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EDITED BY
Michele Turco,
University of Calabria, Italy

REVIEWED BY
Luca Brocca,
National Research Council (CNR), Italy
Anna Chiara Brusco,
University of Calabria, Italy

*CORRESPONDENCE
Helen Underhill,
helen.underhill@uwe.ac.uk

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"That's the dream, right?": reflections on the co-design of an environmental digital twin by flood risk management professionals

Helen Underhill[1]*, Lindsey McEwen[1] and Thomas Coulthard[2]

[1]College of Arts, Technology and Environment, University of the West of England, Bristol, United Kingdom, [2]Department of Natural Sciences, Manchester Metropolitan University, Manchester, United Kingdom

A Digital Twin (DT) dynamically represents the near-real-time status of a system, allowing users to visualise its current and forecasted status, and test interventions. Emerging technologies, such as DTs, could be transformative for working practices in environmental risk management. However, the development of DTs for environmental management and disaster risk reduction involves extensive challenges. Within Flood Risk Management (FRM), this process is complicated by the involvement of multiple professional stakeholders with diverse statutory responsibilities, priorities, and needs. There is also no formal method for the design of DTs or established method of accounting for end user needs. Processes tend to be top-down and technology driven, rather than bottom-up and user focused. This paper presents one of the first attempts to explore user co-design within the development of a DT. It stems from FLOODTWIN - an interdisciplinary DT demonstrator project for FRM in Hull and the East Riding of Yorkshire (United Kingdom), a region with complex, compound flood risk. Using data from participatory workshops and interviews, we explore the project's co-creation process with professional FRM stakeholders, mapping emerging opportunities and challenges in the development of DTs and their interfaces from a qualitative, ethnographic perspective. We reflect on the diverse perspectives of professional users, how they engage with emerging technologies, the politics of data-sharing, and the role of academic research in shaping future development of DTs in FRM practice. We present a new evidence-base to inform future research on the co-creation of digital tools in multi-agency decision-making for FRM and wider environmental management. The paper proposes a research planning framework for navigating co-design processes in future projects to develop environmental DTs. In so doing, the paper also illustrates ways in which sub-optimal water risk management is socially constructed, and not merely a technical challenge to be surmounted.

KEYWORDS

co-design, digital twins, emerging technology, flood risk management, professional stakeholder engagement, research planning framework

1 Introduction

Using a federated data infrastructure and numerical modelling, a digital twin (DT) dynamically represents the near-real-time status of a system, allowing users to visualise its current and forecasted status and test interventions. As rapidly emerging technology, DTs are increasingly being explored as potentially important in water management (Brocca et al., 2024; Ghaith et al., 2022; Henriksen et al., 2023; Pal et al., 2025; Rico Carranza et al., 2023; Rico Carranza, 2024; Roudbari et al., 2024; Wang et al., 2025; Yin et al., 2024) and disaster risk reduction (Fan et al., 2021; Ford and Wolf, 2020). This follows on from earlier discussions around the increasing importance of Big Data and improvements in data visualisation for FRM (Haynes et al., 2018; Towe et al., 2020). A flood risk management DT is a dynamic, interactive virtual copy of catchment water dynamics that matches its real-world partner as far as possible. This 'cloning' of a real system is limited by the resolution (spatial and temporal), accuracy of modelling within the DT and of the data that informs it. The latter can include earth observation data, rain radar data, and live data feeds from sensors in the field (such as river flow gauges).

The DT concept comes from manufacturing, as digital tools for planning and operating more efficient infrastructure, minimising costs and environmental impact. The trend towards 'smart cities' and 3D city modelling has produced several DTs for cities designed to improve infrastructure management, energy efficiency, sustainable development, and public health, among other purposes (Masoumi et al., 2023; Weil et al., 2023) with accompanying research on the integration of georeferenced aggregated social data (e.g., urban planning, disaster management, transportation, or sustainability) within such urban models (Abdeen et al., 2023; Cardullo and Kitchin, 2019; Maiullari et al., 2024; Yossef Ravid and Aharon-Gutman, 2023). DTs are also used to simulate infrastructural assets and connected built environments, such as wind farms, solar farms, water treatment works, dams, train networks, and oil rigs; for purposes including construction, maintenance, safety, efficiency, resilience, and sustainability planning (Bentley Systems, 2022). Digital Twins are highly visual, consolidating data and allowing users to explore change through time and thus gain insights for decision making (Kikuchi, 2022).

The development of DTs for environmental management and disaster risk reduction constitutes a relatively new field with extensive challenges (Fan et al., 2021). For instance, environmental sensor networks are not as comprehensive as those in manufacturing settings. Nonetheless, with increasing computing and data storage capacity it is rapidly becoming viable to replicate parts of the Earth system digitally (Attinger et al., 2024). Environmental challenges, as wicked problems, bring together multiple stakeholders, each with differing priorities and problems to solve. Most published research on DTs concerns their technical aspects and implementation, often learnings from manufacturing in aerospace and automobile industries (Liu et al., 2021; Tao et al., 2019; Qi et al., 2021), giving a top-down technical problem focused approach. However, DTs ultimately have users and the successful development and implementation of environmental DTs therefore need to rely on effective stakeholder involvement in development and design.

