check dam on streams and rivers] were also used to harvest water for irrigation.

At present most of the lands is cultivated in Manila village, and the whole land is recorded in Cadastral Maps.

In Manimoole hamlet, there has been no property transfer due to selling, so all the families are native, but in Manila whole village, there may be cases when properties have been sold.

According to government rates, dry land is 600 Rs per cent of the land, so one acre of dry land will cost 60,000 Rs.

Rs 10 is charged annually for maintenance fees by the government for the farmers having more than 20 acres of land. For wetland, Rs 100 is charged annually.

Three types of land are

Khadim: Varga land

Bagayat: Fully wetland, two to three crops of paddy could be cultivated

Dryland: Complete dry land, no cultivation.

My land is categorised as completely dry land at the time of assessment. The last assessment was done somewhere before 1960. So if an assessment is done at present, the government can get more revenue because a large portion of dry land has been converted into plantation by the farmers. There has not been any assessment since 1960.

Land reforms were done by the state government between 1974-1975 CE, which made the cultivators the owners of the land and tenants became owners. So all the people who were cultivating lands in 1974 CE, irrespective of the ownership, become the legal owner of their cultivated land. The original owners were given some compensation for the land they lost. So after losing lands, a number of landlords moved to town and cities.

There were so many examples when large landlords lost the whole of their land holdings to their tenants or farm labourers, who were cultivating their lands. Houses were not included in such transfers. Because usually landlords were well-off so they used to let the landless labourers cultivate their land, and these labourers used to pay a set portion of their produce or income to the landlord.

In Manila village, approximately one hundred acres of land was given to the labourers. For example, ******* lost a large part of his land. All the previous personal land records of landlords became useless at this point because a labourer could claim his cultivated area in front of the land reform committees.

I lost 60 cents[6] of the land to my farm labourer during that time.

[6] cent is a unit of land measurement, commonly used in south India, and 1 cent equals approximately 40.46 square metre.

Another example, my maternal grandfather was not cultivating any of his lands himself, but with the help of labourers. The labourers claimed to that land, and a court case was already in place before 1974 CE and because the court made the judgement in 1973 CE and the labourers lost it. So they could not claim the land after the land reforms act was applied in 1974.

Some labourers who were not cultivating any land as land tenants, but used to work as day labourers, did not get any land. So these labourers could not claim any lands, but only the labourers living on the same land and cultivating were given land.

[So land reforms act indirectly stopped the practice of leasing the land, and labourers were hired now only as farm labourers rather than as labourers living in the farmstead. In the past, the labourers used to live in the outhouses of landlords.]

After independence, there was no help from the government to the farmers, and farmers were striving to increase cultivation by converting dry land to cultivated land, and that was only possible by increasing water resources. Borewells were not introduced by that time, and only well and open well were the only solutions. In some places, open wells were not successful [for example, undulating topography of Manila village], but *Suranga* emerged as an alternative for the farmers living in undulating dry terrain. Therefore, *Suranga* became popular in the mid-20th century.

Green revolution may also have created increased water requirements for farming.

In the 1930s, there was only one family (our family), and a couple of labourers houses was there in Manimoole. Cultivated land was very less approximately 1 acre then family increased with time, one joint family was divided into two families, and more cultivatable land was required for the families to survive. So these new two families put efforts to cultivate more land by slowly converting dry land to cultivable. In this process, they covered more land. We used to grow sugarcane in those times, and there was only one water source for all families. So, these two families started to share the water on a daily basis. Three days first family used to get water, and the next three days for the 2nd family.

These agreements were written. [Allocated water days were mainly for irrigation, for drinking and for household, and no such rules.]

In 1950 the two families further divided into a total of four families, and the total land holdings were now divided into four parts. So the single water sources were now to be shared between four families. Now each of the four families used to get two days of water supply for irrigation in turns, and the number of allocated water days were also issued according to the land size. So some family used to get only one day of allocated water supply. Therefore, in addition to the shared water resource, families started to explore and create their private water resources, such as ponds, wells, open well, and *suranga,* in their lands. These situations also attracted water issues among the families, such as water-related court cases, and further led to the development of private water resources.

Nowadays, all of these families have improved financial condition that means they can be more self-dependent about water buy making borewells or any other water resources. Moreover, low-income families can also develop their water resources by taking loans from banks.

MGB says that though government support for the farmers has increased over time, there are some nonsense rules also in places made by the government, such as APL and BPL families. Because there are incentives for BPL families by the government, there are many cases when non-eligible families are also getting the BPL status due to their contacts in the local government, and on the other hand, the poor people cannot get the BPL status because they are powerless and are served as APL families.

A BPL family, irrespective of the number of family members, gets 2kg sugar, 10 kg wheat, and 30 kg of rice at reduced prices. For example, 30 kg rice is charged at 1 Rs/kg.

These incentives are making small BPL families, which are mainly labourers, motivated not to go to work because they have food security at negligible prices. Hence increase labourer scarcity.

APL families in Karnataka state do not get any food incentives, but the APL card just used as a form of identity.

MGB says that rebellious APL families who complain to the local government are sometimes moved to the BPL category by the politicians so that they can claim the benefits of BPL.

Furthermore, for the last ten years, farmers can get loans at zero per cent for one year. One can get between a minimum of 100000 to a maximum of 500000 Rs according to their landholdings. Some of the well-off farmers are exploiting this scheme by taking zero per cent loan and investing it into other financial schemes for one year rather than applying to their farm. On the other hands, landless and marginal farmers cannot get the loan because of small landholdings. Sometimes influential farmers default on their loans as well, and no action is taken against them because they are related to the ruling party. At the same time, strict action is taken against defaulting poor farmers.

So this zero per cent loan scheme for farmers by the government is not serving the purpose but motivating corruption. Moreover, non-ruling parties also promise impractical but attractive offers such as loan write off to the larger population if they come to power in the next election.

Finish

Example 2

(SRD 21OCT12)

Before making *Suranga*, we used to fetch drinking water from a neighbour, and it was difficult to get water. There used to be problems from the water owner.

The *Suranga* worker, ******, used to come to Goa nearly every year. Finally, my father decided to make a *Suranga*. We did not get water even after excavating to a great length. The soil used to be wet, but we could not find a water source. Then my father decided to retreat and make a branch on the right side of *suranga*. After excavating nearly 8 metres, the branch started to collapse. So another branch was made on the left side. It started collapsing also. Then a small pond was made inside the left branch because we found a very low water source, which would collect approximately 25 litres of water in a night. We used to syphon water from this underground pond. For one year we used this water.

Next year ***** made a *suranga* at a lower level just below the previous *suranga* and connected it to the first *Suranga*. Now the water could be easily collected.

Suranga are not found in Goa. Only well and borewell are primary water sources for agriculture. In some of the areas, there are natural spring water sources. Water is available in lower valleys or flat areas. Our house is situated in a hilly area, so there was a water shortage.

Since we made *suranga,* our water issues were solved. Previously we used to pump water from the stream for agriculture.

My father's name is ******, and he is 75 years old. My name is ********, and I work at an industrial factory.

We used cow manure and other organic fertilizers because if you apply chemical fertilizers, then every year, chemical fertilizer is required. Chemical fertilizers spoil the soil, while organic fertilizers are not compulsory every year. More irrigation is also needed in chemical fertilizers.

There is another family who has got two *suranga*, but their *suranga* has blocked due to collapse and water is blocked inside the *suranga*. So they have made a borewell now.

We made a well as well, which was 60 metres deep, but we did not found the water, so we blocked it.

Previously we used to get water from a neighbour on a humanitarian basis, but they stopped it afterwards because of some issues.

Presently *Suranga* is our only water source. We are planning to make one more *suranga* because we have just optimum water. We cannot make borewell because neighbours object, as they think borewell can adversely affect their water sources. So there are no borewells in this area. Everyone will agree to a community borewell. *Suranga* does not attract any objections from the neighbours.

We use sprinklers for irrigations.

We will have to find and bring a *suranga* worker from Kerala, as there are no such workers in this area because we do annual maintenance with local workers, so it is possible that we can make a *suranga* with local workers.

My father first saw *Suranga* in his in-law's house in Bayar village in Kerala. My maternal uncle always used to suggest is to make *suranga*, but we could not decide because there was no history of *suranga* in this area. Finally, **** came to this place, and he made his first *suranga* in ***** and ****s house.

Some of the families live approximately ten km from here.

We share our *suranga* water with my Uncle’s family.

My father used to help **** in the *suranga* construction. We spent 25000 Rs on our *suranga* in 1982. We financed this *suranga* our self, and any future *suranga* will have to be self-financed as well. However, we can take an agriculture loan for a well and invest that money into a *suranga*, but that will be cheating.

Discharge in our *suranga* has remained the same since it was made provided. We undertake annual maintenance. The first *suranga* was made in 1978 in this area.

It was all my father decided to make this *suranga* because he had seen *suranga* in Bayar village. The other family members, neighbours and relative used to make fun of *suranga* and predicted failure, but my father went ahead with his decision to make a *suranga* because we did not have any other water resource. Once we successfully made our *suranga*, then friends and other relatives used to visit our *suranga* curiously, and they used to ask many questions and used to take water samples from us because our water tested different to their water.

Unfortunately, *suranga* could not attract a wider population or media attention. So the only a limited number of people in Goa know about *suranga*.

Four years ago, some people came to us and wanted to make *suranga*, and we provided them ***** address in Kerala.

I think if people make *suranga* in this area, they will be successful and will get fresh water.

There are other *kharad* communities in this area but not of them as *suranga*.

No other local worker attempted to learn or to make a *suranga* himself.

Our soil (yellow) is soft in comparison, so it is slightly challenging to make *suranga*.

**** used to use candle inside the *suranga*. One day my father and **** both were working inside the *suranga* when **** show the candle started to fall. So he quickly grabbed my father and came out, and they escaped a major landslide inside the *suranga*. We did not get afraid of it but made the *suranga* deeper later on. We used to use a bucket on the head to remove the soil from inside the *Suranga*.

My mother is also keen to make a new *suranga*.

We do not have water diviners in this area.

**** used to come here in dry seasons and to excavate up to two *suranga* in a trip, and he used to come for several years.

If some *Suranga* workers come to this area, then many people would like to make *Suranga*.

*****'s wife: I used to fetch water on a vessel for the whole joint family. We needed 25 times the water of that vessel. So I used to walk a minimum of one km to get this water on my head or my hands. We used to get only two hours' time slot to get the water because it was a shared water source, and sometimes other people used to create indirect problems for us.

[one-way distance was approximately half km, and she used to fetch water approximately 25 times a day.]

But since we made our *suranga,* I am very much relaxed now. I do not need to go anywhere to get water, and water is at our doorsteps. We got this water from god's choice. We all are very happy now.

Finish

Example 3

(JGB 23SEP12)

Only 30% of our land is being cultivated. Because it's dry land, so a lot of investment and labour problem is a secondary problem, this year we are trying to make a road in our property so that it is accessible.

We have an Ayurveda hospital, pharmacy and a small medicines manufacturing unit. We grow medical plants.

I constructed a huge water storage tank above the ground level, but it failed because water percolates into the ground, so it needs further investment in waterproofing material.

It could store approximately 22 lakh litres of water only by collecting rainwater. We get 300+ inches of annual rainfall in this area.

It was Ganesh Chaturthi yesterday, and it marks the start of Agricultural activities for this year, after long dry summers and heavy rain season.

We have biodigesters in which cow dung is converted into liquid bio fertilisers.

We have five open wells, five *Suranga*, and two circular concrete well. All of our *Suranga* produce perennial water.

One well next to our house is assumed auspicious, so we use that water for drinking and cooking, and for the rest of the household activities, we use *Suranga* water.

I am a strong opponent of borewells. In my opinion, first, we should use surface water. If there is no surface water, then one should think about borewells. Rainwater harvesting is another option, so borewell should be the last option. Luckily till now, we didn’t need to make borewell.

In this area, we are the only farmers not using borewell. Neighbouring borewells do not [adversely] affect our water because our property is in the valley of this hilly area. So our water sources are not affected our borewells.

Twenty years ago, observing our rich water resources, one of the neighbours tried to make a borewell near to the boundaries of our property. We objected to that borewell. However, finally, the borewell did not strike water. Our neighbouring properties are completely borewell dependent.

Summertime, we get water shortage for irrigation because we have large plantations. So we have started to recycle water from the house, and manufacturing unit with basic filtering systems and that water is provided to irrigate Arecanut plantations. We use sprinklers and drip for irrigation.

