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Review Article

Three-dimensional and immersive visualisation for flood risk communication: a critical review of mechanisms, evidence and evaluation

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ABSTRACT

Flood risk visualisation has advanced rapidly over approximately the past decade, but technological sophistication has not always been matched by evidence of communication effectiveness or operational readiness. This critical review examines when, why, and under what conditions 3D and immersive visualisation supports flood risk communication. Following a PRISMA-guided process a final analytical corpus comprised 42 studies. The findings reveal a shift from static and technically oriented flood representation toward situated experience, public communication, evacuation training, collaborative interpretation, and decision support. GIS, BIM, and web-based 3D systems continue to provide the analytical foundation of the field, while virtual, augmented, and mixed-reality tools increasingly translate flood information into place-based and experiential forms. The most consistently reported benefits relate to spatial understanding, engagement, perceived realism, risk awareness, and decision support. However, these benefits are highly dependent on audience expertise, communication purpose, representational complexity, and the task being supported. Evidence quality remains uneven, with many studies relying on prototypes, small samples, expert feedback, or short-term usability assessments, and relatively few progressing to comparative, longitudinal, or operational validation. The review challenges the assumption that more immersive visualisation is necessarily more effective. Instead, effectiveness depends on alignment among audience, communication mechanism, flood-management stage, evaluation maturity, and implementation conditions. To support this alignment, the review proposes the Audience, Mechanism, Stage, Evaluation, Implementation framework, which links design choices, evidence strength, and implementation requirements. The central question is whether a particular visualisation approach provides a credible, accessible, and decision-relevant improvement for a defined audience and context.

1. Introduction

Flood risk communication constitutes a behavioural and decision-support process through which hazard information is interpreted, evaluated and translated into preparedness or protective action [1,2]. Its effectiveness depends not only on the technical accuracy of the information provided, but also on its clarity, perceived relevance, credibility, accessibility and capacity to support feasible responses among different user groups [3,4]. Empirical research has consistently shown that greater awareness of flood risk does not automatically result in preparedness or protective behaviour; instead, communication outcomes are influenced by trust, coping appraisal, perceived agency, prior attitudes and the extent to which the information is locally meaningful and actionable [5–7]. Accordingly, communicating modelled flood information requires representational forms that enable intended users to interpret the spatial and personal implications of the hazard, evaluate its relevance and identify appropriate mitigation, preparedness or evacuation actions.

Three-dimensional and immersive approaches attempt to can reduce this abstraction by relating flood information to buildings, streets,

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homes and recognisable landscapes [1,8,9]. The field now includes 3D GIS, BIM-integrated models, web-based city models, virtual reality, augmented and mixed reality, serious games, digital twins, 360-degree video and photorealistic street-level simulations [10,11]. These technologies can communicate water depth and spatial scale, support scenario exploration and allow users to experience flood conditions from situated or first-person perspectives [12,13]. Recent comparative evidence indicates that dynamic street-level 3D representations can make flood magnitude and evacuation challenges easier to judge than conventional two-dimensional maps, while immersive virtual environments can improve the recall of flood heights and the interpretation of spatial information [9,12,14]. Mixed-reality and digital-twin systems also provide opportunities for stakeholders to view simulated inundation within real environments and to share place-specific risk information across multiple devices [13].

However, greater visual realism or technological immersion does not automatically produce better risk understanding or safer decisions [9,15,16]. Immersive experiences may increase attention, presence and emotional salience, but their effects can vary according to the outcome being measured. For example, immersive storm-surge simulation improved real-world flood-height estimation but did not consistently produce more precautionary evacuation decisions, demonstrating that spatial learning, perceived environmental damage and personal protective action are distinct outcomes [12]. Similarly, visually enhanced 3D disaster messages may attract attention while also increasing extraneous cognitive load and reducing knowledge acquisition when visual effects distract from essential warning information [17]. Realistic representations may therefore support comprehension and engagement, but they can also create overconfidence, cognitive burden, emotional responses disconnected from feasible action, or misleading impressions of model certainty. These findings demonstrate the importance of distinguishing immediate engagement from comprehension, decision performance and sustained behavioural change.

The rapid expansion of visualisation technologies has been accompanied by several reviews addressing different aspects of disaster management, flood-risk communication and flood-risk management. Khanal et al. [18] reviewed virtual and augmented reality applications across the broader disaster-management domain and identified their use in preparedness, training, response and recovery, while also highlighting persistent limitations related to system validation, hardware integration, sensing and mapping, and user-related health effects. Bakhtiari et al. [10] subsequently examined virtual reality, augmented reality and digital-twin applications specifically across urban flood-management stages, identifying a concentration of research in preparedness and mitigation and recurring constraints related to technological complexity, cost and accessibility. Their stakeholder-focused review further showed that existing applications predominantly addressed water utilities and public communication, whereas policymakers, researchers, insurers and other influential stakeholder groups received comparatively limited attention [10]. From a behavioural perspective, Forsyth et al. [4] systematically examined barriers that prevent flood-risk communication from producing household preparedness, highlighting the importance of agency, relevance and actionable information. More recently, Yousaf et al. [2] reviewed flood-risk maps at the intersection of visual design, framing, risk perception and behavioural response, showing that readability, technical language, colour conventions, trust and contextual framing influence how mapped risk is interpreted and acted upon. Piadeh et al. [11] focused specifically on digital-twin implementation in flood-risk management and governance, concluding that development remains at an early stage and that governance, institutional integration and human–nature interactions remain insufficiently addressed. Together, these reviews provide valuable insights into disaster-management technologies, flood-management applications, stakeholder needs, behavioural barriers, map design and digital-twin implementation. However, they do not systematically integrate specific visualisation mechanisms with audience type, flood-management stage, evaluation maturity and implementation conditions across the broader body of 3D and immersive flood-risk-communication research [18].

Despite these contributions, the existing review literature does not provide an integrated account of how specific visualisation mechanisms influence different user groups, how these mechanisms align with flood-management tasks, or how strongly their reported effects have been evaluated. In this context, user differences include not only broad audience categories such as expert or technical users, non-expert public or community users, and mixed stakeholder groups, but also differences in expertise, digital literacy, hazard knowledge, vulnerability and decision responsibility. These characteristics can influence the level of technical complexity that users can interpret, the type of interaction they require, and their ability to access and use immersive technologies. Expert users may require technical accuracy, transparency, parameter control and compatibility with established workflows, whereas non-expert users may benefit more from intuitive representation, recognisable places, clear narrative framing and reduced cognitive burden. Mixed stakeholder settings may require layered representations that enable users with different levels of technical knowledge to interpret and discuss the same risk information. In particular, limited synthesis has examined whether benefits arise through spatial perspective, place familiarity, presence, emotional salience, interaction or collaborative interpretation, and whether these mechanisms lead to improvements in usability, comprehension, risk perception, decision-making, protective behaviour or operational practice. This gap limits the ability to distinguish technological capability from demonstrated communication effectiveness.

The principal unresolved issue is therefore the limited integration of explanatory and evaluative evidence. Technological sophistication does not necessarily correspond to communication effectiveness. Comparative user studies have found that adding a third visual dimension may not significantly improve flood-risk judgements and can increase decision time, while greater visual realism may produce nuanced or inconsistent user responses rather than uniformly better understanding [19–21]. Similarly, immersive representations may improve some aspects of spatial learning while producing mixed effects on protective decision-making [12]. The evidential basis for claims of effectiveness also varies substantially, from technical demonstrations and informal expert feedback to usability studies, controlled comparisons and behavioural assessments. Distinguishing among communication mechanism, audience, decision task, flood-management stage and evaluation maturity is therefore necessary to avoid treating technological novelty as demonstrated communication effectiveness.

This review advances the literature by explaining when, why and under what conditions three-dimensional and immersive tools contribute to flood-risk communication. It develops an explanatory synthesis around five linked elements: audience, communication mechanism, flood-management stage, evaluation maturity and implementation conditions. It also examines whether studies published in 2025 and 2026 represent a substantive change in the field or primarily reinforce previously emerging patterns. The resulting contribution is an evidence-based explanatory framework rather than a catalogue of technologies. Accordingly, the review is intentionally focused on studies in which 3D or immersive visualisation forms a substantive component of flood-risk communication, preparedness, training, planning or decision support. It does not seek to comprehensively review the broader literature on flood impacts, hydrological modelling or flood-risk assessment where visual communication is not a central research component. This defined scope is intended to enable a focused critical synthesis of communication mechanisms and evaluation evidence, rather than a general review of all dimensions of flood-risk research.