Interactivity is a key aspect of DTs and their potential to help with decision making under climate change scenarios; understanding stakeholder interactions with DTs is crucial (Voinov and Bousquet, 2010). Despite recent enthusiasm, DTs have not reached implementation 'maturity' and there is limited literature on social interaction with DTs, user understandings of these systems, and social barriers to adoption within operational use (Kober et al., 2024; Tartia and Hämäläinen, 2024). Stakeholder involvement in DT development presents several challenges: diverse scientific and technical backgrounds and levels of understanding among stakeholders; balancing conflicting interests and priorities; reckoning with tensions and conflict between stakeholders; brokering different organisational cultures; ensuring a diversity of users are involved and sustaining their engagement throughout the process, whilst managing expectations about DT capabilities, particularly at development stage. However, co-working with stakeholders provides potential opportunities to bring a plethora of different knowledges–individually and collectively - to co-creation processes, including local and contextual, operational/emergency management, institutional, and risk communication (O'Donnell et al., 2018; Knighton et al., 2018; McEwen et al., 2022). This supports valuable stakeholder-researcher knowledge exchange as well as stakeholder-stakeholder social learning. In addition, there are different potential modes for the exchange of this knowledge and its use in knowledge co-generation with professionals - whether co-production, co-creation or co-design.

It is crucial to differentiate at the outset between co-creation, co-production, and co-design, as these terms are often deployed interchangeably in ways which can confuse researchers and participants (Vargas et al., 2022). Co-creation can be thought of as an overarching principle or aim to use collaborative and creative approaches to collectively solving a problem (Reed et al., 2023). Co-production requires joint definition of the needs of users and stakeholders at a very early stage, ideally pre-funding allocation; its aim is the *implementation* of solutions determined through a process of co-creation (Hickey et al., 2021; McEwen, 2024). Process is important alongside outcomes, with emphasis on longitudinal knowledge sharing. Co-design involves the active participation of researchers and stakeholders in decision-making concerning the response to the pre-specified problem (Vargas et al., 2022). These early stages of discussion are complex but offer potential for knowledge sharing and integration; outcomes and benefits need to be clarified individually, organisationally and collectively.

Participatory modelling with professional stakeholders and/or communities is increasingly recognised to have significant value for water risk management (see Landström et al., 2011; Coletta et al., 2024; Landström et al., 2025). Positive impacts can include better decision quality through diverse knowledges; better representation of local risk conditions; legitimacy and trust; improved communication; shared understanding and mutual capacity building; and stronger stakeholder buy-in and ownership. One recent paper addresses participatory modelling engaging the public as citizen scientists in modelling and decision-making surrounding pluvial flood risk, using the example of DT development for South Korea's Gangnam region (Park et al., 2024). Another study investigated DTs for decision making and stakeholder communication within urban planning and decarbonisation (Maiullari et al., 2024). Tripathi et al. (2024)

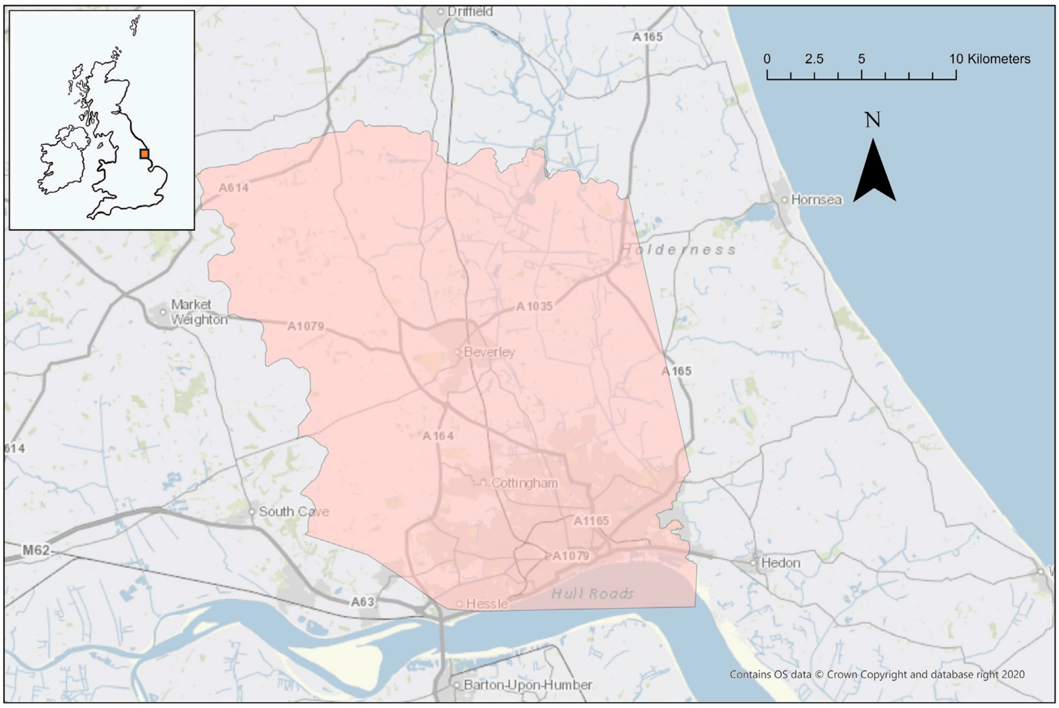

FIGURE 1
Location map for Hull and region within the United Kingdom, showing DT area highlighted in pink.