We have plans to make *suranga* and a Madaka. Though most people suggested making a borewell because *suranga* are old systems, I would still like to make *suranga*. I have further plans to develop my farm as a model sustainable farm.

My grandfather made two *suranga*, and I crawled inside *suranga* with my grandfather when I was a child.

There are no community-managed *suranga* in this area. However, when a joint family divides and has only one *suranga*, then *suranga* must be shared between the separated families.

Airshafts in the *Suranga* are common in flatlands.

During excavating, care is taken that *suranga* does not infiltrate into other property for ethical reasons and avoid any issues. All my *suranga* are on my property. During the excavation of our last *Suranga*, the direction suggested by the water diviner was leading *Suranga* into neighbour's property, so we did not go ahead in that direction.

Afforestation or a plantation can increase water supply in the *Suranga*.

It looks like the *suranga* technique would have been improvised over time.

Previously there was no *suranga* on our property. Approximately 70 years ago, my grandfather made four *Suranga,* and one *suranga* was made five years ago.

Overall, water availability has decreased since I was a child because rainfall patterns have changed quite a lot. I can remember that water streams used to flow for longer seasons.

In the past, labourers used to work for only food because of poverty.

………….

Researcher's observation: This family is an excellent example of *suranga* uses over three generations. The farm is entirely dependent on *suranga* and dug wells, while neighbours use bore wells. They have a small clinic and pharmacy where natural medicines are manufactured. The water used during manufacturing is recycled and used for irrigations. The farm used organic manure produce in bio-digesters and distributed it through a pipe network. The owner invested a large amount of money in making a considerable large water collection tank above ground level. Still, it became a failure because it could not retain water; however, more investment and modification can make it feasible. This big house is an example of a traditional south Indian house with a front yard and a garden with a variety of plants. There is a natural spring that is shared between two families, and each family gets three days to turn for each and one day for replenishing. Still, this family has ignored this source to avoid any conflicts. The owner is a naturopathy doctor and can speak good English. The Grandfather constructed 4 *Suranga* (in the 1940s), and one *Suranga* developed was made by the father and the owner (2007). Two *Suranga* have one airshaft each, and the owner suggests that there can be many *Suranga* with airshafts in the area.

Finish

Appendix J: Qualitative analysis codebook for in-depth interviews

Name	Sources	References
Agriculture	135	417
History	10	23
Crop pattern	42	81
Arecanut	12	13
Banana	7	9
Cashew plantations	4	4
Cashew trees in dry land	2	2
Cocoa	2	2
Coconut	11	11
Crop storage	1	1
Crop yielding	1	1
Dry and wet cultivation	2	2
Medicinal plants	1	1
Paddy for self-use	2	2
Paddy cultivation	13	17
Pepper	5	5
Pineapple	1	1
Rubber plantation	8	8
Sugarcane	1	1
Current agriculture practice	15	17
Agriculture loan	11	12
Agriculture practice	4	4
Large scale farming	1	1
Farmworkers	2	9
Farmworkers	2	5
Farmers and farm workers symbiosis	2	4
Irrigation	85	129
Excess water used for irrigation	2	2
Hosepipe irrigation	6	6
Irrigation from a stream	1	1
Irrigation from *kere*	4	4
Irrigation from river water	4	4
Irrigation from spring water	2	2
Irrigation from *suranga* water	1	1
Irrigation not needed until December	1	1
Irrigation plan	3	3
Irrigation season	6	6
Irrigation through channels	3	3
Irrigation with borewell	6	6
Irrigation with dugwell	20	20
Irrigation with well	2	2
Issues due to no irrigation	1	1
Manual irrigation	8	8
No irrigation in summer	2	2
Suranga water for irrigation	3	3
Water-efficient irrigation	50	54
Issues related to agriculture	33	37
Agriculture and migration	7	8
Agriculture issues	6	6
Cultivable land increase not possible	1	1

Limited water resources		
Large water demand	1	1
Small farmers	2	2
Small scale agriculture	3	3
No agriculture	2	2
Whole land not cultivated	14	14
Organic farming	76	82
Chemical and organic farming	17	18
Organic fertilisers	61	62
Varanasi research centre Adyanadka	2	2
Soil type	4	7
Black stone	1	1
Laterite	1	3
Soft soil	2	2
Soil types soil layers	1	1
Transforming agriculture	18	32
Biodigesters	2	2
Changing agricultural pattern	8	14
Developing water resources for agriculture	1	1
Farm on contract	1	1
Increasing cultivation	4	5
Kalpa-rasha	1	1
New agriculture technology	2	2
Plans to increase the cultivated area	2	2
Satisfaction from agriculture	1	1
Sustainable farming	2	3
Geography and climate	63	123
Climate	12	26
Climate change	4	7
Rain	8	16
Delayed rain	1	1
High rainfall	1	1
Monsoonal Rain	3	6
Rainwater harvesting	4	7
Rainy season	1	1
Summer	3	3
Geography	36	44
Deforestation	1	1
Diffcult terrain	2	2
Elevation	2	2
Forest area	2	2
Granite	1	1
Hilly terrain	5	5
Natural cave	5	6
No water scarcity	15	16
Possdigumpe hill	4	4
Water rich area	5	5
Villages	30	53
Bayar	3	3
Bedadka village	1	1
Goa	1	1
Mahalinga Nayak	1	1
Manila village	11	20
Manimoole history	15	24
Sheni hamlet	3	3
Miscellaneous ideas	21	33
Archives	1	1
My observation	19	20

Other research works	1	11
Issues with old documents	1	1
Society and economy	156	559
Cooperative organisations	3	8
Benefits for coconut society members	1	2
CAMPCO	1	3
Coconut society Manila village	1	1
Cooperative organisations	2	2
Family size	89	90
Large family (more than six members)	29	30
Medium size family (4-6 members)	27	27
Small family (Upto four members)	33	33
Joint families	30	39
Division of a joint family	25	27
Division of property	4	5
Joint Family	6	7
Labourer	51	64
Caste-based farmworkers	1	1
Labour shortage	11	12
Labourer cost	4	4
Labourer working days	1	1
No land for agriculture	4	4
No livestock	2	2
Occupation Labourer	34	34
Shortage of farmworkers	3	5
Walk to work	1	1
Landholdings	43	68
Assigned land from the government	1	1
Distributed land	2	2
Dryland	3	3
Land completely cultivated	11	11
Land fragmentation	2	2
Land management	2	5
Land not suitable for agriculture	16	16
Land not suitable for borewell	4	5
Land not suitable for well	4	5
Land reforms	0	0
Land reforms act	4	7
Lost or gained land during land reforms	4	8
Land tenancy	3	3
Large land holdings	2	2
Prospecting Land	4	13
Local administration	13	23
Electricity shortage	1	2
Government policies	6	8
Grant for water tank or pond	1	1
Green revolution	1	1
Low-cost electricity for agriculture	2	2
Panchayat funding	5	6
Subsidy	2	3
Local culture	32	76
Alcohol addiction	1	2
Bunts	2	2
Changing society	7	8
education	1	1
Happy in the village	1	1
Health issues	1	1
History of the area	19	28

Increasing population	3	4
Kedwesa	4	6
Muslim family	4	5
Myths	1	1
Property inherited to women	2	2
SC & ST	1	1
Social distribution	4	8
Standard of living	1	2
Tulu culture	1	4
Local economy	15	20
Barter economy	1	1
Below poverty line	4	5
Breadwinner	1	1
Economy issues	0	0
Hard work	1	1
Increasing costs	2	2
Money crisis	4	4
Money problem	5	5
Tourism	1	1
Migration to cities	33	51
Bought this property	9	11
Initial settelements	1	1
Kharad migration	6	10
Migration	23	28
Sold the property and migrated	1	1
Occupation	88	120
Agriculture main occupation.	61	61
Bidi making	3	3
Changing occupation	1	1
Changing occupation because of education	1	1
Farming main occupation	2	2
Main occupation	7	7
Plan to sell the farm	6	6
Plan to stay in farming	1	1
Secondary occupation	37	37
Unskilled job	1	1
Water	159	1547
Drinking water	22	23
Drinking and household water from dugwell in summer	1	1
Drinking water from borewell	2	2
Drinking water from dugwell or openwell	5	5
Drinking water from a well	8	8
Used to fetch drinking water	6	7
Future water plans	35	43
Developing water resources for agriculture	1	1
Hydropower generator	1	2
Planning to make a dugwell myself	2	2
No plan to make any new water resource	12	12
Plan to make a borewell	9	9
Plan to make a dugwell openwell	5	5
Plan to make a *madaka*	1	1
Plan to make *katta*	1	1
Plans to make a well	2	2
Reason for making borewell	6	6
Water recycling	2	2
Groundwater	16	19
Abundant groundwater	2	2
Decreasing groundwater	10	11

Groundwater quality	1	1
Groundwater shortage	4	5
Traditional water harvesting	0	0
Water issues	60	82
Drought	2	2
Failed water plan	1	2
Ignorance about water recharge	5	6
Seasonal river	2	2
Seasonal stream	4	4
Water quality	5	7
Water shortage	49	59
Water management	18	21
A combination of water resources	3	3
Community water management	3	3
No pumping needed	2	3
No water sharing	3	3
Private water resources	2	2
Syphon water	2	2
Water conservation	1	1
Water rights	4	4
Water resources	157	1281
Borewell	41	69
Artesian well	1	1
Borewell	19	21
Borewell approval	2	2
Borewell can affect *suranga* water	2	2
Borewell getting popular	3	5
Borewell issues	2	2
Borewell not popular	3	3
Borewell only used in summer for irrigation	7	7
Borewell was not introduced to this area	1	1
Cannot afford a borewell	8	8
Community borewell	1	1
Completely dependent on borewell	2	2
I do not like borewell	3	4
Drying borewell	1	1
Objection for borewell	2	2
Unsuccessful borewell	7	7
Check dams	5	7
Katta, check dam	5	5
Kindi aane kattu, concrete wood check dam	2	2
Government water supply	6	6
Natural spring	4	4
Springwater in summer	1	1
Natural waterfall	1	1
No water reservoir in the region	1	1
Others water resources	8	19
Kai-dambe	1	1
Madaka	1	1
Traditional water knowledge	5	10
Yeta	1	1
Pond or *kere*	18	20
River	1	1
Sufficient water availaibiity	18	18
Suranga	59	62
Suranga water harvesting system	150	948
Benefits of *suranga*	87	121
Benefits of *suranga*	5	6

Dry *suranga* used as cesspit	1	1
Only the first *suranga* produced water	1	1
Suranga irrigation	8	8
Suranga made due to water shortage	1	1
Suranga made for drinking water	1	1
Suranga only water source	20	22
Suranga solved the water crisis	1	1
Suranga used in the past for irrigation	1	1
Suranga water for drinking and household	58	63
Suranga water for only household activity	2	2
Suranga used for domestic and irrigation	9	9
Suranga water used for washing	1	1
Suranga were popular	3	4
Ecology inside *suranga*	6	10
Bats	3	4
Inside a *suranga*	5	6
Future for *suranga*	24	42
No government support	1	1
Financial issues, self excavate	2	2
No plan to make a *suranga*	6	6
Plan to revive a *suranga*	1	1
Plans to extend the *suranga*	1	1
Plans to make a new *suranga*	9	9
Suranga based agriculture	1	1
Suranga decreasing demand	3	3
Suranga decreasing popularity	3	3
Suranga limitations	1	1
Suranga still in demand	2	2
Suranga technology transfer	0	0
Suranga workers decreasing	3	5
Suranga workers shortage	5	5
Suranga work decreasing	1	1
Workers not interested in *suranga* work	1	1
Making of a *suranga*	88	207
Failed *suranga*	4	4
How to avoid collapse inside a *suranga*	4	5
Kolu	2	2
Learning by observations	13	14
Suranga being excavated	5	6
Suranga cost	14	14
Suranga excavated by owner	42	45
Suranga excavated in evenings or part-time	11	11
Suranga excavated in part-time	7	7
Suranga excavation	19	26
Suranga excavated by workers	9	9
Suranga funding	3	3
Suranga health and safety	7	9
Suranga inside the property	8	8
Suranga maintenance	15	17
Suranga not inside the property	6	6
Suranga not maintained	8	8
Suranga worker	11	11
Underground excavation techniques	1	1
Management of *suranga*	13	15
Suranga are private property	7	7
Suranga management	8	8
Origin of *suranga*	102	137
Last *suranga*	8	8