1.1. Review aims and research questions

The aim of this paper is to explain the conditions under which 3D and

immersive visualisation can support flood risk communication and to distinguish technological capability from demonstrated communication effectiveness. The review addresses four research questions:

- RQ1. How have visualisation technologies, audiences and flood management applications evolved between 2014 and 2026?
- RQ2. Through which communication mechanisms do 3D and immersive tools seek to influence understanding, risk perception, decision making and preparedness?
- RQ3. How mature is the evidence supporting claims of communication and effectiveness?
- RQ4. How can audience, mechanism, flood management stage, evaluation maturity and implementation conditions be integrated into a traceable design framework?

2. Methodology

2.1. Review design

The review followed a PRISMA guided workflow covering the 2014 to 2026 period. All database searching, screening, citation chasing, full text eligibility assessment and coding are reported as one consolidated review process. A consolidated workflow ensured that consistent eligibility and coding criteria were applied across the complete review period."The review combined systematic searching with evidence mapping. The systematic component provides transparency in record identification, screening and inclusion. The evidence mapping component supports structured synthesis across heterogeneous studies that vary in technology, audience, evaluation method and practical maturity. This combined design is appropriate because the field is interdisciplinary and includes engineering, hydrology, disaster management, geospatial science, computer graphics, communication studies and human computer interaction.

2.2. Search strategy and sources

The literature search was conducted across Scopus, Web of Science and IEEE Xplore. The original database search was conducted on 10 February 2025 and covered publications from 2014 to 2024, using the search expression: flood AND "risk communication" AND (visualisation OR "3D" OR "AR" OR "Augmented Reality" OR "VR" OR "Virtual Reality" OR "MR" OR "Mixed Reality"). The search was restricted to English-language, peer-reviewed journal articles and conference papers. The search was subsequently updated in 2026 to extend the review period to 2026, with the same review question and eligibility criteria applied to the additional records.

Backward and forward citation chasing was also used to identify additional relevant records that were not captured through database indexing alone. Backward citation chasing involved screening the reference lists of eligible studies to identify earlier potentially relevant publications, while forward citation chasing involved identifying subsequent publications that cited the eligible studies. Records identified through citation chasing were assessed using the same eligibility criteria and screening process as records retrieved through the database searches. The search and citation chasing outputs were merged into one screening pool.

2.3. Corpus coding and synthesis

Studies were eligible when they were English-language, peer-reviewed journal articles or conference papers published between 2014 and 2026; addressed flooding, storm surge, waterlogging, flood-related evacuation or a closely related flood-risk context; and used 3D or immersive visualisation as a substantive component of risk communication, awareness, preparedness, training, planning or decision support. Studies also needed to provide sufficient methodological information to code the visualisation approach, target audience, flood-management stage and evaluation approach. Reviews, theses, preprints and other non-peer-reviewed publications were excluded, as were studies focused solely on hydraulic or hydrological modelling without a substantive communication component, studies in which visualisation was incidental, and records with insufficient methodological information for coding. The same eligibility criteria were applied to records identified through both database searching and citation chasing (Fig. 1).

The final corpus size was determined by application of these predefined eligibility criteria rather than by a target number of studies. The search identified 984 database records and a further 18 records through backward and forward citation chasing. After removal of duplicates and non-retrievable records, 945 records underwent title and abstract screening, 115 proceeded to full-text assessment, and 42 studies met the criteria for inclusion in the analytical corpus. The resulting corpus therefore represents the body of peer-reviewed research identified within the defined scope of 3D and immersive visualisation for flood-risk communication, rather than the substantially broader literature on flood impacts, hydraulic modelling, or flood-risk assessment.

2.4. Corpus coding and synthesis

The synthesis combined descriptive evidence mapping with an explanatory, mechanism focused analysis (Table 1). First, cross tabulations were used to compare tool family, audience, flood management stage and evaluation design. Second, the studies were coded for six recurrent communication mechanisms: spatial perspective and depth cues, place familiarity, presence, emotional salience, interaction or agency, and collaborative interpretation. Third, evaluation evidence was ordered through a maturity ladder: technical demonstration, expert validation, user/usability testing, controlled or comparative testing, behavioural follow up and operational or field validation. A compact classification of the coded corpus is provided in Table A1. Finally, framework components were retained only when they could be traced to repeated evidence patterns in the corpus. Two additional rule-based syntheses were undertaken. First, each study was scored from 1 to 5 across eight dimensions: interactivity and usability, emotional engagement and clarity, technical fidelity and precision, behavioural impact and retention, audience diversity consideration, evaluation rigour, decision-support capability, and risk communication and awareness. The first author extracted and coded used for scoring and predefined the scoring criteria for each dimension. Scores were then generated using a rule-based Python script applied to the coded study fields. For each dimension, the algorithm applied predefined evidence thresholds, generally ordered from the strongest evidence level (score 5) to the weakest (score 1), and assigned the score associated with the first satisfied criterion. Evaluation Rigour was anchored to the coded evaluation-design category and further differentiated according to study-design characteristics such as pre/post assessment, comparison or control groups, randomisation, and use of validated measures. The study-level scores and their textual bases are reported in the Supporting Information. Mean scores were then calculated for expert, non-expert and mixed-audience studies. Second, studies were mapped by evaluation strength and operational-orientation score. Evaluation strength was derived directly from the evaluation-design category, while the operational-orientation score distinguished static or conceptual representations, interactive prototypes, and systems designed for operational or decision-support use. This latter score is an analytical proxy and does not demonstrate routine field deployment. These procedures supported transparent traceability between the coded evidence, analytical figures and the proposed framework.



Fig. 1. One stage PRISMA flow diagram for the integrated 2014 to 2026 review corpus.

Table 1
Integrated review eligibility and coding framework.

Component	One stage treatment	Purpose
Time window	2014 to 2026	Frames the review as one integrated systematic study.
Sources	Scopus, Web of Science, IEEE Xplore and citation chasing	Captures engineering, GIS, disaster management and HCI literature.
Inclusion focus	Flood related risk communication using 3D, immersive, web based or image-based visualisation	Keeps the review centred on communication rather than modelling alone.
Coding fields	Tool/platform, audience, risk stage, evaluation, effectiveness and limitations	Supports analytical figures and critical synthesis.
Evidence interpretation	Tool families and evaluation depth compared across the corpus	Moves the paper beyond a simple descriptive review.

3. Results

3.1. Bibliometric analysis

3.1.1. Overall development of the field

The study analytical corpus contains 17 GIS/BIM/web 3D studies (40.5%), 11 VR/serious game studies (26.2%), eight AR/MR/XR studies (19.0%) and 6 2.5D/image/video/animation studies (14.3%). Across the full 2014 to 2026 period, GIS/BIM/web 3D remains the largest tool family, while the more recent literature shows a stronger emphasis on immersive formats. This pattern does not indicate that immersive systems have replaced GIS. Rather, it suggests a layered technology ecosystem in which modelling and geospatial platforms provide the analytical backbone, while immersive interfaces increasingly translate hazard information into situated experiences, training scenarios and public communication.

The temporal pattern therefore represents a gradual shift from hazard representation toward situated experience and action rehearsal. This change is visible not only in platform choice, but also in audience and application. Mixed audiences form the largest group across the complete corpus, accounting for 15 of the 42 studies (36.6%). The recent 2025 to 2026 literature, however, shows a stronger orientation toward nonexpert users, with five of the eight studies (62.5%) targeting public, student or community audiences. Response-focused applications also become more prominent in the recent literature, appearing in 75.0% of the 2025 to 2026 studies. Overall, these trends indicate that the field is increasingly moving toward public preparedness, evacuation and emergency response, while technical planning and decision-support applications remain important.

3.1.2. Keyword and conceptual structure

The keyword cooccurrence map identifies three major conceptual zones. The first is a geospatial and modelling zone, linking GIS, DEM/terrain, BIM/Revit, CityEngine, Cesium/WebGL, LiDAR/TLS, UAV/photogrammetry and hydrodynamic modelling (Fig. 2). The second is an immersive technology zone, linking VR, AR, MR/XR, Unity/Unreal, gamification, photorealism and 360 degree video. The third is a communication and action zone, linking risk perception, user evaluation, preparedness/training, decision support, evacuation/response, behavioural change and uncertainty/cognitive load. The most important interpretation is that these zones are connected but unevenly integrated. Many studies are strong in either technical modelling or engagement design, but fewer combine rigorous hazard data, accessible communication and strong behavioural evaluation.

The temporal overlay map shows that the field has moved from GIS, terrain modelling and flood depth representation toward immersive and designed for users concepts (Fig. 3). Earlier emphases include hydrodynamic modelling, GIS, DEM/terrain, flood extent and decision support. More recent emphases include MR/XR, digital twins, machine learning, real time/dynamic visualisation, 360 degree video, evacuation/response and behavioural change. This pattern is important for the review argument: the frontier of the field is not only more realistic visualisation, but also more situated, dynamic and user centred communication.