offer a systemic literature review on stakeholder collaboration within development of industrial DTs, highlighting complexity and noting challenges arising in their development. This paper constitutes the first study to investigate multi-agency professional stakeholder engagement in developing DTs for FRM. Furthermore, it explores challenges of using co-creation methods in research on DTs in a complex, multi-stakeholder FRM environment. This fills an important gap in the developing literature:

> '[...] little is known about the detailed characteristics and dynamics inside DT projects [...] there are no insights into detailed DT communication challenges and their countermeasures that support scholars and practitioners with solving these issues.' (Kober et al., 2024, 2).

FLOODTWIN was one of five research projects funded under the NERC[1] TWINE (Twinning capability for the Natural Environment) demonstrator scheme.[2] Academic partners from three universities and one research consultancy combined their expertise in stakeholder engagement and co-design, surface hydrology and hydrological modelling, remote sensing, groundwater modelling, and interface design. FLOODTWIN aimed to develop and test a demonstrator DT for Hull and region (see Figure 1), in consultation with professional FRM stakeholders.

The city of Kingston upon Hull and much of the surrounding area is especially vulnerable to flooding. Much of the present-day city lies on reclaimed marshland, lying below the level of mean high tides, and has a long history of flooding.[3] Following the significant and damaging storm surge of 1953, extensive coastal and estuary front, flood defences were constructed and major revisions of the city's drainage system in the 1970's and early 2000's reduced flooding occurrences in Hull. Nonetheless, lying below tidal levels means Hull relies on a pumped drainage system and in June 2007, the city experienced after the drainage system was overwhelmed (Coulthard and Frostick, 2010). Over 8,000 homes were flooded, and the event was one of several that summer that informed the post-2007 development of the current national FRM ecosystem via the Pitt report and its recommendations (Cabinet Office, 2008; Haughton et al., 2015). Additionally, parts of the city and more extensively the wider region were damaged by a tidal storm surge event in December 2013 (Hull City Council, 2014). Given Hull's low-lying location and subsequent large number of properties at risk, following the 2007 floods, the city has been successful at applying for funding for flood protection schemes from flooding

1 Natural Environment Research Council (NERC) is one of nine research councils within United Kingdom Research and Innovation (UKRI) - a non-departmental public body sponsored by the Department for Science, Innovation and Technology (DSIT).

2 https://www.ukri.org/news/digital-twin-projects-to-transform-environmental-science/.

3 Summary long-term climate data can be found at: https://www.metoffice.gov.uk/research/climate/maps-and-data/location-specific-long-term-averages/gcx9zcuz2.

from the estuary,[4] the river Hull, and for storage lagoons addressing groundwater and surface water flooding[5],[6]. Additionally, models and tools to predict flooding have been developed for the region (Environment Agency, 2022) and communication between the local stakeholders enhanced.

Within the context of wider FLOODTWIN project activities, this paper reflects on stakeholder engagement and co-creation processes through the following research questions:

Q1. How can we ensure that stakeholder voices are foundational to the development of DTs to better understand user needs and contexts for decision making?
Q2. What do good co-creation and co-design processes look like for DTs, from both researcher and stakeholder perspectives?
Q3. What should a research planning framework for the set-up of a DT co-creation process comprise?

We explored these through a series of sub-questions which structured stakeholder interactions in workshops and interviews:

Q4. What uses do professional stakeholders envisage for DTs in FRM?
Q5. In what ways could a DT be useful for individual, inter-organisational, or multi-organisation working?
Q6. How can DTs help stakeholders make decisions (in what context, with what level of risk, and with what levels of knowledge and expertise required)?

Emerging technologies such as DTs, could be transformational for the environmental management of risk. As one scientist from the environmental regulator explained, 'our understanding is very much at the start' but 'our longer-term goal would be: to assess the risks, costs and learnings from other sectors on the pros and cons of using digital twins' (anonymised email communication, 16/12/24). This paper explores the process of professionals working with ideas and emerging digital technologies that straddle the gap between 'blue sky' or transformative, and the practical and familiar (tools, models, and programmes in operational use). It aims to contribute to debates around responsible development of technology including DTs, AI, and other emergent technology for environmental management, foregrounding stakeholder voices within the process. This paper also provides detail on the contemporary status of FRM, including the relationship between day-to-day practice (operational management of assets, planning, decision making, numerical modelling) and processes (research and development, sharing of data, outsourcing and use of consultancies), which can provide context for future research design in this arena.