Reason for making a *suranga*	18	20
Religious cave	1	1
Suranga history	83	91
No information	5	7
Made by the previous owner	5	5
Old tradition	4	5
Suranga design principles	99	201
A connecting *suranga*	1	1
Airshafts	0	0
Airshaft	5	6
Airshaft cum openwell	2	3
No airshaft	5	5
Reason for making airshaft	1	2
How to increase water in a *suranga*	17	17
Ideal *suranga* setting	1	1
Large numbers of *suranga*	2	3
Long *suranga*	2	2
Suranga abandoned	6	6
Suranga at various heights	1	1
Suranga bad design	1	1
Suranga blocked	1	1
Suranga branches	15	16
Suranga collapse reasons	8	13
Suranga collapsed	10	12
Suranga collapsed but yields water	4	4
Suranga connected	3	3
Suranga connecting two open wells	3	4
Suranga covered	2	2
Suranga design	16	16
Suranga elevated	10	10
Suranga especial design	10	12
Suranga extended	1	1
Suranga inside a well	6	7
Suranga inside a dugwell or openwell	25	29
Suranga next to a pond	7	7
Suranga no water pumping needed	2	2
Suranga on hilltop	1	1
Suranga oxygen problem	1	1
Suranga at a higher elevation	1	1
Suranga straight	2	2
Suranga to transport water	1	1
Suranga to transport water from an open well	3	3
Suranga water collected in a dugwell	1	1
Suranga water collected in a pond	11	11
Suranga water collected in a well	1	1
Suranga water conveyed through PVC pipes	6	6
Small bund inside the *suranga*	2	2
Suranga hydrology	98	170
Suranga not in use	4	4
Finding water in a *suranga*	1	1
Hydrology of *suranga*	6	6
Land not suitable for *suranga*	5	6
Land suitable for *suranga*	12	13
Source of water in a *suranga*	1	1
Suranga dry	21	23
Suranga dry in summer	5	5
Suranga dugwell based water	8	8
Suranga hard rock	14	17

Suranga perennial	26	26
Suranga water discharge	47	59
No decrease in *suranga* discharge	1	1
Seasonal *suranga*	10	12
Suranga discharge	10	12
Suranga seasonal water	1	1
Suranga water decrease in summer	13	13
Suranga water decreased	3	3
Suranga water decreased due to borewells	8	9
Suranga water increase	4	4
Suranga water quantity constant	3	3
Suranga water unaffected by borewell	1	1
Suranga yield	1	1
Suranga spatial distribution	11	17
Suranga distribution	4	6
Suranga in Kannur district of Kerala	1	1
Suranga in Ponda district of Goa	5	6
Suranga in Shimoga district	1	1
Suranga in Wayand district of Kerala	1	1
Suranga location	1	1
Suranga water quality	13	13
Suranga worker	9	15
Claim	2	3
Number of *suranga* workers	1	1
My husband does not know *suranga* work.	1	1
Suranga assistant	2	3
Suranga worker died in a *suranga*	1	1
Suranga workers	5	5
Suranga workers high wages in the past	1	1
Water divining	32	41
Water diviner	19	19
Water divining	17	21
Wells	63	84
Area suitable for well	2	2
Bavi, a circular concrete well	3	3
Difference between dug well and circular well	1	1
Digging a well	1	1
Found water by accident	1	1
Horizontal bore in a well	3	3
How to increase water in a dug well	4	5
How to increase water in a well	1	1
Open well, dug well, well	58	63
Riverbed well	3	4
Water sharing	49	78
Shared water issues	6	13
Water sharing for drinking and household	34	44
Water sharing for irrigation	15	21

Appendix K: MCA of socioeconomic characteristics

Table K1: Summary statistics from MCA of socioeconomic characteristics.

Variable	Categories	Frequencies	%
Main occupation (MO)	Farming (FA)	93	61.18
	Skilled employment (EMS)	7	4.61
	Labouring (LB)	49	32.24
	Self-employment (SE)	3	1.97
Secondary occupation (SO)	Yes (Y)	43	28.29
	No (N)	109	71.71
Secondary occupation type (SOT)	Skilled employment (EMS)	13	8.55
	No secondary employment (N)	109	71.71
	Farming (FA)	22	14.47
	Self-employment (SE)	7	4.61
	Labouring (LB)	1	0.66
Family status (FS)	Above the poverty line (APL)	90	59.21
	Below poverty line (BPL)	62	40.79
Farmers category (FC)	Medium (MM)	23	15.13
	Small-medium (SM)	36	23.68
	Marginal (MA)	50	32.89
	Small (SL)	40	26.32
	Landless (LL)	1	0.66
	Large (LA)	2	1.32
Cows (CO)	Yes (Y)	130	85.53
	No (N)	22	14.47
Chickens (CH)	No (N)	127	83.55
	Yes (Y)	25	16.45
Goats (GH)	No (N)	149	98.03
	Yes (Y)	3	1.97
Village (V)	Manila (MN)	60	39.47
	Bayar (BR)	7	4.61
	Enmakaje (EN)	47	30.92
	Peruvai (PU)	4	2.63
	Padre (PR)	10	6.58
	Kanyana (KN)	3	1.97
	Alike (AL)	2	1.32
	Kepu (KU)	11	7.24
	Karvapadi (KV)	4	2.63
	Paddvanuru (PD)	1	0.66
	Priyol (PY)	3	1.97

Table K2: Eigenvalues and percentages of inertia for the socioeconomic survey.

	F1	F2	F3	F4	F5	F6	F7
Eigenvalue	0.39	0.28	0.19	0.16	0.15	0.14	0.13
Inertia (%)	18.33	13.17	8.93	7.73	7.25	6.63	6.09
Cumulative %	18.33	31.49	40.42	48.15	55.41	62.03	68.12
Adjusted Inertia	0.09	0.03	0.01	0.00	0.00	0.00	0.00
Adjusted Inertia (%)	53.26	18.25	3.20	1.17	0.65	0.19	0.01
Cumulative %	53.26	71.51	74.71	75.89	76.53	76.72	76.74

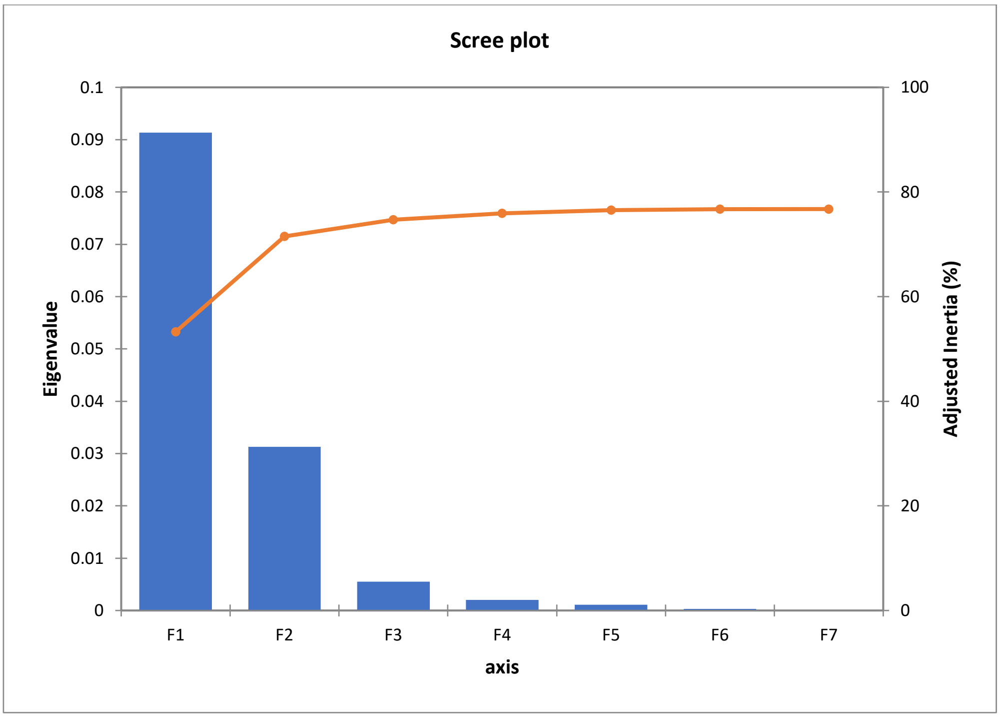


Figure K1: Scree plot of eigenvalue and adjusted inertia (%) for the socioeconomic survey.

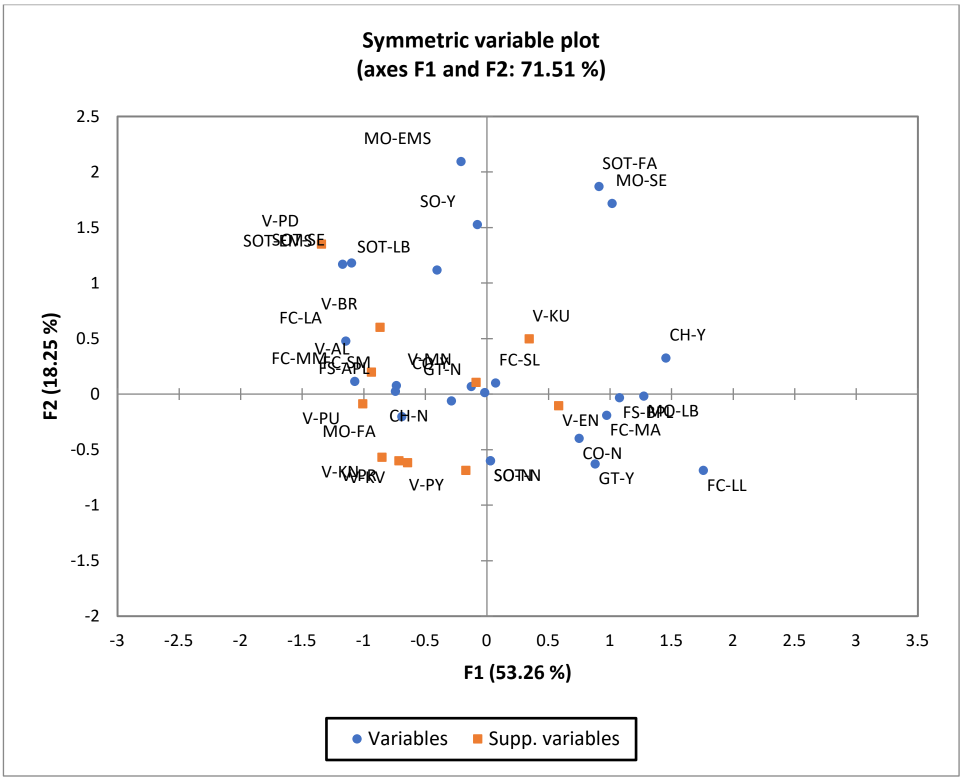


Figure K2: Symmetric variable plot of socioeconomic MCA.

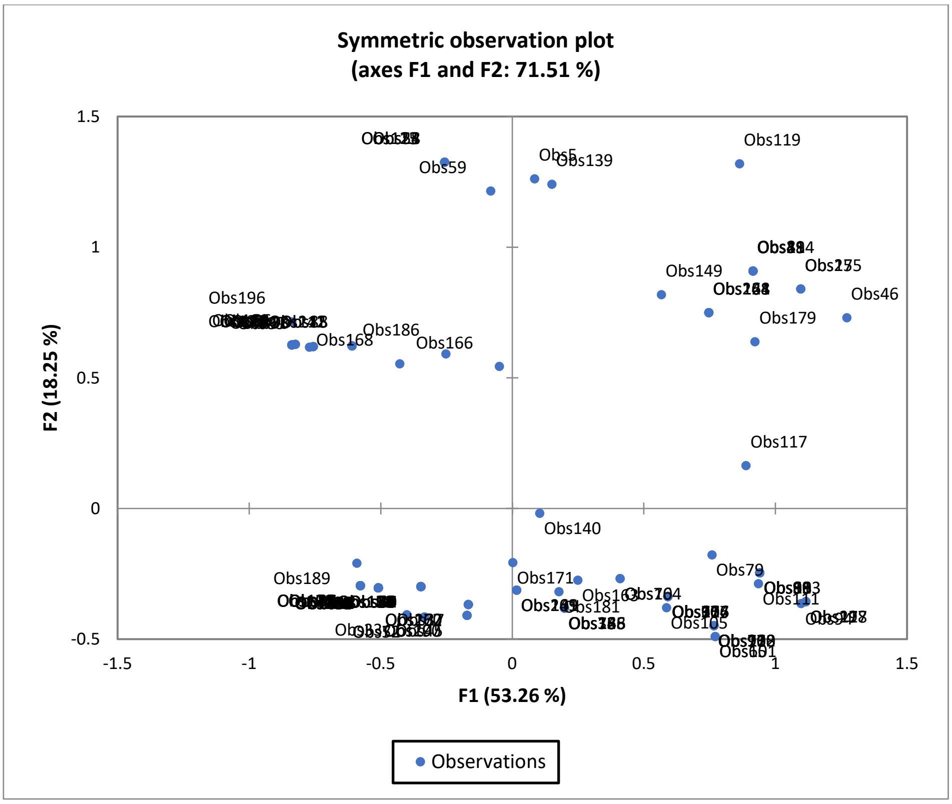


Figure K3: Symmetric observation plot of socioeconomic MCA.