The tool/platform frequency map was regenerated directly from the Supplementary Table S1 column titled ‘Tool used for 3D visualisation’. Fig. 4 therefore does not use VOSviewer output; it reports study level occurrences of named software, platforms, data sources and modelling environments extracted from that column. Custom or unspecified pipelines were recorded separately but not used for word sizing, so the figure reflects identifiable tool evidence. The dominant named tool environment is the GIS/ArcGIS suite, followed by Unity/Unity3D,

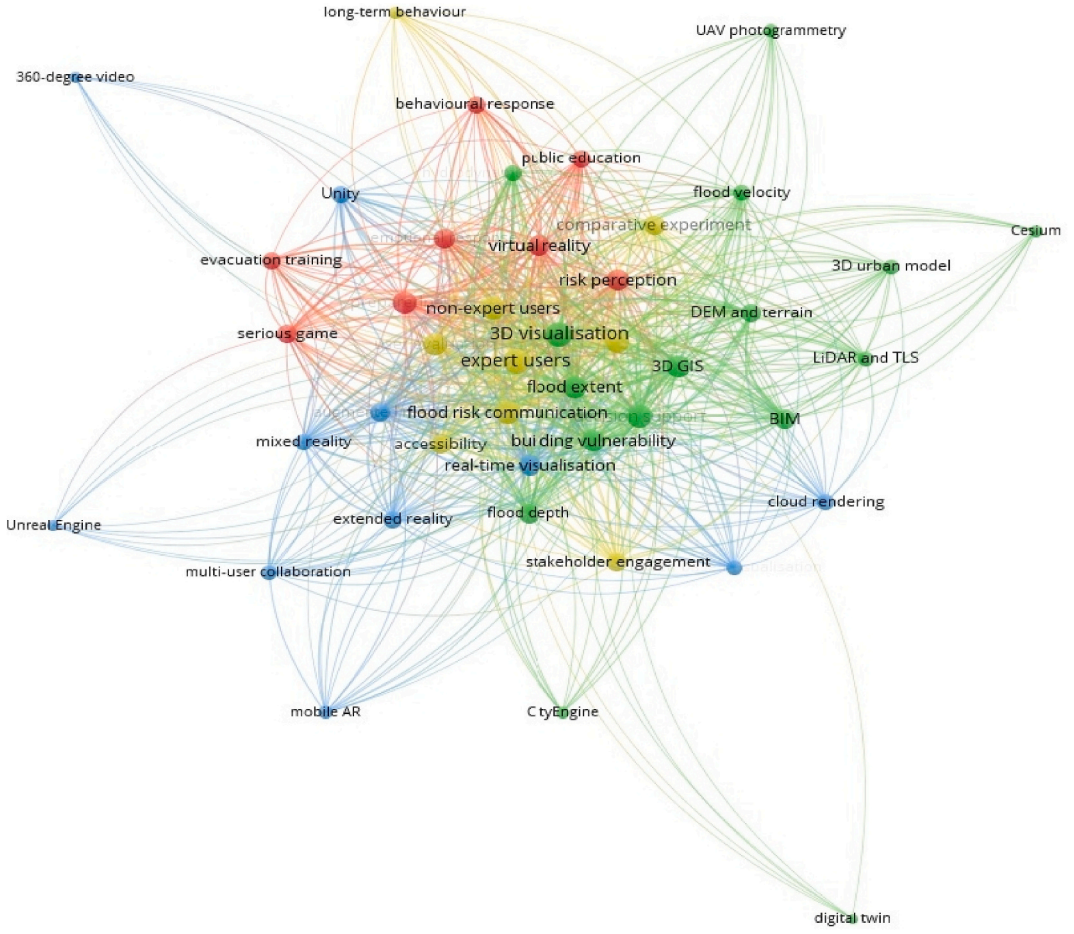


Fig. 2. VOS viewer network visualisation of keyword cooccurrence in the coded corpus. Node size indicates term frequency, link thickness indicates cooccurrence strength, and colours denote thematic clusters.

LiDAR/TLS and point cloud data, VR headsets, DEM/DTM terrain data, Google Earth/Maps, WebGL/JavaScript/WebRTC, CityEngine, Cesium, SketchUp and UAV/photogrammetry workflows.

3.2. Critical analysis

3.2.1. Tool families, audiences and evaluation evidence

The relationship between tool type, audience and evaluation depth is central to the review. GIS/BIM/web 3D tools dominate technically complex applications, particularly where the objective is to support planning, building scale impact assessment, scenario comparison or operational dashboards (Table 2). These systems are often directed toward experts or mixed stakeholders. In contrast, VR and serious games more commonly target nonexpert users and training contexts, using immersion to strengthen risk perception, learning and preparedness. AR/MR/XR tools occupy an intermediate position: they can support expert co design and planning, but their ability to overlay risk on real environments also makes them attractive for public communication.

The Sankey flow makes the imbalance visible (Fig. 5). Tool families do not distribute evenly across audiences or evaluation types. Nonexpert studies are more likely to use VR, serious games, 2.5D image based visualisation or immersive experiences, while expert studies are more likely to use GIS/BIM/web 3D platforms. Mixed audience studies are valuable because they reveal conflicting user priorities: experts tend to value accuracy, control and compatibility with existing workflows, while nonexperts value realism, clarity and emotional resonance.

Evaluation remains the weakest component of the corpus. A substantial number of technically sophisticated systems report no user evaluation. Others rely on informal demonstrations, expert validation or after use satisfaction measures. Controlled or comparative studies are more limited, although they are crucial because they can test whether 3D or immersive visualisation actually improves comprehension, decision making or behavioural intention compared with conventional maps. Importantly, positive user feedback should not be treated as proof of protective action. Several studies show that users may find immersive systems engaging while still failing to translate experience into improved evacuation timing, long term mitigation or sustained preparedness (Table 3).

3.2.2. Risk stage alignment

The heatmap shows that preparedness and mitigation dominate the corpus (Fig. 6). Preparedness appears strongly in VR, AR/MR/XR and image/video based approaches because these tools are well suited to awareness, training and evacuation rehearsal. Mitigation and planning are more strongly associated with GIS/BIM/web 3D tools because these systems support building exposure, infrastructure planning and scenario comparison.

Response focused applications are increasing in recent literature, especially through real time web systems, mixed reality, virtual flood experience systems and evacuation planning tools (Table 4). Recovery remains the least developed stage, even though 3D visualisation could support damaged communication, reconstruction planning, insurance assessment and after event public learning.