4 https://www.gov.uk/government/news/hulls-42m-tidal-flood-scheme-gets-the-green-light.

5 https://storymaps.arcgis.com/stories/60526831811643978d878e1cb0cd3ed6.

6 https://www.hull.gov.uk/downloads/file/2154/Local_Flood_Risk_Management_Strategy.pdf.

2 Methodology

The original terminology used - and ethos aspired to - within the wider interdisciplinary FLOODTWIN project was co-creation and co-design (Vargas et al., 2022) rather than co-production (Hickey et al., 2021; McEwen et al., 2024), recognising the extent and location of possible co-working within the process. The operational definitions of co-creation and co-design used in FLOODTWIN were as follows:

Co-creation is a process produced when diverse stakeholders are deliberately brought together to jointly generate ideas, knowledge, or solutions through a structured sequence of collaborative activities.

Co-design is a state generated when stakeholders participate directly in design of a tool through structured, design procedures.

Here co-creation was an overarching process bringing together diverse professional stakeholders (here in co-design) to generate value (here a DT interface) through shared knowledge, creativity, and resources. Our overarching principles in co-working included partnership, shared power and decision making, open dialogue and transparency, and iterative engagement. A Stakeholder Panel was constructed for the co-creation work to reflect the complexity of both flood risk and the FRM ecosystem. This drew together a diverse range of FRM stakeholders from Hull and the region, including a water utility company, the environmental regulator, the city and local government, and a board responsible for managing internal drainage channels, each with different remits and statutory responsibilities. The role of the Stakeholder Panel was primarily to input on the background contexts, functionality and design of the interface–alongside establishing likely 'use cases' or how users might interact with the DT - and wider reflections on the use of emergent technologies in FRM.

The evidence base reflected on here comprises data gathered from: three participatory stakeholder workshops, nine one-to-one interviews (ranging in duration from 47 min to 1 h 22 min), transcripts of four research team discussions, and two one-to-one interviews with modellers and interface developers within the research team (themes are outlined in Figure 2; stakeholder interview schedule included as Supplementary Appendix A). Interview participants were 4 males; 4 females; length of time in professional role ranging from 2 to 26 years (number of individuals: local government– 4; environmental regulator – 2; water utility company – 1; drainage board – 1). In total, 12 stakeholders were involved in the co-creation process from five organisations. Participation by organisation at the 3 workshops: local government – 7; environmental regulator – 7; water utility company – 1; drainage board – 2). Additionally, we received other asynchronous contributions via email.

The transcripts were initially coded thematically in a colour-coded spreadsheet by the first author using grounded theory techniques (Corbin and Strauss, 2015). During this process, the first coder convened iteratively with the second coder (second author) to discuss, refine and validate emergent themes. Logged notes were kept to support transparency of these interpretive decisions. In cases where interpretations diverged, deliberation between the two coders resulted in resolution or recoding. Triangulation across workshop and interview transcripts, and the

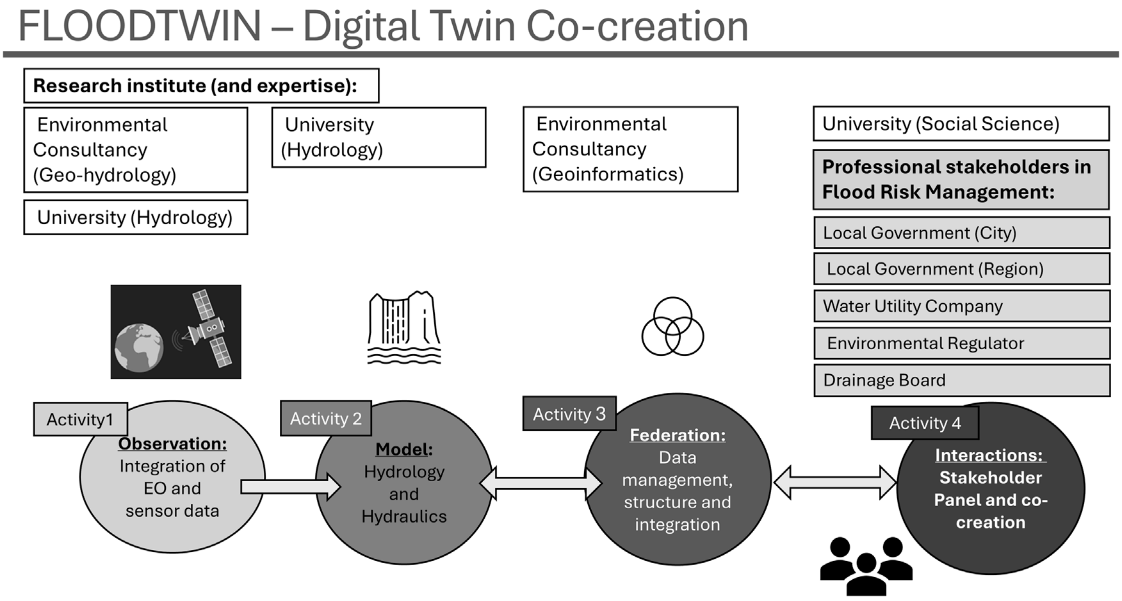

FIGURE 2
Project activities, research partners and stakeholders.

researchers' reflective notes (post participatory workshops) strengthened identification of themes.