Results for the variables:

Principal coordinates (Variables):

	F1	F2	F3	F4	F5	F6
MO-FA	-0.69	-0.20	0.13	-0.01	-0.10	-0.03
MO-EMS	-0.21	2.09	-3.21	-0.41	0.85	0.34
MO-LB	1.28	-0.02	0.17	0.21	0.26	-0.07
MO-SE	1.02	1.71	0.66	-2.13	-3.33	1.24
SO-Y	-0.08	1.53	0.25	0.15	0.18	-0.07
SO-N	0.03	-0.60	-0.10	-0.06	-0.07	0.03
SOT-EMS	-1.17	1.17	1.60	-0.79	1.37	-0.29
SOT-N	0.03	-0.60	-0.10	-0.06	-0.07	0.03
SOT-FA	0.91	1.87	-0.61	-0.30	-0.21	0.02
SOT-SE	-1.10	1.18	0.62	3.02	-0.55	1.20
SOT-LB	-0.40	1.12	-0.81	2.43	-1.46	-8.01
FS-APL	-0.74	0.02	-0.13	-0.14	-0.05	0.11
FS-BPL	1.08	-0.03	0.19	0.21	0.07	-0.16
FC-MM	-1.07	0.11	1.04	-0.20	0.88	-0.06
FC-SM	-0.73	0.08	-1.04	0.32	-0.45	-0.61
FC-MA	0.97	-0.19	0.11	0.43	0.45	-0.11
FC-SL	0.07	0.10	0.13	-0.94	-0.50	0.56
FC-LL	1.76	-0.69	1.56	0.15	-2.66	-2.02
FC-LA	-1.14	0.48	0.74	4.66	-1.88	4.26
CO-Y	-0.13	0.07	0.10	0.04	-0.10	-0.09
CO-N	0.75	-0.40	-0.60	-0.21	0.60	0.52
CH-N	-0.29	-0.06	-0.10	0.06	0.13	-0.01
CH-Y	1.46	0.32	0.50	-0.30	-0.64	0.06
GT-N	-0.02	0.01	0.05	0.00	-0.06	-0.04
GT-Y	0.88	-0.63	-2.30	-0.13	3.17	2.06
V-MN	-0.09	0.10	-0.01	-0.13	0.13	0.08
V-BR	-0.87	0.60	0.27	-0.41	0.64	-0.25
V-EN	0.59	-0.11	0.10	0.23	-0.03	-0.20
V-PU	-1.01	-0.09	0.53	0.63	-0.03	0.69
V-PR	-0.71	-0.60	-0.19	-0.22	-0.18	-0.09
V-KN	-0.85	-0.57	-0.32	-0.03	-0.27	-0.38
V-AL	-0.94	0.20	0.35	-0.39	0.88	-0.21
V-KU	0.35	0.50	-0.56	-0.20	-0.59	-0.10
V-KV	-0.64	-0.62	-0.17	-0.52	-0.24	0.23
V-PD	-1.34	1.35	1.10	5.92	-1.97	4.73
V-PY	-0.17	-0.69	-0.10	-0.48	-0.19	0.39

Contributions (Variables):

	Weight	Weight (relative)	F1	F2	F3	F4
MO-FA	93	0.08	0.09	0.01	0.01	0.00
MO-EMS	7	0.01	0.00	0.09	0.31	0.01
MO-LB	49	0.04	0.17	0.00	0.01	0.01
MO-SE	3	0.00	0.01	0.03	0.01	0.07
SO-Y	43	0.04	0.00	0.29	0.01	0.01
SO-N	109	0.09	0.00	0.12	0.00	0.00
SOT-EMS	13	0.01	0.04	0.05	0.14	0.04
SOT-N	109	0.09	0.00	0.12	0.00	0.00
SOT-FA	22	0.02	0.04	0.23	0.04	0.01
SOT-SE	7	0.01	0.02	0.03	0.01	0.32
SOT-LB	1	0.00	0.00	0.00	0.00	0.03
FS-APL	90	0.07	0.10	0.00	0.01	0.01
FS-BPL	62	0.05	0.15	0.00	0.01	0.01
FC-MM	23	0.02	0.06	0.00	0.11	0.00
FC-SM	36	0.03	0.04	0.00	0.17	0.02
FC-MA	50	0.04	0.10	0.01	0.00	0.05
FC-SL	40	0.03	0.00	0.00	0.00	0.18
FC-LL	1	0.00	0.01	0.00	0.01	0.00
FC-LA	2	0.00	0.01	0.00	0.00	0.22
CO-Y	130	0.11	0.00	0.00	0.01	0.00
CO-N	22	0.02	0.03	0.01	0.03	0.01
CH-N	127	0.10	0.02	0.00	0.01	0.00
CH-Y	25	0.02	0.11	0.01	0.03	0.01
GT-N	149	0.12	0.00	0.00	0.00	0.00
GT-Y	3	0.00	0.00	0.00	0.07	0.00
V-MN	60	0.05	0.00	0.00	0.00	0.00
V-BR	7	0.01	0.00	0.00	0.00	0.00
V-EN	47	0.04	0.00	0.00	0.00	0.00
V-PU	4	0.00	0.00	0.00	0.00	0.00
V-PR	10	0.01	0.00	0.00	0.00	0.00
V-KN	3	0.00	0.00	0.00	0.00	0.00
V-AL	2	0.00	0.00	0.00	0.00	0.00
V-KU	11	0.01	0.00	0.00	0.00	0.00
V-KV	4	0.00	0.00	0.00	0.00	0.00
V-PD	1	0.00	0.00	0.00	0.00	0.00
V-PY	3	0.00	0.00	0.00	0.00	0.00

Squared cosines (Variables):

	F1	F2	F3	F4	F5	F6
MO-FA	0.75	0.06	0.03	0.00	0.01	0.00
MO-EMS	0.00	0.21	0.50	0.01	0.03	0.01
MO-LB	0.77	0.00	0.01	0.02	0.03	0.00
MO-SE	0.02	0.06	0.01	0.09	0.22	0.03
SO-Y	0.00	0.92	0.02	0.01	0.01	0.00
SO-N	0.00	0.92	0.02	0.01	0.01	0.00
SOT-EMS	0.13	0.13	0.24	0.06	0.18	0.01
SOT-N	0.00	0.92	0.02	0.01	0.01	0.00
SOT-FA	0.14	0.59	0.06	0.02	0.01	0.00
SOT-SE	0.06	0.07	0.02	0.44	0.01	0.07
SOT-LB	0.00	0.01	0.00	0.04	0.01	0.42
FS-APL	0.80	0.00	0.02	0.03	0.00	0.02
FS-BPL	0.80	0.00	0.02	0.03	0.00	0.02
FC-MM	0.21	0.00	0.19	0.01	0.14	0.00
FC-SM	0.17	0.00	0.33	0.03	0.06	0.12
FC-MA	0.47	0.02	0.01	0.09	0.10	0.01
FC-SL	0.00	0.00	0.01	0.32	0.09	0.11
FC-LL	0.02	0.00	0.02	0.00	0.05	0.03
FC-LA	0.02	0.00	0.01	0.29	0.05	0.24
CO-Y	0.10	0.03	0.06	0.01	0.06	0.05
CO-N	0.10	0.03	0.06	0.01	0.06	0.05
CH-N	0.42	0.02	0.05	0.02	0.08	0.00
CH-Y	0.42	0.02	0.05	0.02	0.08	0.00
GT-N	0.02	0.01	0.11	0.00	0.20	0.09
GT-Y	0.02	0.01	0.11	0.00	0.20	0.09
V-MN	0.00	0.01	0.00	0.01	0.01	0.00
V-BR	0.04	0.02	0.00	0.01	0.02	0.00
V-EN	0.15	0.01	0.00	0.02	0.00	0.02
V-PU	0.03	0.00	0.01	0.01	0.00	0.01
V-PR	0.04	0.03	0.00	0.00	0.00	0.00
V-KN	0.01	0.01	0.00	0.00	0.00	0.00
V-AL	0.01	0.00	0.00	0.00	0.01	0.00
V-KU	0.01	0.02	0.02	0.00	0.03	0.00
V-KV	0.01	0.01	0.00	0.01	0.00	0.00
V-PD	0.01	0.01	0.01	0.23	0.03	0.15
V-PY	0.00	0.01	0.00	0.00	0.00	0.00

Test values (Variables):

	F1	F2	F3	F4	F5	F6
MO-FA	-10.63	-3.13	2.05	-0.21	-1.47	-0.40
MO-EMS	-0.57	5.65	-8.66	-1.11	2.29	0.91
MO-LB	10.81	-0.16	1.41	1.82	2.23	-0.64
MO-SE	1.77	2.99	1.16	-3.72	-5.81	2.16
SO-Y	-0.58	11.78	1.93	1.19	1.40	-0.52
SO-N	0.58	-11.78	-1.93	-1.19	-1.40	0.52
SOT-EMS	-4.40	4.39	6.00	-2.98	5.16	-1.10
SOT-N	0.58	-11.78	-1.93	-1.19	-1.40	0.52
SOT-FA	4.61	9.44	-3.11	-1.53	-1.08	0.12
SOT-SE	-2.96	3.19	1.67	8.15	-1.49	3.24
SOT-LB	-0.40	1.12	-0.81	2.43	-1.46	-8.01
FS-APL	-10.99	0.34	-1.92	-2.14	-0.68	1.68
FS-BPL	10.99	-0.34	1.92	2.14	0.68	-1.68
FC-MM	-5.57	0.58	5.39	-1.06	4.56	-0.29
FC-SM	-5.03	0.52	-7.10	2.17	-3.11	-4.19
FC-MA	8.39	-1.65	0.91	3.68	3.91	-0.92
FC-SL	0.53	0.73	0.94	-6.90	-3.70	4.08
FC-LL	1.76	-0.69	1.56	0.15	-2.66	-2.02
FC-LA	-1.62	0.67	1.06	6.62	-2.67	6.04
CO-Y	-3.79	2.03	3.01	1.08	-3.03	-2.65
CO-N	3.79	-2.03	-3.01	-1.08	3.03	2.65
CH-N	-7.94	-1.76	-2.75	1.61	3.50	-0.33
CH-Y	7.94	1.76	2.75	-1.61	-3.50	0.33
GT-N	-1.54	1.10	4.01	0.22	-5.52	-3.60
GT-Y	1.54	-1.10	-4.01	-0.22	5.52	3.60
V-MN	-0.86	1.04	-0.12	-1.27	1.33	0.79
V-BR	**-2.34**	1.62	0.73	-1.10	1.74	-0.66
V-EN	**4.81**	-0.88	0.85	1.90	-0.26	-1.61
V-PU	**-2.03**	-0.18	1.08	1.28	-0.07	1.39
V-PR	**-2.32**	**-1.96**	-0.61	-0.71	-0.60	-0.29
V-KN	-1.48	-1.00	-0.56	-0.05	-0.47	-0.66
V-AL	-1.33	0.28	0.49	-0.55	1.25	-0.30
V-KU	1.19	1.70	-1.91	-0.68	**-2.04**	-0.33
V-KV	-1.30	-1.25	-0.34	-1.06	-0.48	0.47
V-PD	-1.34	1.35	1.10	**5.92**	**-1.97**	**4.73**
V-PY	-0.30	-1.20	-0.17	-0.84	-0.33	0.69

Values displayed in bold are significant at the level alpha=0.05

Appendix L: MCA of agricultural practices

Table L1. Summary statistics for agricultural practices.