3.2.3. Audience, evidence depth and implementation readiness

The bubble matrix (Fig. 7a), audience and evaluation radar chart

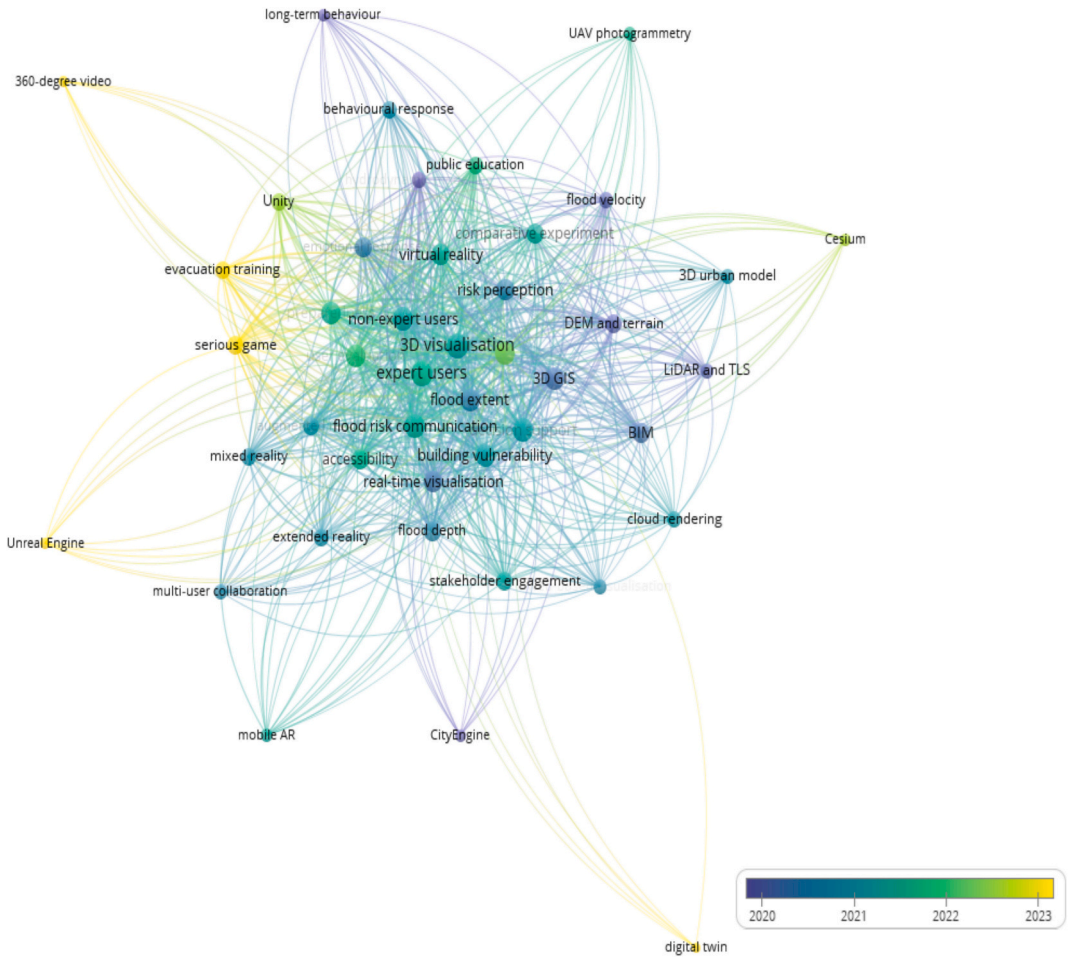


Fig. 3. VOSviewer overlay visualisation of the coded corpus. Colours indicate the average publication year of terms, showing the shift from earlier modelling centred topics toward newer immersive, real time and user centred communication topics.

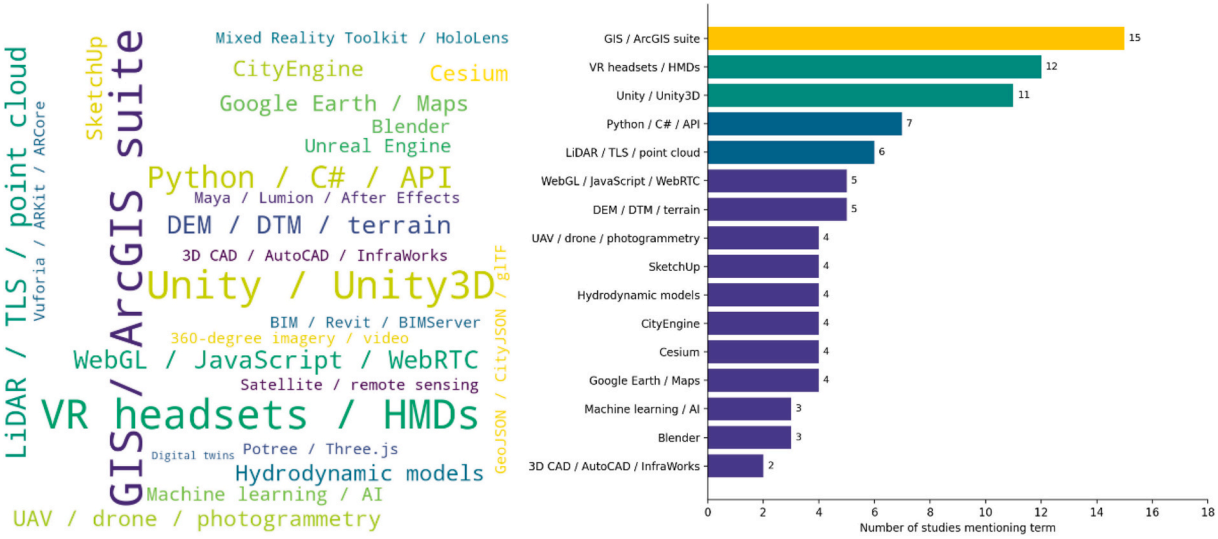


Fig. 4. Tool/platform frequency map generated from the Supplementary Table S1 'Tool used for 3D visualisation' column. Panel A presents a word cloud of normalized named tool/platform terms; Panel B ranks the most frequently mentioned terms at study level.

(Fig. 7b), and evidence-to-implementation gap map (Fig. 7c) show that the most visually advanced technologies are not always supported by the strongest empirical evidence. Some immersive tools provide high levels of engagement but remain limited to prototype-based, small-sample, or short-term evaluations. In contrast, some GIS-, BIM-, and web-based 3D tools demonstrate greater technical maturity but lack evaluation of their effectiveness as public communication interfaces. Mixed-reality and digital-twin systems also show potential for operational use; however,

Table 2
Tool family typology and evidence interpretation.

Tool family	Core studies	Dominant use	Typical audience	Evidence strength	Main limitation
GIS/BIM/web 3D	18	Hazard mapping, building exposure, scenario planning, web dashboards	Experts and mixed users	Strong technical modelling but often weak user testing	Can remain expert focused and difficult for public interpretation
VR/serious game	11	Immersive learning, evacuation training, flood awareness	Nonexperts and mixed users	Good engagement evidence; some controlled studies	Hardware dependency, novelty bias and uncertain behavioural persistence
AR/MR/XR	8	On site overlays, collaborative planning, situated risk experience	Mixed, planners and communities	Promising usability evidence but uneven evaluation	Tracking, alignment, field of view and device limitations
2.5D/image/ video/ animation	5	Street level images, animated flooding, isometric or oblique views	Mostly nonexperts	Useful comparative and perception evidence	Often less interactive and may not support real time decisions

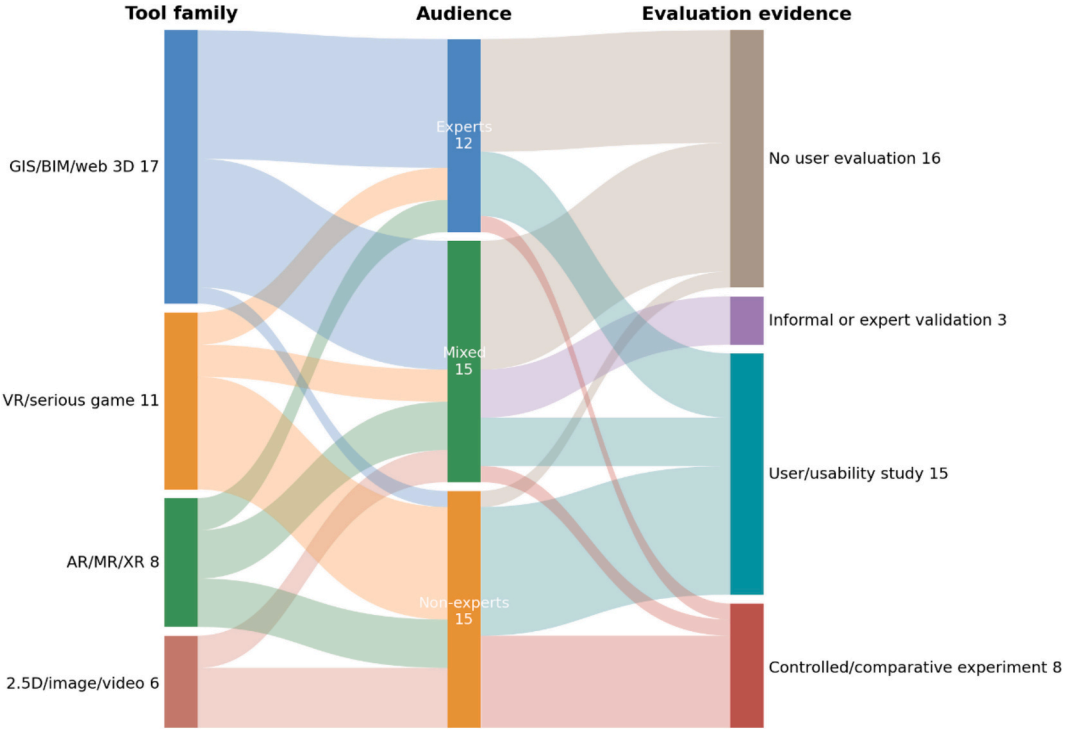


Fig. 5. Sankey flows from visualisation family to target audience and evaluation evidence.

Table 3
Evaluation depth by family tool in the core corpus.

Family tool	No user evaluation	Informal or expert validation	User/usability study	Controlled/comparative experiment	Share
GIS/BIM/web 3D	26.2%	4.8%	9.5%	2.4%	40.5%
VR/serious game	2.4%	2.4%	14.3%	7.1%	26.2%
AR/MR/XR	7.1%	0.0%	9.5%	2.4%	19.0%
2.5D/image/video	2.4%	0.0%	2.4%	7.1%	14.3%
Total	38.1%	7.1%	35.7%	19.0%	100%

their evaluation often stops before real-world emergency deployment. This mismatch helps explain why the field may appear technologically advanced while remaining difficult to translate into policy and practice.