Participatory workshops, focused around exploring key questions, were designed to draw on diverse stakeholder experience and expertise, and to capture local and organisational knowledge of water flow patterns in complex flood situations, alongside insights into FRM strategies - past, present and future - at different scales in the Hull and East Riding area. The workshops also integrated a sequence of knowledge sharing by the research team (see Supplementary Appendix B for details of workshop aims and contents). This data collection was conducted through online (Zoom) meetings and in person. Individual contributions from stakeholders were anonymised in line with the research project's ethics approval at the lead institution for the stakeholder work. DT developments are complex by their nature, requiring teamwork by experts from multiple disciplines, 'who may only know parts of the DT in detail' (Kober et al., 2024: 5). As such, our evidence base includes recordings of project research team discussions, and reflexive discussions with individual team members to incorporate their practical and conceptual perspectives on doing this type of work collaboratively.

Logistical concerns were to establish the right person or people within each organisation to contribute to a project with this focus, and to ensure longevity of individual participation. Processes adhered to best practice in stakeholder engagement (McEwen et al., 2022), with attention to managing the knowledge relationships, shifts from knowledge transfer to knowledge co-generation (McEwen, 2024) and the boundary spanning between academia and the workplace (Bartunek and Rynes, 2014; Dolmans et al., 2022). Concerns about how to build a new community of practice (cf. Wenger, 2000) were alleviated by the fact that most stakeholders were part of the cross-organisational, place-based, water risk management initiative–*Living with Water* (LWW)[7] - that was already undertaking its own hydrological modelling in Hull and East Riding region. A further concern was how to build and broker relationships and trust between researchers and stakeholders (Filipe et al., 2017). In part, this was mitigated by the fact that the lead hydrologist was based in the case-study setting, with prior working relationships with several stakeholders.

Two challenges involved managing stakeholder expectations and the need for tailoring workshops to participants. Given that the funding was for the development of an exploratory demonstrator–not intended for future operational use in the workplace, the research team could not promise to action all requests and suggestions made by stakeholders. Planned workshop activities (see Figure 3; Supplementary Appendix B) could require nimble adjustment to the changing realities of workshop participation. For example, at our second (in person) workshop, we expected representatives from four separate stakeholder organisations; instead, we had an in-depth discussion with three colleagues from the environmental regulator. While we had anticipated cross-organisation discussion about two potential use cases for the DT, we were able to gain insight into knowledge and technological needs within an organisation across different roles and levels of experience. This change, however, required management of wider research team expectations of data garnered for co-design. The first and third workshops had a much larger diversity of stakeholders.

7 *Living With Water* is a partnership between organisations which play a role in managing water in Hull and the East Riding: https://livingwithwater.co.uk/.