Variable	Categories	Frequencies	%
Farmer category (FC)	Medium (MM)	22	15.71
	Small-medium (SM)	39	27.86
	Marginal (MA)	37	26.43
	Small (SL)	39	27.86
	Large (LA)	3	2.14
Arecanut (AR)	Yes (Y)	129	92.14
	No (N)	11	7.86
Coconut (CC)	Yes (Y)	133	95.00
	No (N)	7	5.00
Cocoa (CA)	Yes (Y)	17	12.14
	No (N)	123	87.86
Pepper (PP)	Yes (Y)	73	52.14
	No (N)	67	47.86
Banana (BA)	Yes (Y)	76	54.29
	No (N)	64	45.71
Cashew (CW)	Yes (Y)	27	19.29
	No (N)	113	80.71
Paddy (PA)	No (N)	124	88.57
	Yes (Y)	16	11.43
Rubber (RU)	No (N)	123	87.86
	Yes (Y)	17	12.14
Organic fertilisers (OF)	Yes (Y)	138	98.57
	No (N)	2	1.43
Chemical fertilisers (CF)	No (N)	113	80.71
	Yes (Y)	27	19.29
Family status (FS)	APL	94	67.14
	BPL	46	32.86

Table L2: Eigenvalues and percentages of inertia.

	F1	F2	F3	F4	F5	F6
Eigenvalue	0.19	0.15	0.12	0.11	0.10	0.10
Inertia (%)	15.05	11.94	9.77	8.91	7.70	7.64
Cumulative %	15.05	26.99	36.76	45.67	53.37	61.00
Adjusted Inertia	0.01	0.00	0.00	0.00	0.00	0.00
Adjusted Inertia (%)	45.75	16.86	5.05	2.29	0.22	0.18
Cumulative %	45.75	62.61	67.66	69.95	70.17	70.35

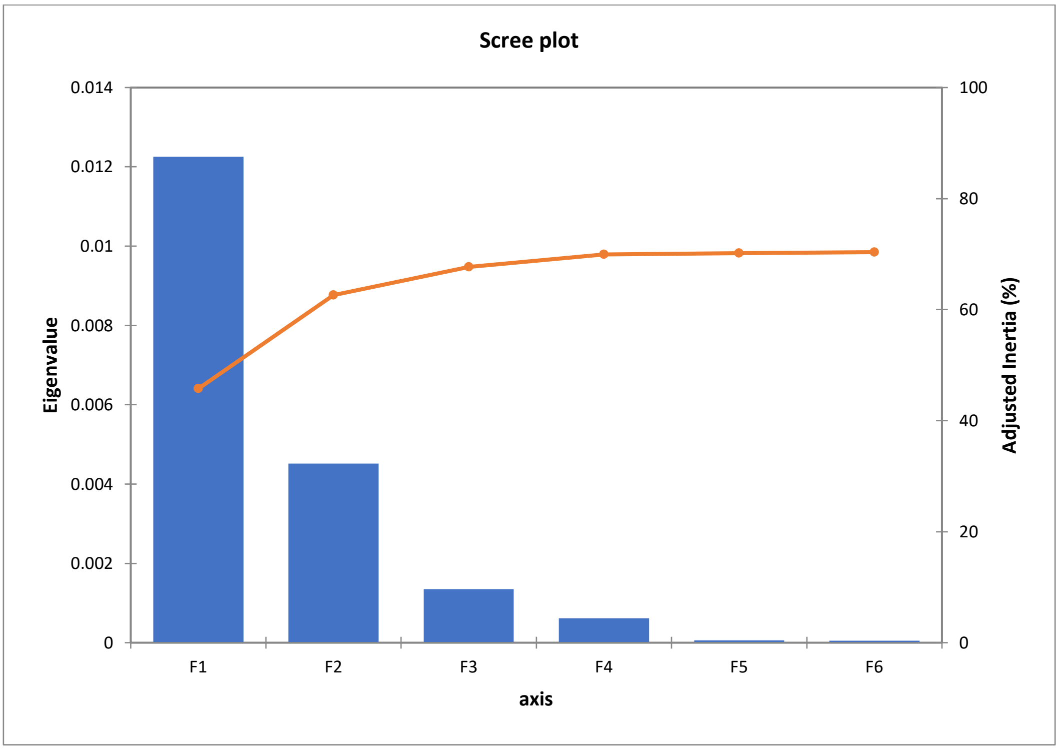


Figure L1: Scree plot of eigenvalues and percentage of inertia.

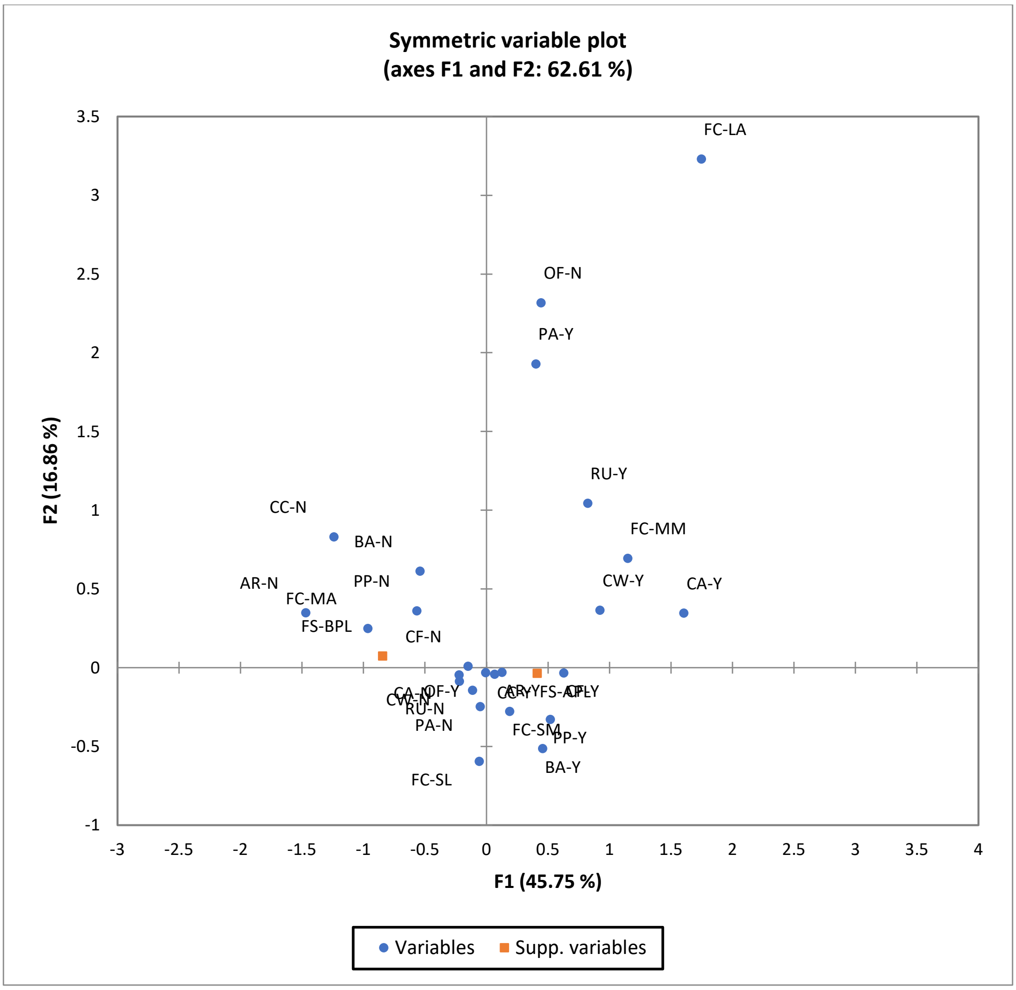


Figure L2: Symmetric variable plot.

Results for the variables:

Principal coordinates (Variables):

	F1	F2	F3	F4	F5	F6
FC-MM	1.15	0.69	0.13	0.01	-1.44	0.62
FC-SM	0.19	-0.28	0.55	-0.15	0.13	-1.30
FC-MA	-0.96	0.25	-0.23	0.47	-0.31	0.13
FC-SL	-0.06	-0.60	-0.45	-0.24	0.65	0.77
FC-LA	1.75	3.23	0.62	-0.65	4.23	0.74
AR-Y	0.13	-0.03	0.01	-0.09	-0.02	-0.01
AR-N	-1.47	0.35	-0.10	1.04	0.18	0.06
CC-Y	0.07	-0.04	-0.03	-0.12	-0.02	0.05
CC-N	-1.24	0.83	0.57	2.26	0.32	-0.91
CA-Y	1.61	0.34	0.50	1.24	-0.21	-0.12
CA-N	-0.22	-0.05	-0.07	-0.17	0.03	0.02
PP-Y	0.52	-0.33	0.08	0.14	-0.01	0.15
PP-N	-0.57	0.36	-0.08	-0.16	0.01	-0.16
BA-Y	0.46	-0.52	-0.14	0.07	-0.05	0.06
BA-N	-0.54	0.61	0.17	-0.09	0.06	-0.07
CW-Y	0.92	0.36	-0.34	1.10	0.51	-0.20
CW-N	-0.22	-0.09	0.08	-0.26	-0.12	0.05
PA-N	-0.05	-0.25	0.08	0.01	-0.01	-0.09
PA-Y	0.40	1.93	-0.61	-0.10	0.09	0.69
RU-N	-0.11	-0.14	-0.17	0.17	0.02	0.05
RU-Y	0.82	1.04	1.22	-1.26	-0.12	-0.33
OF-Y	-0.01	-0.03	0.08	0.01	0.04	0.03
OF-N	0.44	2.32	-5.57	-0.66	-2.59	-2.38
CF-N	-0.15	0.01	0.30	0.10	-0.10	0.17
CF-Y	0.63	-0.03	-1.27	-0.41	0.42	-0.70
FS-APL	0.41	-0.04	0.06	-0.12	-0.02	-0.17
FS-BPL	-0.84	0.07	-0.12	0.25	0.04	0.34

Contributions (Variables):

	Weight	Weight (relative)	F1	F2	F3	F4
FC-MM	22	0.01	0.10	0.05	0.00	0.00
FC-SM	39	0.03	0.00	0.01	0.06	0.01
FC-MA	37	0.02	0.12	0.01	0.01	0.05
FC-SL	39	0.03	0.00	0.06	0.04	0.01
FC-LA	3	0.00	0.03	0.13	0.01	0.01
AR-Y	129	0.08	0.01	0.00	0.00	0.01

AR-N	11	0.01	0.08	0.01	0.00	0.07
CC-Y	133	0.09	0.00	0.00	0.00	0.01
CC-N	7	0.00	0.04	0.02	0.01	0.21
CA-Y	17	0.01	0.15	0.01	0.02	0.15
CA-N	123	0.08	0.02	0.00	0.00	0.02
PP-Y	73	0.05	0.07	0.03	0.00	0.01
PP-N	67	0.04	0.07	0.04	0.00	0.01
BA-Y	76	0.05	0.05	0.09	0.01	0.00
BA-N	64	0.04	0.06	0.10	0.01	0.00
CW-Y	27	0.02	0.08	0.02	0.02	0.19
CW-N	113	0.07	0.02	0.00	0.00	0.04
PA-N	124	0.08	0.00	0.03	0.00	0.00
PA-Y	16	0.01	0.01	0.25	0.03	0.00
RU-N	123	0.08	0.01	0.01	0.02	0.02
RU-Y	17	0.01	0.04	0.08	0.13	0.15
OF-Y	138	0.09	0.00	0.00	0.00	0.00
OF-N	2	0.00	0.00	0.05	0.32	0.01
CF-N	113	0.07	0.01	0.00	0.05	0.01
CF-Y	27	0.02	0.04	0.00	0.23	0.03
FS-APL	94	0.06	0.00	0.00	0.00	0.00
FS-BPL	46	0.03	0.00	0.00	0.00	0.00

Squared cosines (Variables)

	F1	F2	F3	F4	F5	F6
FC-MM	0.25	0.09	0.00	0.00	0.39	0.07
FC-SM	0.01	0.03	0.12	0.01	0.01	0.65
FC-MA	0.33	0.02	0.02	0.08	0.03	0.01
FC-SL	0.00	0.14	0.08	0.02	0.16	0.23
FC-LA	0.07	0.23	0.01	0.01	0.39	0.01
AR-Y	0.18	0.01	0.00	0.09	0.00	0.00
AR-N	0.18	0.01	0.00	0.09	0.00	0.00
CC-Y	0.08	0.04	0.02	0.27	0.01	0.04
CC-N	0.08	0.04	0.02	0.27	0.01	0.04
CA-Y	0.36	0.02	0.04	0.21	0.01	0.00
CA-N	0.36	0.02	0.04	0.21	0.01	0.00
PP-Y	0.29	0.12	0.01	0.02	0.00	0.02
PP-N	0.29	0.12	0.01	0.02	0.00	0.02
BA-Y	0.25	0.32	0.02	0.01	0.00	0.00
BA-N	0.25	0.32	0.02	0.01	0.00	0.00
CW-Y	0.20	0.03	0.03	0.29	0.06	0.01
CW-N	0.20	0.03	0.03	0.29	0.06	0.01