Fig. 7b presents the relationship between evaluation strength and operational readiness across the reviewed studies. Evaluation strength was scored on a scale from 0, indicating no user evaluation, to 3, representing a controlled or comparative experiment. The vertical axis distinguishes static or conceptual representations, interactive prototypes, and systems designed for operational or decision-support use. Each marker represents an individual study, while marker shape identifies the relevant tool family. Minor jitter was applied solely to reveal overlapping observations.

Fig. 7c presents the ordinal scores assigned to each study across eight dimensions, ranging from 1 to 5, using a transparent, rule-based rubric applied to the coded fields in Supplementary Table S1. Mean scores were subsequently calculated for expert-focused, non-expert-focused, and mixed-audience studies. Mixed-audience studies achieved the highest mean scores for interactivity and usability, technical fidelity and precision, and consideration of audience diversity. Non-expert-focused studies achieved the highest mean scores for emotional engagement and clarity, behavioural impact and retention, evaluation rigour, decision-support capability, and risk communication and awareness. Expert-focused studies demonstrated moderate scores for technical performance and decision-support capability but comparatively limited evaluation rigour and behavioural evidence. Overall, scores remained low to moderate across all three audience groups, reflecting the limited

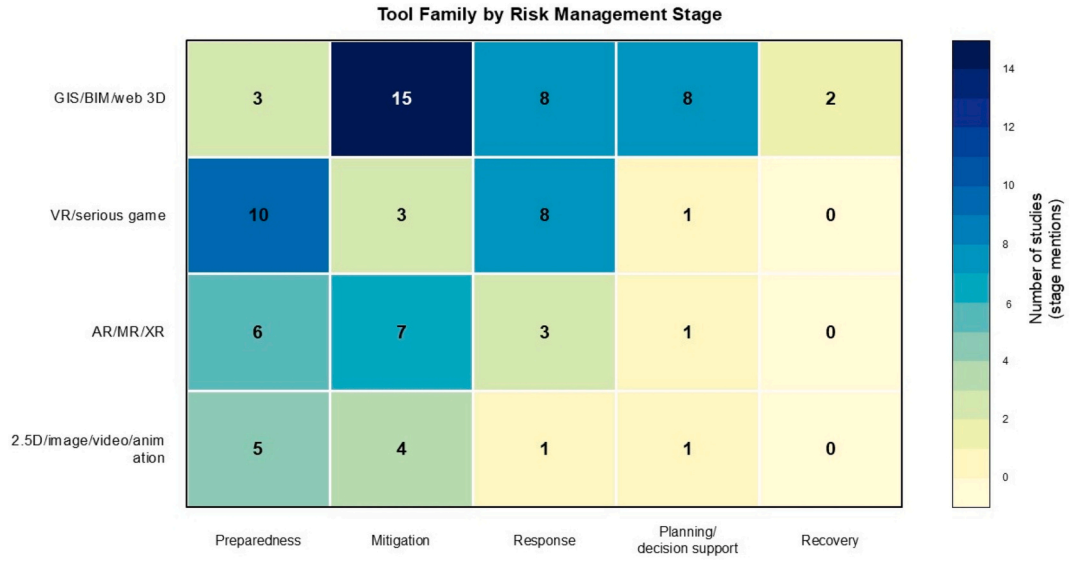


Fig. 6. Heatmap of visualisation family by flood risk management stage.

Table 4
Flood risk management stage alignment by family tool.

Family tool	Preparedness	Mitigation	Response	Recovery	Planning/ decision support
GIS/ BIM/ web 3D	4	15	8	2	8
VR/ serious game	10	3	8	0	1
AR/MR/ XR	6	7	3	0	1
2.5D/ image/ video	4	3	1	0	1

use of longitudinal assessments, validated behavioural measures, and operational testing in the reviewed literature.

The distribution indicates that technical or decision-support readiness does not consistently coincide with strong evaluation evidence. Several systems classified as operationally ready reported limited or no user evaluation, whereas some controlled studies examined tools that remained conceptual or prototype-based. The operational-readiness score should therefore be interpreted as an analytical proxy rather than evidence of routine field deployment or institutional adoption.

3.3. Temporal evolution

The line graph summarises the temporal evolution of tool families (Fig. 8). GIS/BIM/web 3D tools provide continuity across the period, while VR/serious games and AR/MR/XR become more visible after 2020. The recent rise of 360-degree video, photorealistic street level visualisation and digital twins suggest that the next stage of the field will be less like isolated visual prototypes and more about integrated, dynamic and place specific communication systems. This does not mean that immersive tools will replace GIS or conventional maps. Rather, the evidence suggests a layered ecosystem: expert systems generate and manage hazard data, while immersive or image-based interfaces translate that data into understandable experiences for particular audiences.

4. Thematic synthesis

4.1. From map legibility to experiential risk communication

The central development across the review period is a move from map legibility toward experiential and situated communication. Earlier systems primarily used terrain, buildings, oblique views and animated flood surfaces to make hazard information easier to interpret. Later systems increasingly place users inside flood scenarios, allow them to explore alternatives, rehearse evacuation or encounter projected consequences in familiar environments. The synthesis indicates that this shift operates through identifiable mechanisms rather than through immersion alone: spatial perspective reduces abstraction; place familiarity increases personal relevance; presence and realism heighten salience; interaction creates agency; and shared viewing supports collaborative interpretation. These advantages are particularly evident where users need to understand flood depth and spatial consequences from a situated perspective. For example, immersive VR has been shown to improve flood-height recall and spatial interpretation, while AR/MR can support place-based understanding by relating simulated inundation directly to familiar physical environments [12,13].

These mechanisms can produce different outcomes and should not be treated as equivalent. Presence may increase emotional engagement without improving evacuation performance; spatial perspective may improve depth estimation while increasing cognitive load; and interactivity may support learning while distracting from warning content. The evidence therefore supports a conditional proposition: immersive and 3D tools are most effective when the mechanism activated by the interface matches the audience's capability and the decision required.

4.2. Expert and nonexpert audiences require different design logic

The evidence shows a persistent divide between expert and nonexpert design requirements. Expert users need tools that are accurate, transparent, parameter controlled and compatible with official modelling workflows. They are likely to ask whether the data pipeline is defensible, whether uncertainty is represented, whether scenarios are reproducible and whether the tool supports real planning decisions. Nonexpert users are more likely to need intuitive representation, clear narrative framing, minimal cognitive burden and a recognisable connection to everyday places. A visually complex expert dashboard may be unsuitable for residents; a dramatic VR experience may be unsuitable for emergency managers who need traceable modelling