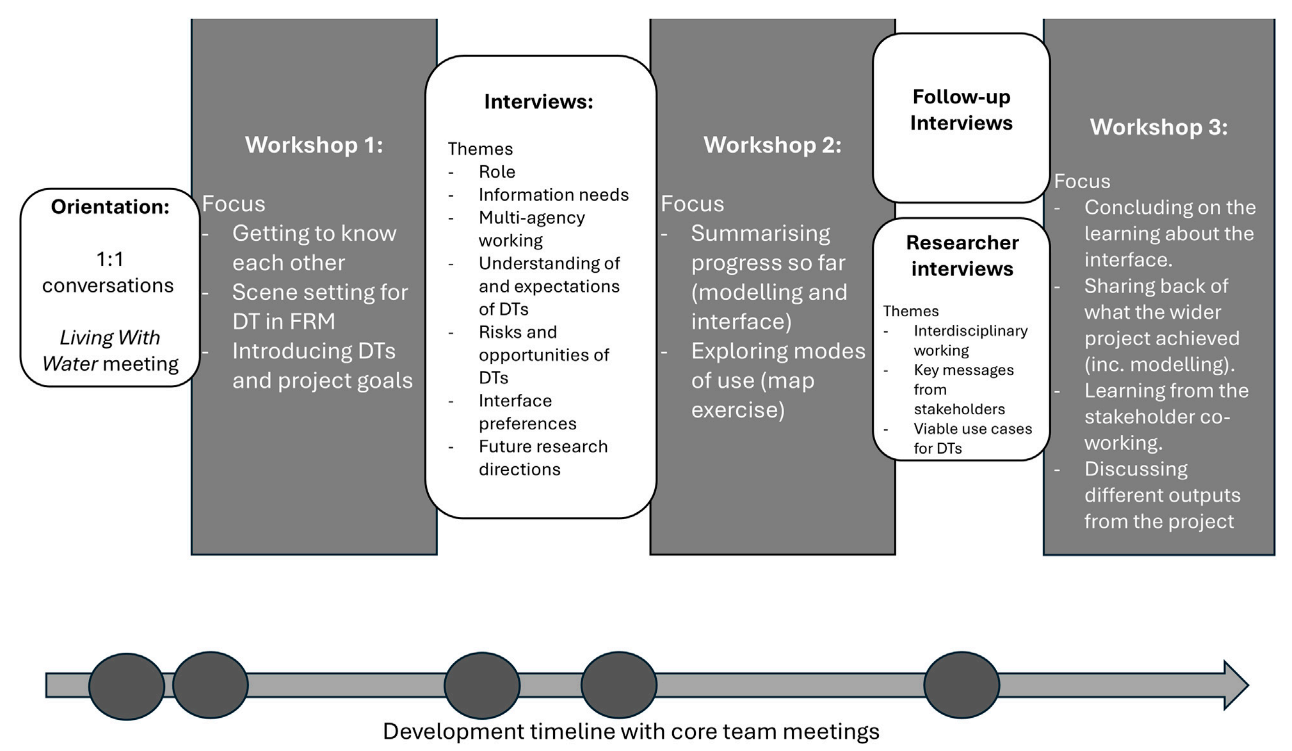

FIGURE 3
Project activities and timelines.

3 Observations and learnings from the FLOODTWIN project

Within this section, we explore the findings of the professional stakeholder engagement and co-creation workstream of FLOODTWIN. Firstly, we illustrate the complexity of the problem context from both environmental and social perspectives. We then outline the potential uses for a DT in this context, illustrated by stakeholder attitudes to each use case. These have been mapped onto the disaster risk management (DRM) cycle (e.g., Bosher, 2005), to show how DTs could contribute to each phase, and across phases as an integrator. This critical reflection supports the subsequent presentation of a proposed research planning framework for developing co-creation activities to explore user engagement with DTs for complex risk management.

3.1 Complexity of the problem context

3.1.1 The environmental context

The City of Kingston-upon-Hull and the East Riding of Yorkshire are the two local government authorities that have the highest number of properties that are likely to flood in England (Environment Agency, 2009: 30). As one stakeholder explained:

> '98% of Hull is [. . .] within what's called the high flood risk area, if we were following national planning policy, we wouldn't be building any more developments in Hull. So, we've had to find [. . .] a way around that, because whilst we're at that high level of flood risk, we also have [a] very high standard of protection from our flood defences' (I-1-LG1).

The wide range of data that must be synthesised in the pursuit of effective FRM illustrates the complexity of this environmental context:

> 'In my role, I [utilise] information around our assets, be that asset condition, size, age, what it's constructed of, type of asset, through to information on the estuary itself in terms of water levels, tide tables, understanding sea level rise [. . .] LiDAR and [BATHI] if we're going to build estuary flood models, [. . .] economics from a defence-type perspective in terms of cost of build, cost of maintenance, carbon costs, but also around the socioeconomics [. . .] understanding what is in the floodplain, receptor database, digital terrain models [. . .] it's a wide range of information we use on a daily, weekly, monthly basis.' (I-4-ER1).

Furthermore, decisions and actions in FRM take place within an evolving natural and infrastructural landscape of change. This results in the interaction of new structures, infrastructure, and flood defences overlaid on an already complex system which is subject to compound risks determined by the ways in which different types of flooding interact.

> 'This data's coming but it's not here yet, [. . .] we've had a lot of investment into new flood defences, so [. . .] there's River Hull, there's Humber Hull Frontages [. . .] so effectively there'll be

TABLE 1 The nature of the user group and its relationships and interdependencies.

Stakeholder ecosystem – Organisation types and responsibilities	
Organisation type	**FRM responsibilities**
Environmental regulator (arms-length government body)	- Taking a strategic overview - Managing the risk of flooding from "main rivers" - Issuing flood warnings - Providing information through flood risk mapping - Operation and management of national flood risk assets (such as flood defences), normally located on main rivers
Local government (unitary authority – city)	- Managing the risk of flooding from surface water, groundwater and "ordinary watercourses" - Operation and management of (some) local flood defences
Local government (unitary authority – region)	- Managing the risk of flooding from surface water, groundwater and "ordinary watercourses" - Operation and management of (some) local flood defences
Private water utility company	- Managing the risks of flooding from piped water and sewage - Providing surface water drainage from buildings and yards
Public sector management group representing 8 internal drainage boards (IDBs) across Yorkshire	- In some areas, such as those with a special need for drainage, internal drainage boards play a similar role to lead local flood authorities such as local councils

Source: https://commonslibrary.parliament.uk/who-is-responsible-for-managing-flood-risk-england/.

> new weak spots, and I don't know where those are at this point.' (I-1-LG1).