PA-N	0.02	0.48	0.05	0.00	0.00	0.06
PA-Y	0.02	0.48	0.05	0.00	0.00	0.06
RU-N	0.09	0.15	0.21	0.22	0.00	0.02
RU-Y	0.09	0.15	0.21	0.22	0.00	0.02
OF-Y	0.00	0.08	0.45	0.01	0.10	0.08
OF-N	0.00	0.08	0.45	0.01	0.10	0.08
CF-N	0.09	0.00	0.39	0.04	0.04	0.12
CF-Y	0.09	0.00	0.39	0.04	0.04	0.12
FS-APL	0.35	0.00	0.01	0.03	0.00	0.06
FS-BPL	0.35	0.00	0.01	0.03	0.00	0.06

Test values (Variables)

	F1	F2	F3	F4	F5	F6
FC-MM	5.85	3.53	0.67	0.04	-7.34	3.17
FC-SM	1.39	-2.04	4.00	-1.12	0.98	-9.49
FC-MA	-6.81	1.75	-1.62	3.31	-2.18	0.89
FC-SL	-0.42	-4.36	-3.30	-1.79	4.75	5.63
FC-LA	3.05	5.63	1.08	-1.13	7.38	1.29
AR-Y	5.06	-1.20	0.33	-3.57	-0.62	-0.22
AR-N	-5.06	1.20	-0.33	3.57	0.62	0.22
CC-Y	3.36	-2.24	-1.56	-6.12	-0.87	2.47
CC-N	-3.36	2.24	1.56	6.12	0.87	-2.47
CA-Y	7.04	1.51	2.21	5.43	-0.92	-0.54
CA-N	-7.04	-1.51	-2.21	-5.43	0.92	0.54
PP-Y	6.39	-4.06	0.96	1.75	-0.11	1.82
PP-N	-6.39	4.06	-0.96	-1.75	0.11	-1.82
BA-Y	5.85	-6.62	-1.85	0.96	-0.64	0.74
BA-N	-5.85	6.62	1.85	-0.96	0.64	-0.74
CW-Y	5.32	2.09	-1.96	6.33	2.91	-1.16
CW-N	-5.32	-2.09	1.96	-6.33	-2.91	1.16
PA-N	-1.70	-8.16	2.57	0.43	-0.39	-2.92
PA-Y	1.70	8.16	-2.57	-0.43	0.39	2.92
RU-N	-3.61	-4.57	-5.35	5.52	0.51	1.45
RU-Y	3.61	4.57	5.35	-5.52	-0.51	-1.45
OF-Y	-0.63	-3.29	7.91	0.94	3.68	3.38
OF-N	0.63	3.29	-7.91	-0.94	-3.68	-3.38
CF-N	-3.62	0.19	7.34	2.35	-2.39	4.04
CF-Y	3.62	-0.19	-7.34	-2.35	2.39	-4.04
FS-APL	6.96	-0.60	0.97	-2.08	-0.29	-2.81
FS-BPL	-6.96	0.60	-0.97	2.08	0.29	2.81

Values displayed in bold are significant at the level alpha=0.05

Appendix M: MCA of water resources

Table M1: Summary statistics of Water resources.

Variable	Categories	Frequencies	%
Suranga (SU1)	Yes (Y)	169	100.00
Borewell (BW1)	No (N)	141	83.43
	Yes (Y)	28	16.57
Well (WL1)	No (N)	156	92.31
	Yes (Y)	13	7.69
Dugwell (DW1)	Yes (Y)	121	71.60
	No (N)	48	28.40
Spring (SP1)	No (N)	160	94.67
	Yes (Y)	9	5.33
Government supply (GS1)	No (N)	168	99.41
	Yes (Y)	1	0.59
Future water plan (FP)	*Suranga* (SU)	25	14.79
	No (N)	124	73.37
	No funds (NF)	1	0.59
	Well (WL)	2	1.18
	Dugwell (DW)	8	4.73
	Borewell (BW)	8	4.73
	Katta (KT)	1	0.59
Water sharing (WS)	Yes (Y)	24	14.20
	No (N)	145	85.80
Suranga water (SU2)	Yes (Y)	160	94.67
	No (N)	9	5.33
Dugwell water (DW2)	No (N)	134	79.29
	Yes (Y)	35	20.71
Well water (WL2)	No (N)	159	94.08
	Yes (Y)	10	5.92
Borewell water (BW2)	No (N)	165	97.63
	Yes (Y)	4	2.37
Spring water (SP2)	No (N)	168	99.41
	Yes (Y)	1	0.59
Government water supply (GS2)	No	169	100.00
Family status (FS)	APL	100	59.17
	BPL	69	40.83

Table M2: Eigenvalues and percentages of inertia

	F1	F2	F3	F4	F5	F6	F7
Eigenvalue	0.18	0.12	0.10	0.10	0.08	0.08	0.07
Inertia (%)	14.71	10.15	8.30	7.92	6.45	6.29	6.00
Cumulative %	14.71	24.86	33.16	41.08	47.53	53.82	59.82
Adjusted Inertia	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Adjusted Inertia (%)	49.01	11.43	3.69	2.61	0.20	0.10	0.01
Cumulative %	49.01	60.44	64.13	66.74	66.94	67.05	67.06

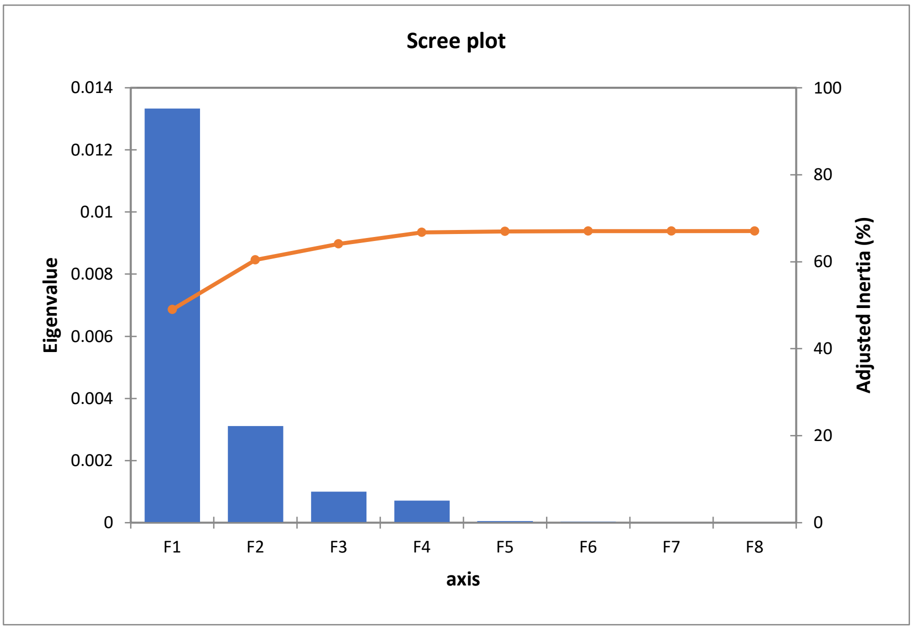


Figure M1: Scree plot of eigenvalues and adjusted inertia (%).

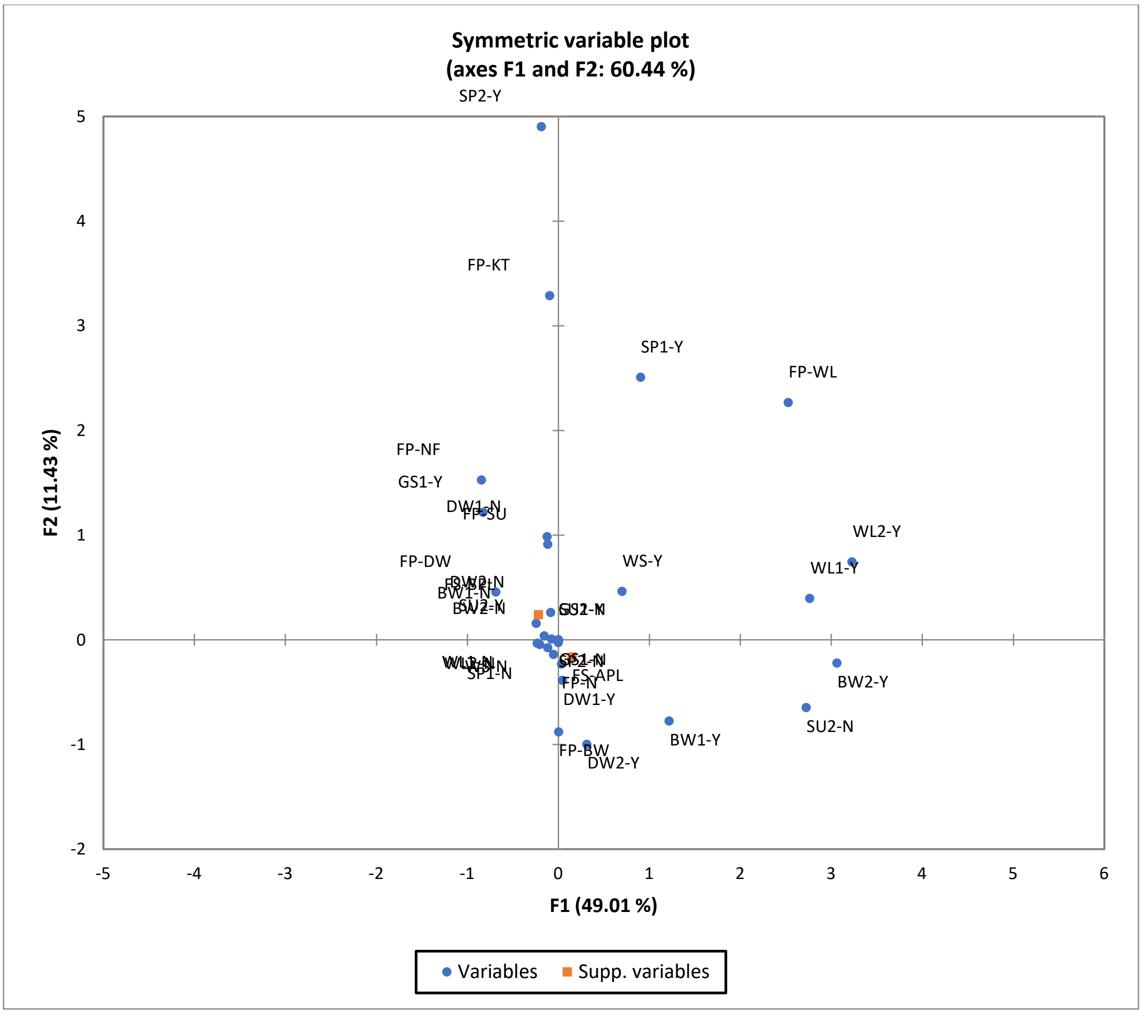


Figure M2: Symmetric observation plot of water resources MCA.