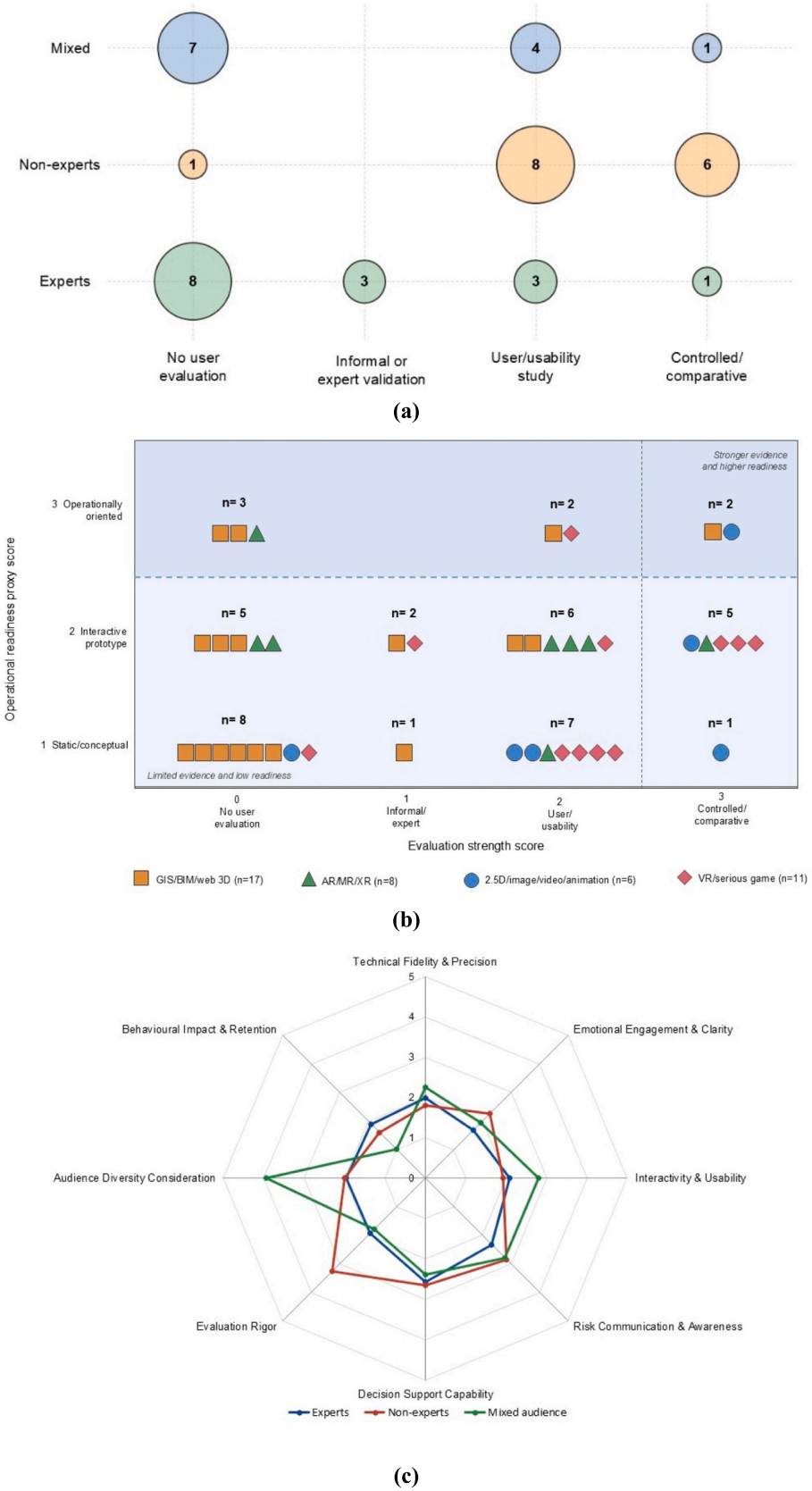


Fig. 7. Audience, evidence depth and implementation readiness: (a) Bubble matrix showing how audience type, evaluation depth and tool family intersect in the corpus, (b) Evidence to implementation gap map analytical corpus. Transparent markers represent individual studies; marker shapes distinguish tool families. Scores are defined in the accompanying scoring rubric, and operational readiness is treated as a proxy, (c) Comparative audience profiles derived from a rule-based scoring rubric analytical corpus. Values represent group means for 12 expert-focused, 15 non-expert-focused and 15 mixed-audience studies. Full study-level scores, scoring rules and textual bases are provided in the Supporting Information.

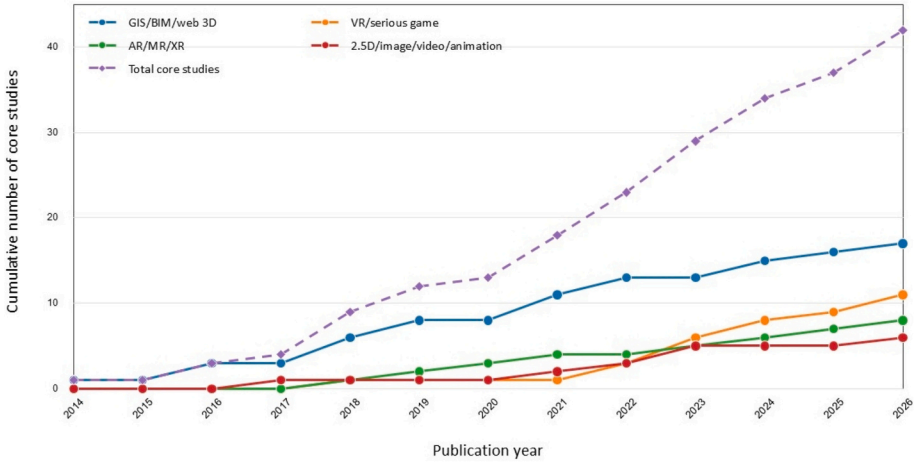


Fig. 8. Temporal evolution of visualisation paradigms in the 2014 to 2026 core corpus, shown as a cumulative line graph by tool family.

assumptions.

The strongest future tools are therefore unlikely to use a single interface for all users. Instead, they should use layered communication architectures: technical layers for model interrogation and decision support, and simplified narrative or experiential layers for public understanding and preparedness. This layered approach is particularly important for councils, emergency agencies and community engagement programmes, where the same hazard data must be communicated to multiple groups with different capacities and decisions.

4.3. Evaluation is the main weakness of the field

The review's most important critical finding is that evaluation has not kept pace with technological innovation. Many studies make persuasive claims about improved understanding, engagement or communication but rely on informal feedback, small samples, prototype demonstrations or after use satisfaction surveys. These methods are useful in early stage development, but they cannot establish whether a tool improves decision quality, evacuation timing, mitigation investment, retention of knowledge or real world preparedness. Longitudinal evidence is especially limited.

Future studies should distinguish between at least five outcomes: usability, comprehension, risk perception, decision performance and behavioural follow through. These outcomes are related but not equivalent. A tool can be usable but not persuasive, persuasive but not accurate, accurate but not memorable, or memorable but not action generating. Review papers should therefore avoid treating positive feedback as a single evidence category. The field needs more controlled comparisons, before and after testing, delayed follow ups and field based implementation studies.

4.4. Accessibility and operationalisation remain unresolved

Accessibility is a recurring limitation. VR headsets, mixed reality displays, high resolution 3D city models, LiDAR/TLS datasets and cloud rendered platforms can be powerful but expensive, technically demanding or unavailable in resource constrained settings. Web based 3D platforms and mobile AR can broaden access, but they still depend on device capability, internet connectivity, interface simplicity and digital literacy. This raises an equity issue: the communities most exposed to flood risk may not be the communities most able to access advanced visualisation tools.

Operationalisation is equally important. Many prototypes are developed for demonstration, education or engagement rather than real time response. To become operational, tools must connect to reliable data streams, official warning systems, emergency protocols and user workflows. They must also be robust under stress, understandable under time pressure and maintainable by agencies after the research project ends. The evidence base currently provides more proof of concept innovation than tested operational integration.

4.5. Evidence derived propositions

The findings suggest that the effectiveness of flood-risk visualisation depends less on the level of technological immersion than on how well the chosen approach aligns with the audience, communication purpose, representational complexity and decision context (Table 5). Immersive tools are frequently associated with greater realism, engagement and immediate understanding. However, the evidence is considerably weaker regarding whether these benefits result in sustained preparedness, improved evacuation performance or protective action. Across the reviewed studies, behavioural outcomes were examined mainly through preparedness, evacuation intentions and observed or self-reported actions, but these outcomes were assessed less consistently than perceptual and cognitive responses.

The literature also indicates a gradual shift from using visualisation primarily to represent flood risk toward supporting preparedness, evacuation training and response planning. Despite this development, the integration of immersive systems into routine operational practice remains limited. Furthermore, most studies continue to focus on communication before or during flood events, while post-event applications remain underexplored. Relatively little attention has been given to the use of visualisation for damage interpretation, post-event learning, insurance processes, reconstruction and longer-term community recovery.

4.6. Research gaps and future agenda

The evidence-derived propositions also reveal several persistent research and implementation gaps. These gaps concern not only technological development but also the quality of behavioural evidence, inclusion of diverse audience groups, operational testing, accessibility, uncertainty communication, and reproducibility (Table 6). Behavioural analysis in this review was conducted by synthesising reported user studies that measured outcomes such as preparedness, evacuation intention, decision accuracy, and (where available) observed or simulated behavioural responses.

However, such evidence remains uneven and often indirect, which limits strong causal interpretation. Taken together, the evidence suggests that the next stage of development will be characterised less by increasing immersion alone and more by integration, accessibility and evidence maturity. Three related directions are apparent. First,

Table 5
Tool to mechanism to outcome synthesis and strength of evidence.

Tool family	Dominant communication mechanisms	Commonly measured outcomes	Evidence interpretation	Recurring limitation
GIS/BIM/ web 3D	Spatial integration; scenario comparison; technical transparency	Spatial understanding; planning; decision support	Moderate technical evidence; limited comparative public evaluation	Complexity, data demands and limited accessibility
VR/serious games	Presence; realism; agency; experiential learning	Engagement; risk perception; preparedness; evacuation performance	Growing user evidence, but limited long term behavioural testing	Hardware, motion sickness, novelty effects and small samples
AR/MR/XR	Situated information; collaborative viewing; interaction in place	Spatial awareness; stakeholder engagement; task performance	Promising but predominantly prototype based evidence	Field of view, tracking, hardware and operational reliability
2.5D/ image/ video	Familiarity; visual salience; reduced abstraction	Awareness; comprehension; perceived risk	Mixed evidence; useful where accessibility matters	Lower interaction and potential oversimplification

Table 6
Research gaps and future agenda for 3D and immersive flood risk communication.