Different organisational players have different informational needs in terms of flood risk. Nonetheless, commonalities arose, for instance, stakeholders from local government and the environmental regulator expressed an interest in a combined groundwater model, as they currently have difficulty predicting groundwater levels and flows. Within existing modelling, some hydrological areas, such as groundwater within the chalk aquifer that underlies the Yorkshire Wolds, and the impact of tidal flows, are underdeveloped, whilst others such as fluvial flood risk are well represented. Tidal flood risk modelling is further complicated by the dynamic nature of features of the coast and its interaction with evolving infrastructure.

> 'Tidal flooding is hard [. . .] it's difficult compared to surface water flooding, because you're not filling low spots essentially within the model, and asset heights can be different depending on conditions. We were subject to a lot of beach lowering in certain areas, which impacts asset performance. And it's not like there's any model in the world that can accurately keep track of where beach levels are at any given time.' (I-5-LG2).

Considering these factors, stakeholders expressed the need for a flood warning system specific to Hull:

> 'We need very good information on the likelihood of flooding, on flood depths, flood velocities, the areas that flood, the standards of protection that the flood defences offer, where they're likely to breach or overtop' (I-1-LG1).

There was consensus around the local specificity of Hull and the inadequacy of the existing national flood warning system, which was deemed too sensitive for this area: '[. . .] along the North Sea coast, we get a lot of flood warnings saying there's risk of overtopping and things like that, when there isn't really' (I-3-LG2). This drove stakeholder interest in the potential of a Hull-specific DT to inform the flood warning system and improve accuracy; the group was keen to 'play' with a model calibrated to work locally.

3.1.2 The social context - stakeholder ecosystem

The case study of the catchment of Hull and the East Riding presented a multi-faceted challenge, as this research project attempted to engage with the whole catchment, so involving multiple professional stakeholders with diverse priorities for the development of a decision-making tool.

This complex stakeholder ecosystem has significant implications, particularly given the different seats of statutory responsibility which create a patchwork (Table 1) in which the environmental regulator are responsible for watercourses and groundwater; local government organisations and their highways departments are responsible for surface water; and water utility companies are responsible for sewerage including surface water once in the drainage system.

Stakeholders across flood risk contexts have different 'types' of problems, statutory responsibilities, priorities, needs for data and evidence, and relationships with technology–both existing and emergent. They may also work at differing temporal scales, with some partners working in 'the here and now', whilst others prioritise 'the long-term space':

> 'People don't realise how long in advance you need to do things, but you have to get everything in place. Some of our habitat creation sites, it's a minimum of 20 years between land purchase and delivery on the ground.' (I-4-ER1).

Through engaging a group of stakeholders who already knew one another, the project was able to proceed swiftly with initial workshops. However, there may have been impacts on FLOODTWIN's processes from a pre-determined social network and hierarchy. There was consensus among stakeholders in citing