Results for the variables:

Principal coordinates (Variables):

	F1	F2	F3	F4	F5
SU1-Y	0.00	0.00	0.00	0.00	0.00
BW1-N	-0.24	0.15	-0.12	-0.05	0.08
BW1-Y	1.22	-0.78	0.62	0.26	-0.42
WL1-N	-0.23	-0.03	0.10	0.06	0.09
WL1-Y	2.76	0.39	-1.23	-0.66	-1.03
DW1-Y	0.05	-0.39	0.04	-0.33	0.06
DW1-N	-0.12	0.98	-0.10	0.83	-0.16
SP1-N	-0.05	-0.14	-0.10	0.10	-0.01
SP1-Y	0.90	2.51	1.86	-1.72	0.12
GS1-N	0.00	-0.01	0.00	-0.02	0.03
GS1-Y	-0.82	1.22	-0.08	3.02	-4.60
FP-SU	-0.12	0.91	-0.54	-0.23	0.80
FP-N	0.03	-0.23	0.17	0.01	-0.11
FP-NF	-0.84	1.53	-0.49	2.95	-3.17
FP-WL	2.53	2.27	-3.04	2.41	1.34
FP-DW	-0.69	0.46	-0.55	0.90	0.59
FP-BW	0.00	-0.88	-0.20	-0.53	-1.36
FP-KT	-0.10	3.29	4.62	-5.63	0.46
WS-Y	0.70	0.46	-0.46	-0.29	1.37
WS-N	-0.12	-0.08	0.08	0.05	-0.23
SU2-Y	-0.15	0.04	-0.07	-0.07	-0.07
SU2-N	2.73	-0.65	1.20	1.28	1.19
DW2-N	-0.08	0.26	0.04	0.15	-0.09
DW2-Y	0.31	-1.00	-0.15	-0.58	0.34
WL2-N	-0.20	-0.05	0.09	0.04	0.05
WL2-Y	3.23	0.74	-1.41	-0.63	-0.81
BW2-N	-0.07	0.01	-0.09	-0.07	-0.02
BW2-Y	3.06	-0.22	3.58	2.77	1.00
SP2-N	0.00	-0.03	-0.03	0.01	0.02
SP2-Y	-0.19	4.90	4.76	-2.32	-3.21
GS2-N	0.00	0.00	0.00	0.00	0.00
FS-APL	0.15	-0.16	0.23	-0.17	-0.12
FS-BPL	-0.22	0.24	-0.33	0.25	0.17

Contributions (Variables):

	Weight	Weight (relative)	F1	F2	F3

SU1-Y	169	0.07	0.00	0.00	0.00
BW1-N	141	0.06	0.02	0.01	0.01
BW1-Y	28	0.01	0.10	0.06	0.05
WL1-N	156	0.07	0.02	0.00	0.01
WL1-Y	13	0.01	0.23	0.01	0.08
DW1-Y	121	0.05	0.00	0.06	0.00
DW1-N	48	0.02	0.00	0.16	0.00
SP1-N	160	0.07	0.00	0.01	0.01
SP1-Y	9	0.00	0.02	0.19	0.13
GS1-N	168	0.07	0.00	0.00	0.00
GS1-Y	1	0.00	0.00	0.01	0.00
FP-SU	25	0.01	0.00	0.07	0.03
FP-N	124	0.05	0.00	0.02	0.02
FP-NF	1	0.00	0.00	0.01	0.00
FP-WL	2	0.00	0.03	0.04	0.08
FP-DW	8	0.00	0.01	0.01	0.01
FP-BW	8	0.00	0.00	0.02	0.00
FP-KT	1	0.00	0.00	0.04	0.09
WS-Y	24	0.01	0.03	0.02	0.02
WS-N	145	0.06	0.00	0.00	0.00
SU2-Y	160	0.07	0.01	0.00	0.00
SU2-N	9	0.00	0.16	0.01	0.05
DW2-N	134	0.06	0.00	0.03	0.00
DW2-Y	35	0.01	0.01	0.12	0.00
WL2-N	159	0.07	0.02	0.00	0.01
WL2-Y	10	0.00	0.25	0.02	0.08
BW2-N	165	0.07	0.00	0.00	0.01
BW2-Y	4	0.00	0.09	0.00	0.21
SP2-N	168	0.07	0.00	0.00	0.00
SP2-Y	1	0.00	0.00	0.08	0.10
GS2-N	169	0.07	0.00	0.00	0.00
FS-APL	100	0.04	0.00	0.00	0.00
FS-BPL	69	0.03	0.00	0.00	0.00

Squared cosines (Variables):

	F1	F2	F3	F4	F5
SU1-Y	0.00	0.00	0.00	0.00	0.00
BW1-N	0.30	0.12	0.08	0.01	0.03
BW1-Y	0.30	0.12	0.08	0.01	0.03
WL1-N	0.64	0.01	0.13	0.04	0.09
WL1-Y	0.64	0.01	0.13	0.04	0.09

DW1-Y	0.01	0.38	0.00	0.27	0.01
DW1-N	0.01	0.38	0.00	0.27	0.01
SP1-N	0.05	0.35	0.19	0.17	0.00
SP1-Y	0.05	0.35	0.19	0.17	0.00
GS1-N	0.00	0.01	0.00	0.05	0.13
GS1-Y	0.00	0.01	0.00	0.05	0.13
FP-SU	0.00	0.14	0.05	0.01	0.11
FP-N	0.00	0.15	0.08	0.00	0.03
FP-NF	0.00	0.01	0.00	0.05	0.06
FP-WL	0.08	0.06	0.11	0.07	0.02
FP-DW	0.02	0.01	0.01	0.04	0.02
FP-BW	0.00	0.04	0.00	0.01	0.09
FP-KT	0.00	0.06	0.13	0.19	0.00
WS-Y	0.08	0.04	0.04	0.01	0.31
WS-N	0.08	0.04	0.04	0.01	0.31
SU2-Y	0.42	0.02	0.08	0.09	0.08
SU2-N	0.42	0.02	0.08	0.09	0.08
DW2-N	0.03	0.26	0.01	0.09	0.03
DW2-Y	0.03	0.26	0.01	0.09	0.03
WL2-N	0.66	0.03	0.12	0.02	0.04
WL2-Y	0.66	0.03	0.12	0.02	0.04
BW2-N	0.23	0.00	0.31	0.19	0.02
BW2-Y	0.23	0.00	0.31	0.19	0.02
SP2-N	0.00	0.14	0.14	0.03	0.06
SP2-Y	0.00	0.14	0.14	0.03	0.06
GS2-N	0.00	0.00	0.00	0.00	0.00
FS-APL	0.03	0.04	0.07	0.04	0.02
FS-BPL	0.03	0.04	0.07	0.04	0.02

Test values (Variables):

	F1	F2	F3	F4	F5
SU1-Y					
BW1-N	-7.04	4.49	-3.58	-1.51	2.41
BW1-Y	7.04	-4.49	3.58	1.51	-2.41
WL1-N	-10.34	-1.48	4.61	2.48	3.85
WL1-Y	10.34	1.48	-4.61	-2.48	-3.85
DW1-Y	0.99	-8.02	0.82	-6.75	1.32
DW1-N	-0.99	8.02	-0.82	6.75	-1.32
SP1-N	-2.78	-7.71	-5.71	5.29	-0.37
SP1-Y	2.78	7.71	5.71	-5.29	0.37
GS1-N	0.82	-1.22	0.08	-3.02	4.60

GS1-Y	-0.82	1.22	-0.08	3.02	-4.60
FP-SU	-0.63	4.92	-2.90	-1.25	4.31
FP-N	0.74	-4.99	3.71	0.13	-2.40
FP-NF	-0.84	1.53	-0.49	2.95	-3.17
FP-WL	3.58	3.21	-4.31	3.42	1.90
FP-DW	-1.98	1.32	-1.58	2.60	1.72
FP-BW	0.01	-2.55	-0.59	-1.54	-3.92
FP-KT	-0.10	3.29	4.62	-5.63	0.46
WS-Y	3.70	2.43	-2.43	-1.54	7.23
WS-N	-3.70	-2.43	2.43	1.54	-7.23
SU2-Y	-8.38	1.99	-3.70	-3.94	-3.66
SU2-N	8.38	-1.99	3.70	3.94	3.66
DW2-N	-2.08	6.62	1.02	3.82	-2.22
DW2-Y	2.08	-6.62	-1.02	-3.82	2.22
WL2-N	-10.50	-2.42	4.57	2.04	2.65
WL2-Y	10.50	2.42	-4.57	-2.04	-2.65
BW2-N	-6.18	0.45	-7.22	-5.59	-2.03
BW2-Y	6.18	-0.45	7.22	5.59	2.03
SP2-N	0.19	-4.90	-4.76	2.32	3.21
SP2-Y	-0.19	4.90	4.76	-2.32	-3.21
GS2-N					
FS-APL	2.35	-2.56	3.52	-2.66	-1.88
FS-BPL	-2.35	2.56	-3.52	2.66	1.88

Values displayed in bold are significant at the level alpha=0.05

Appendix N: MCA of irrigation practices

Table N1: Summary statistics for irrigations practices.

Variable	Categories	Frequencies	%
Suranga (SU3)	Y	62	43.97
	N	79	56.03
Dugwell (DW3)	N	60	42.55
	Y	81	57.45
Well (WL3)	N	140	99.29
	Y	1	0.71
Kere (KE3)	N	138	97.87
	Y	3	2.13
Borewell (BW3)	N	116	82.27
	Y	25	17.73
Spring (SP3)	N	139	98.58
	Y	2	1.42
River (RR3)	N	130	92.20
	Y	11	7.80
Katta (KT3)	N	139	98.58
	Y	2	1.42
Drip and fogger (DF)	Y	41	29.08
	N	100	70.92
Sprinkler (SN)	Y	64	45.39
	N	77	54.61
Channel (CN)	N	138	97.87
	Y	3	2.13
Manual (MH)	N	106	75.18
	Y	35	24.82
No irrigation undertaken (NR)	N	131	92.91
	Y	10	7.09
Electric pump (EP)	N	31	21.99
	Y	110	78.01
Other pump (OP)	N	132	93.62
	Y	9	6.38

Table N2: Eigenvalues and percentages of inertia for irrigations practices.

	F1	F2	F3	F4	F5	F6	F7
Eigenvalue	0.15	0.11	0.10	0.08	0.07	0.07	0.07
Inertia (%)	15.27	11.45	9.54	8.05	7.48	7.34	6.76
Cumulative %	15.27	26.72	36.26	44.31	51.80	59.14	65.90
Adjusted Inertia	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Adjusted Inertia (%)	46.26	14.34	5.17	1.20	0.42	0.28	0.01
Cumulative %	46.26	60.60	65.77	66.97	67.39	67.67	67.68

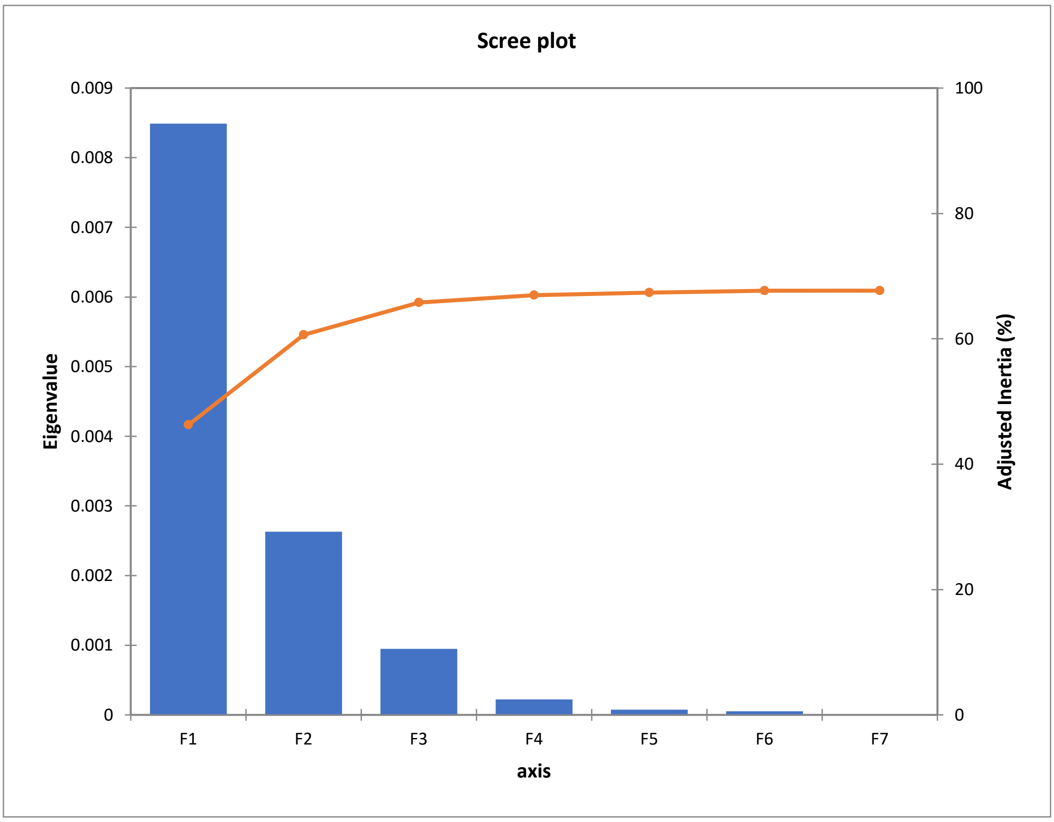


Figure N1: Scree plot for irrigations practices.