Gap	Why it matters	Recommended response
Weak behavioural evidence	Engagement does not necessarily translate into preparedness or evacuation action.	Use before and after experiments, delayed follow ups and real world preparedness measures.
Limited across audience groups comparison	Expert and public users interpret visualisations differently.	Test the same tool with planners, emergency staff, residents and vulnerable groups.
Underuse in response and recovery	Most tools remain focused on preparedness and mitigation.	Develop tools linked to warnings, response coordination, damage assessment and recovery planning.
Accessibility barriers	High end XR tools may exclude resource constrained communities.	Design mobile, web based and low cost alternatives alongside immersive systems.
Unclear uncertainty communication	Realistic visuals can overstate confidence if uncertainty is hidden.	Represent model uncertainty clearly and test whether users understand it.
Poor reporting of data pipelines	Technical reproducibility is often limited.	Report data sources, software, model assumptions, validation and interface design decisions.

Table 7
Evidence claims matrix for major conclusions in the review.

Claim	Evidence pattern in the corpus	Confidence	Reason for confidence rating
Immersive formats increase engagement and perceived realism	Repeated positive findings across user studies	Moderate to high	Consistent immediate outcomes, although measures vary
3D/immersive formats improve spatial understanding	Generally positive but not universal	Moderate	Benefits depend on task, user expertise and cognitive load
Immersion improves evacuation or protective behaviour	Inconsistent and infrequently tested longitudinally	Low	Few delayed or real world behavioural measures
GIS/BIM/web 3D supports expert decision making	Strong technical capability; fewer controlled comparisons	Moderate	Operational relevance is plausible but rarely evaluated experimentally
MR/digital twins are ready for emergency operations	Promising prototypes with limited field deployment evidence	Low	Technical readiness is not equivalent to institutional adoption
Recovery applications are established	Very few studies	Very low	Recovery is largely absent from the corpus

technically robust GIS, modelling and digital-twin environments are likely to be increasingly connected with audience-facing interfaces such as web-based 3D, mobile AR/MR and other place-based visualisations. Second, evaluation is likely to move beyond short-term usability and engagement toward comparative, longitudinal and behavioural assessment, particularly where claims concern preparedness, evacuation or protective action. Third, applications are likely to extend beyond preparedness and mitigation toward more operational uses in warning, emergency response, damage interpretation and recovery. Progress in the field may therefore depend increasingly on interoperability, real-time data integration, accessibility and demonstrated decision value, rather than on visual realism or technological novelty alone.

5. Discussion

This review makes four contributions beyond descriptive technology mapping. First, it identifies the mechanisms through which visualisation may influence flood risk understanding, including spatial perspective, place familiarity, presence, emotional salience, interaction and collaborative interpretation. Second, it explains how effectiveness depends on alignment among audience, mechanism, flood management stage, evaluation maturity and implementation conditions. Third, it distinguishes technological capability from demonstrated communication effectiveness through a staged evaluation model. Fourth, it translates these findings into a traceable framework in which every component is linked directly to evidence patterns identified in the reviewed studies (Table 7).

The comparative audience profiles and evidence-to-implementation map extend this finding. Mixed-audience studies more frequently combine technical fidelity, interactivity and broader audience coverage, whereas non-expert-focused studies show stronger evaluation rigour, emotional engagement and risk-communication emphasis. At the same time, the implementation map shows that technically or operationally oriented systems are not necessarily supported by stronger user evidence. Together, these results reinforce the distinction between technological capability, intended implementation and demonstrated communication effectiveness.

The findings challenge the assumption that 3D or immersion is inherently superior to conventional representation. These formats are valuable when they activate a mechanism that is relevant to the task: for example, place familiarity for household preparedness, presence for experiential learning, or spatial integration for planning. They can be counterproductive when visual complexity increases cognitive load, uncertainty is hidden, hardware excludes users, or emotional salience is disconnected from feasible action. The appropriate comparison is therefore not “2D versus 3D” in general, but whether a representation and mechanism combination improves a defined outcome for a defined audience.

For researchers, the key implication is that study design should begin with a mechanism and an outcome, not with a new platform. A stronger study would specify why a given interface should improve a particular

decision, compare it with credible alternatives, measure comprehension and decision performance separately, include diverse users, and test whether effects persist. The evaluation ladder proposed here provides minimum expectations: technical validation for model accuracy, structured user testing for usability and comprehension claims, controlled comparison for causal claims, delayed follow up for retention or preparedness claims, and field validation for operational claims.

For practitioners, the evidence supports a layered architecture. GIS, BIM and web based systems can provide the analytical backbone, while immersive, mobile or street level interfaces translate selected information for specific audiences and tasks. Tool selection should therefore follow the communication objective rather than novelty. A public preparedness tool may prioritise clarity, place familiarity and accessible delivery; an emergency response tool must prioritise data currency, reliability and rapid interpretation; and a planning tool must preserve uncertainty, traceability and scenario control.

6. AMSEI alignment framework for future research and practice

The Audience, Mechanism, Stage, Evaluation and Implementation (AMSEI) framework translates the review findings into five sequential design decisions. First, define the audience in terms of expertise, digital literacy, hazard knowledge, vulnerability and decision responsibility. Second, select the mechanism needed to achieve the communication purpose: spatial perspective, place familiarity, presence, emotional salience, interaction or collaboration. Third, align the interface with the flood management stage and action required. Fourth, match the evaluation design to the claim being made using the evaluation maturity ladder. Fifth, assess implementation conditions, including cost, accessibility, data quality, interoperability, institutional capacity and operational reliability. A tool should be considered effective only when these elements are aligned and supported by evidence appropriate to the claim (Table 8). Fig. 9 operationalises the AMSEI framework as a practical roadmap for the design, deployment and evaluation of 3D flood-risk communication tools.

7. Conclusion

This review shows that the 2014 to 2026 literature is moving from technical flood representation toward situated, immersive and response focused communication. The newest studies strengthen this direction by targeting nonexpert audiences more frequently and using more structured evaluation. Nevertheless, the review does not support a simple conclusion that greater immersion produces greater effectiveness. The most consistent benefits concern engagement, realism and immediate spatial understanding; evidence is weaker for sustained preparedness, evacuation behaviour, operational performance and recovery.

The paper therefore reframes the field as an alignment and evidence maturity problem. Its novel contribution is the AMSEI framework, which links audience, communication mechanism, flood management stage, evaluation maturity and implementation conditions, together with an evidence and claim matrix and evaluation ladder. Future research should move beyond prototype novelty by specifying causal mechanisms, comparing credible alternatives, using delayed behavioural measures and validating systems in operational settings. The decisive question is no longer whether flood risk can be visualised in 3D, but whether a particular visualisation mechanism produces a demonstrable and durable improvement for a particular audience and decision.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT, developed by OpenAI, to support grammar correction and language editing. The authors reviewed and revised the output as needed and take full responsibility for the content of the published article.

Table 8
Traceability of the AMSEI framework to review evidence and design implications.

Decision	What it requires	Design considerations	Roadmap step (s)
Audience	Define the audience in terms of expertise, digital literacy, hazard knowledge, vulnerability and decision responsibility.	Segment users; co-design separate expert and non-expert interfaces; assess accessibility, affordability, device capability and connectivity.	1. Define audience
Mechanism	Select the mechanism needed to achieve the communication purpose: spatial perspective, place familiarity, presence, emotional salience, interaction or collaboration.	Choose the tool and data architecture, i. e. VR, AR/MR, web GIS, BIM, digital twins, AI-generated content or real-time data, according to the communication purpose.	3. Match tool family
Stage	Align the interface with the flood management stage and the action required of the user.	Match tools to preparedness, response, mitigation, recovery or planning decisions; translate technically credible evidence into understandable, decision-relevant communication.	2. Select risk stage; 4. Co-design interface
Evaluation	Match the evaluation design to the claim being made, using the evaluation maturity ladder.	Use before-and-after testing, control groups, and measures of usability, retention and behaviour, scaled to the strength of the claim.	5. Test short-term outcomes; 6. Track long-term behaviour
Implementation	Assess implementation conditions: cost, accessibility, data quality, interoperability, institutional capacity and operational reliability.	Grounded in protection motivation theory, dual coding theory and cognitive load theory; adapt interfaces to community, city and operational scales; track retention and uptake beyond immediate post-use feedback.	7.Operational integration