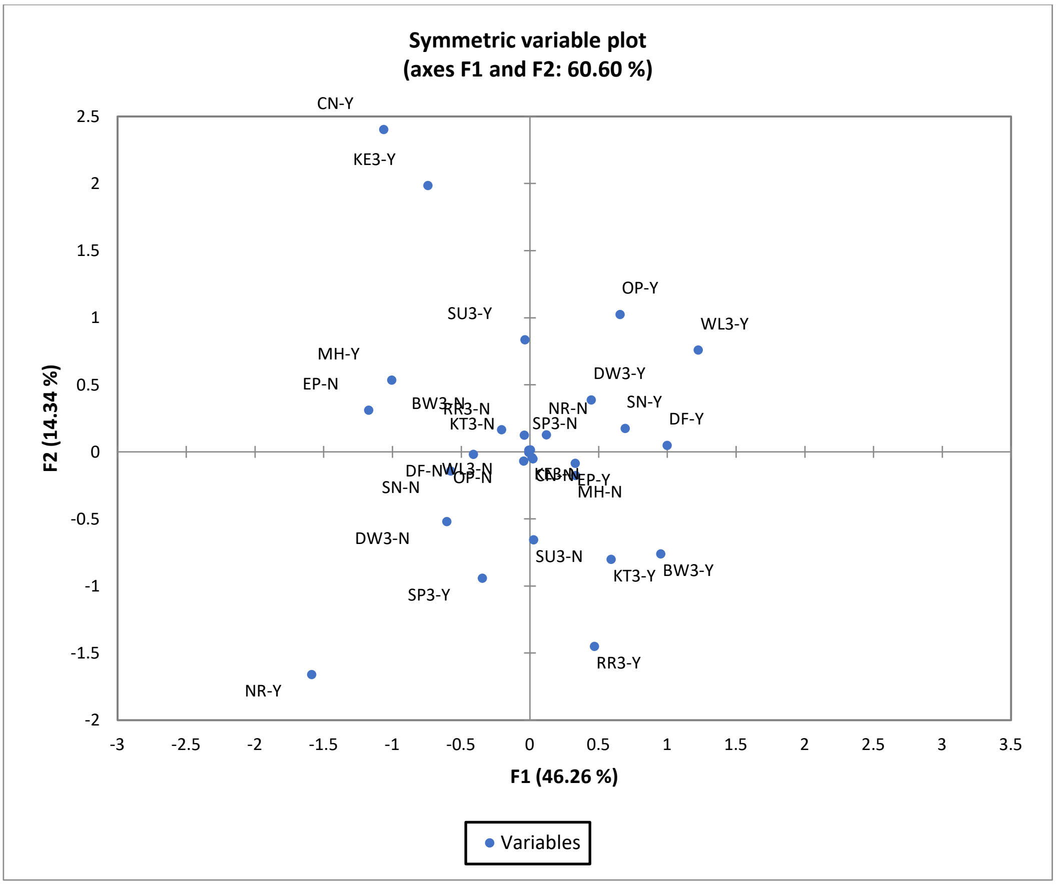


Figure N2: Symmetrical plot of variables for irrigation practices.

Results for the variables:

Principal coordinates (Variables):

	F1	F2	F3	F4	F5	F6
SU3-Y	-0.04	0.84	-0.25	0.20	-0.14	0.05
SU3-N	0.03	-0.66	0.19	-0.16	0.11	-0.04
DW3-N	-0.60	-0.52	0.16	0.19	-0.47	0.26
DW3-Y	0.45	0.39	-0.12	-0.14	0.35	-0.19
WL3-N	-0.01	-0.01	0.01	-0.03	0.06	0.01
WL3-Y	1.23	0.76	-1.35	4.05	-8.60	-0.93
KE3-N	0.02	-0.04	-0.10	0.02	0.03	0.01
KE3-Y	-0.74	1.98	4.55	-0.84	-1.46	-0.59
BW3-N	-0.21	0.16	-0.09	-0.10	-0.08	-0.17
BW3-Y	0.95	-0.76	0.42	0.48	0.38	0.77
SP3-N	0.00	0.01	0.02	0.06	0.06	-0.05
SP3-Y	-0.35	-0.94	-1.13	-3.89	-3.82	3.18
RR3-N	-0.04	0.12	-0.06	0.06	0.00	-0.10
RR3-Y	0.47	-1.45	0.77	-0.73	-0.06	1.17
KT3-N	-0.01	0.01	0.01	0.06	0.02	0.06
KT3-Y	0.59	-0.80	-0.52	-3.98	-1.30	-4.42
DF-Y	1.00	0.05	-0.04	0.75	-0.14	-0.01
DF-N	-0.41	-0.02	0.01	-0.31	0.06	0.01
SN-Y	0.69	0.17	-0.17	-0.22	-0.30	0.05
SN-N	-0.58	-0.14	0.14	0.19	0.25	-0.04
CN-N	0.02	-0.05	-0.09	0.02	0.00	0.01
CN-Y	-1.06	2.40	4.22	-0.97	-0.22	-0.35
MH-N	0.33	-0.18	0.19	0.07	-0.07	-0.21
MH-Y	-1.00	0.53	-0.59	-0.22	0.20	0.64
NR-N	0.12	0.13	-0.03	-0.08	0.02	0.11
NR-Y	-1.59	-1.66	0.39	0.99	-0.21	-1.45
EP-N	-1.17	0.31	-0.02	0.55	-0.07	0.20
EP-Y	0.33	-0.09	0.01	-0.16	0.02	-0.06
OP-N	-0.04	-0.07	-0.13	-0.03	0.00	-0.06
OP-Y	0.66	1.02	1.94	0.38	0.07	0.84

Contributions (Variables):

	Weight	Weight (relative)	F1	F2	F3	F4
SU3-Y	62	0.03	0.00	0.18	0.02	0.02
SU3-N	79	0.04	0.00	0.14	0.01	0.01
DW3-N	60	0.03	0.07	0.07	0.01	0.01

DW3-Y	81	0.04	0.05	0.05	0.01	0.01
WL3-N	140	0.07	0.00	0.00	0.00	0.00
WL3-Y	1	0.00	0.00	0.00	0.01	0.10
KE3-N	138	0.07	0.00	0.00	0.01	0.00
KE3-Y	3	0.00	0.01	0.05	0.31	0.01
BW3-N	116	0.05	0.02	0.01	0.00	0.01
BW3-Y	25	0.01	0.07	0.06	0.02	0.03
SP3-N	139	0.07	0.00	0.00	0.00	0.00
SP3-Y	2	0.00	0.00	0.01	0.01	0.18
RR3-N	130	0.06	0.00	0.01	0.00	0.00
RR3-Y	11	0.01	0.01	0.10	0.03	0.03
KT3-N	139	0.07	0.00	0.00	0.00	0.00
KT3-Y	2	0.00	0.00	0.01	0.00	0.19
DF-Y	41	0.02	0.13	0.00	0.00	0.13
DF-N	100	0.05	0.05	0.00	0.00	0.06
SN-Y	64	0.03	0.10	0.01	0.01	0.02
SN-N	77	0.04	0.08	0.01	0.01	0.02
CN-N	138	0.07	0.00	0.00	0.01	0.00
CN-Y	3	0.00	0.01	0.07	0.26	0.02
MH-N	106	0.05	0.04	0.01	0.02	0.00
MH-Y	35	0.02	0.11	0.04	0.06	0.01
NR-N	131	0.06	0.01	0.01	0.00	0.00
NR-Y	10	0.00	0.08	0.11	0.01	0.06
EP-N	31	0.01	0.13	0.01	0.00	0.06
EP-Y	110	0.05	0.04	0.00	0.00	0.02
OP-N	132	0.06	0.00	0.00	0.01	0.00
OP-Y	9	0.00	0.01	0.04	0.17	0.01

Squared cosines (Variables):

	F1	F2	F3	F4	F5	F6
SU3-Y	0.00	0.55	0.05	0.03	0.01	0.00
SU3-N	0.00	0.55	0.05	0.03	0.01	0.00
DW3-N	0.27	0.20	0.02	0.03	0.16	0.05
DW3-Y	0.27	0.20	0.02	0.03	0.16	0.05
WL3-N	0.01	0.00	0.01	0.12	0.53	0.01
WL3-Y	0.01	0.00	0.01	0.12	0.53	0.01
KE3-N	0.01	0.09	0.45	0.02	0.05	0.01
KE3-Y	0.01	0.09	0.45	0.02	0.05	0.01
BW3-N	0.20	0.12	0.04	0.05	0.03	0.13
BW3-Y	0.20	0.12	0.04	0.05	0.03	0.13
SP3-N	0.00	0.01	0.02	0.22	0.21	0.15

SP3-Y	0.00	0.01	0.02	0.22	0.21	0.15
RR3-N	0.02	0.18	0.05	0.04	0.00	0.12
RR3-Y	0.02	0.18	0.05	0.04	0.00	0.12
KT3-N	0.01	0.01	0.00	0.23	0.02	0.28
KT3-Y	0.01	0.01	0.00	0.23	0.02	0.28
DF-Y	0.41	0.00	0.00	0.23	0.01	0.00
DF-N	0.41	0.00	0.00	0.23	0.01	0.00
SN-Y	0.40	0.02	0.02	0.04	0.08	0.00
SN-N	0.40	0.02	0.02	0.04	0.08	0.00
CN-N	0.02	0.13	0.39	0.02	0.00	0.00
CN-Y	0.02	0.13	0.39	0.02	0.00	0.00
MH-N	0.33	0.09	0.11	0.02	0.01	0.14
MH-Y	0.33	0.09	0.11	0.02	0.01	0.14
NR-N	0.19	0.21	0.01	0.07	0.00	0.16
NR-Y	0.19	0.21	0.01	0.07	0.00	0.16
EP-N	0.39	0.03	0.00	0.09	0.00	0.01
EP-Y	0.39	0.03	0.00	0.09	0.00	0.01
OP-N	0.03	0.07	0.26	0.01	0.00	0.05
OP-Y	0.03	0.07	0.26	0.01	0.00	0.05

Test values (Variables):

	F1	F2	F3	F4	F5	F6
SU3-Y	-0.38	8.76	-2.59	2.14	-1.42	0.51
SU3-N	0.38	-8.76	2.59	-2.14	1.42	-0.51
DW3-N	-6.15	-5.31	1.59	1.90	-4.79	2.67
DW3-Y	6.15	5.31	-1.59	-1.90	4.79	-2.67
WL3-N	-1.23	-0.76	1.35	-4.05	8.60	0.93
WL3-Y	1.23	0.76	-1.35	4.05	-8.60	-0.93
KE3-N	1.29	-3.46	-7.93	1.46	2.55	1.03
KE3-Y	-1.29	3.46	7.93	-1.46	-2.55	-1.03
BW3-N	-5.23	4.18	-2.29	-2.61	-2.06	-4.24
BW3-Y	5.23	-4.18	2.29	2.61	2.06	4.24
SP3-N	0.49	1.34	1.60	5.53	5.43	-4.51
SP3-Y	-0.49	-1.34	-1.60	-5.53	-5.43	4.51
RR3-N	-1.62	5.00	-2.64	2.50	0.20	-4.04
RR3-Y	1.62	-5.00	2.64	-2.50	-0.20	4.04
KT3-N	-0.84	1.14	0.73	5.65	1.84	6.28
KT3-Y	0.84	-1.14	-0.73	-5.65	-1.84	-6.28
DF-Y	7.57	0.35	-0.27	5.66	-1.09	-0.11
DF-N	-7.57	-0.35	0.27	-5.66	1.09	0.11
SN-Y	7.47	1.87	-1.85	-2.41	-3.27	0.57

SN-N	-7.47	-1.87	1.85	2.41	3.27	-0.57
CN-N	1.85	-4.19	-7.36	1.68	0.39	0.60
CN-Y	-1.85	4.19	7.36	-1.68	-0.39	-0.60
MH-N	6.83	-3.63	3.99	1.49	-1.39	-4.39
MH-Y	-6.83	3.63	-3.99	-1.49	1.39	4.39
NR-N	5.19	5.43	-1.29	-3.23	0.70	4.75
NR-Y	-5.19	-5.43	1.29	3.23	-0.70	-4.75
EP-N	-7.36	1.94	-0.15	3.48	-0.41	1.27
EP-Y	7.36	-1.94	0.15	-3.48	0.41	-1.27
OP-N	-2.03	-3.16	-5.99	-1.18	-0.21	-2.59
OP-Y	2.03	3.16	5.99	1.18	0.21	2.59

Values displayed in bold are significant at the level alpha=0.05