CRediT authorship contribution statement

Fatemeh Kaleshani: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mostafa Babaeian Jelodar:** Writing – review & editing, Supervision, Conceptualization. **Farzad Piadeh:** Writing – review & editing, Supervision, Conceptualization. **Suzanne Wilkinson:** Writing – review & editing, Supervision. **Bruce Balaei:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

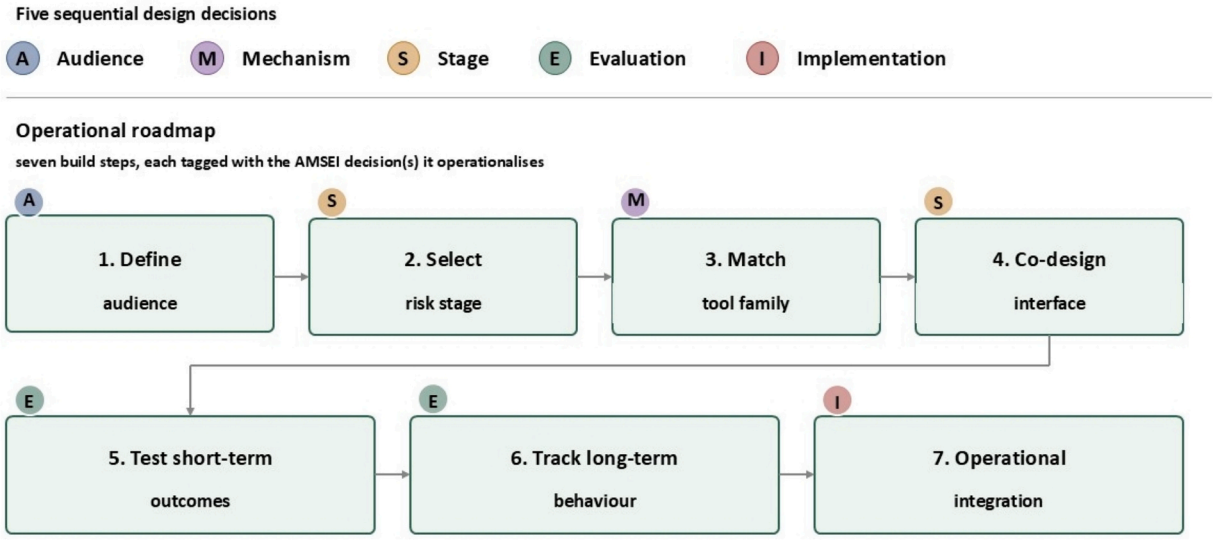


Fig. 9. Roadmap for designing, deploying and evaluating 3D flood risk communication tools.

Appendix A. Compact corpus classification

Table A1
Compact classification of the coded corpus.

Study	Family	Audience	Title
[22]	2.5D/image/video	Non-experts	Climate change awareness and strategies for communicating the risk of coastal flooding: A Canadian Maritime case example
[23]	GIS/BIM/web 3D	Mixed	A BIM-GIS integration method in support of the assessment and 3D visualisation of flood damage to a building
[20]	GIS/BIM/web 3D	Experts	Visualisation and evaluation of flood uncertainties based on ensemble modelling
[24]	GIS/BIM/web 3D	Non-experts	Exploring Flood Resilience Thinking in the Retail Sector under Climate Change: A Case Study of an Estuarine Region of Taipei City
[25]	GIS/BIM/web 3D	Experts	3D visualisation tool for improving the resilience to urban and coastal flooding in Torbay, UK
[15]	GIS/BIM/web 3D	Mixed	Terrestrial and airborne laser scanning and 2-D modelling for 3-D flood hazard maps in urban areas: new opportunities and perspectives
[26]	AR/MR/XR	Experts	Mobile Augmented Reality for Flood Visualisation
[27]	GIS/BIM/web 3D	Mixed	Dynamic 3d Visualisation of Floods: Case of the Netherlands
[28]	VR/serious game	Mixed	Flood Action VR: A Virtual Reality Framework for Disaster Awareness and Emergency Response Training
[29]	GIS/BIM/web 3D	Mixed	Moving to 3-D flood hazard maps for enhancing risk communication
[30]	AR/MR/XR	Mixed	Interactive Landscape Design and Flood Visualisation in Augmented Reality
[31]	GIS/BIM/web 3D	Mixed	Flood risk management in sponge cities: The role of integrated simulation and 3D visualisation
[32]	AR/MR/XR	Non-experts	The Case for Low-Cost, Personalized Visualisation for Enhancing Natural Hazard Preparedness
[33]	GIS/BIM/web 3D	Experts	Three-dimensional simulation of regional urban waterlogging based on high-precision DEM model
[15]	GIS/BIM/web 3D	Mixed	Terrestrial and airborne laser scanning and 2-D modelling for 3-D flood hazard maps in urban areas: new opportunities and perspectives
[34]	GIS/BIM/web 3D	Experts	Techniques of 3D Visualisation using Unmanned Aerial Vehicle for Flood Protection
[35]	AR/MR/XR	Experts	Mixed Reality Flood Visualisations: Reflections on Development and Usability of Current Systems
[8]	2.5D/image/video	Mixed	Superimposing height-controllable and animated flood surfaces into street-level photographs for risk communication
[36]	GIS/BIM/web 3D	Experts	A Preliminary Contribution toward a Risk-Based Model for Flood Management Planning Using BIM: A Case Study of Lisbon
[37]	GIS/BIM/web 3D	Experts	Three-dimensional virtual representation for the whole process of dam-break floods from a geospatial storytelling perspective
[12]	VR/serious game	Non-experts	Immersive storm surge flooding: Scale and risk perception in virtual reality

(*continued on next page*)

Table A1 (*continued*)

Study	Family	Audience	Title
[38]	VR/serious game	Non-experts	After the virtual flood: Risk perceptions and flood preparedness after virtual reality risk communication
[39]	2.5D/image/video	Non-experts	Persuasion illustrated: Motivating people to undertake self-protective measures in case of floods using 3D animation focused on components of protection motivation theory
[40]	VR/serious game	Non-experts	A non-immersive virtual reality serious game application for flood safety training
[41]	VR/serious game	Mixed	A 3D-Panoramic fusion flood enhanced visualisation method for VR
[19]	2.5D/image/video	Mixed	How does your viewing perspective matter for decision-making with flood risk maps?
[42]	AR/MR/XR	Mixed	Extended Reality (XR) Environments for Flood Risk Management with 3D GIS and Open Source 3D Graphics Cross-Platform Game Engines: Advances in Immersive Sea Level Rise Planning Technologies for Student Learning and Community Engagement
[43]	VR/serious game	Non-experts	Enhancing Flood Disaster Preparedness Through Virtual Reality: A VR-based Flood Simulator Game
[44]	GIS/BIM/web 3D	Experts	Flood Impact Risk Mapping in Settlement Areas from a 3D Perspective: A Case Study of Hurricane Matthew
[45]	VR/serious game	Experts	Immersive visualisation in infrastructure planning: Enhancing long-term resilience and sustainability
[46]	GIS/BIM/web 3D	Mixed	RETRACTED: A 3D virtual geographic environment for flood representation toward risk communication
[47]	VR/serious game	Non-experts	Development of a virtual flood experience system and its suitability as a flood risk communication tool
[13]	AR/MR/XR	Mixed	Server-enabled mixed reality for flood risk communication: On-site visualisation with digital twins and multi-client support
[48]	GIS/BIM/web 3D	Experts	Integration of Disaster Risk and Shelter Information into a 3D Urban Model for Intuitive Evacuation Planning in Yokohama City
[49]	AR/MR/XR	Non-experts	Risk perception and awareness in an augmented reality flood response game: The role of player perspectives
[16]	VR/serious game	Experts	Virtual reality-assisted visualisation of flood susceptibility using optimized machine learning models
[50]	2.5D/image/video	Non-experts	Realistic Virtual Flood Experience System Using 360° Videos and 3D City Models Constructed from Building Footprints
[51]	VR/serious game	Non-experts	Evaluating the Effects of a Virtual Reality Serious Game on Flood Risk Awareness
[52]	GIS/BIM/web 3D	Experts	Hydro3DJS: A modular web-based library for real-time 3D visualisation of watershed dynamics and digital twin integration
[14]	AR/MR/XR	Non-experts	Troubled water: Enhancing flood preparedness with eXtended reality
[53]	VR/serious game	Non-experts	Using virtual reality to study human response to flood risk across controlled experiments

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2026.100739.

Data availability

The data supporting the findings of this review are provided in the article and its Supporting Information, including the study-level coding table and scoring criteria.

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