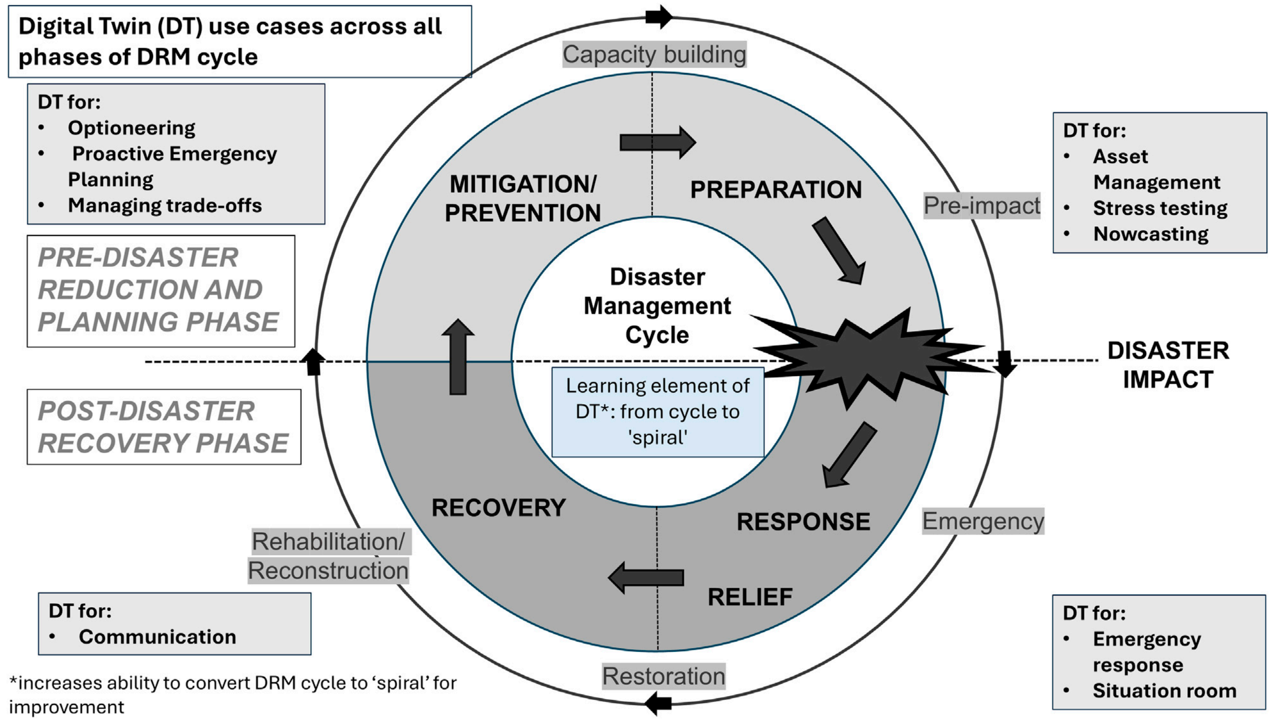

FIGURE 4
DT use cases across all phases of the disaster risk management (DRM) cycle (overlaid on Figure from McEwen, 2024b, adapted from Bosher, 2005; Bosher and Chmutina, 2017, permission Lee Bosher).

good working relationships for FRM in the region through LWW. The LWW initiative has 'top-down control' which means that requests for time, representation and resources are answered (I-3-LG2). Early in the process, FLOODTWIN researchers were able to sit in on a LWW meeting (Figure 3). As this is a group who have had contact across a variety of roles and organisations, these connections are both personal and professional, with an interwoven social network. One interviewee described how this communication worked within both the LWW forum, and emergency response scenarios:

> '. . . we have the formal route for the LRF [Local Resilience Forum, which coordinates emergency response], but actually, because we're working together anyway [. . .] if the formal route doesn't work, we use the work route, or the informal route as well.' (I-2-ER1).

Stakeholders across the panel expressed confidence that inter-agency working had improved post 2007, with emergency response now well practised in both theory and reality: 'it's coordinated quite efficiently. Far more than it used to be, because in the past it really wasn't, before 2007' (I-1-LG1). This involved an ongoing process of re-integration of response responsibility, more holistic working, and 'ending the blame game':

> 'We were all one authority at one point, so prior to [the environmental regulator], the water companies, privatisation and everything, we would have been seen as the Water Board [. . .] And then we've been split up, [so] we have to now work out whose water is whose before we can do anything about it. So, [. . .] what we've tried to do with Living with Water, is [. . .] stop that blame game, stop it being about that's your water, that's your water, I'm not having your water going into my pipe or water course.' (I-1-LG1).

This highlights the complexity of interactions between the environmental and social ecosystems involved in FRM in Hull.

3.2 Use cases - DTs for decision making

The envisaged use cases for a DT varied depending on the priorities of each organisation. We now discuss stakeholder attitudes to these use cases in more detail. While we initially split these into 'past–present–future' scenarios for workshop organisation purposes, we found that stakeholders responded with much more creative hybridity. The following discussion is structured according to stages in the Disaster Risk Management (DRM) cycle, for clarity and wider resonance with existing debates in resilience-building (Figure 4).

3.2.1 Mitigation and prevention

Use cases discussed included optioneering (rapid exploration of various alternative risk mitigation strategies). A key area of alignment was recognition that development of DTs presents an opportunity to improve existing modelling–particularly in relation to cost and speed of model runs. A DT offers the ability to swiftly check multiple scenarios and narrow down those which are most credible to be modelled in more detail: 'I think the real usefulness is probably in the speed at which it can help you look at your possibilities' (I-4-ER1). For this group of users, same-day results would be considered 'speedy'. Some felt that a DT could be used to demonstrate value and need when writing funding bids:

> 'With it being so expensive to run the Living with Water model, and given the cost of the schemes that we tend to do, it would be really useful to have a model like the digital twin to run a scheme through, and then, we use that information within a funding bid.' (I-7-LG1).

Stakeholders were interested in using DTs to explore different scales for intervention in a catchment system, for instance, local-level interventions such as sustainable drainage systems (SuDS) or leaky dams: 'actually, that's [where] a lot of modelling is missing, [for] those smaller scale interventions [. . .] it's just not what [the models are] built for' (I-5-LG2). The expense of modelling can make establishing the impact of small-scale interventions such as retrofitting SuDS schemes unaffordable:

> 'So one of our biggest issues at the moment is when we're trying to model surface water schemes, it takes [. . .] about two weeks to run it through a model and costs a fortune, and the model falls over before we've even finished it, and then all of this just ends up costing far more than the scheme itself actually costs. So, something that you can quickly and easily run test scenarios through would be really, really useful.' (W-1-LG1).

This evidence base could be used both at a local, operational level, and for presenting a case to politicians as 'optioneering at a high (ministerial) level' (W-2-LG1-1).

Local government stakeholders were interested in proactive planning for emergency response, exploring potential responses to different rainfall events and their impact on different areas of the city: 'Acting out different scenarios, and thinking of what we can do, which routes we can take.' (I-7-LG1). Stakeholders were also interested in the potential for visualisation of other 'flows' besides water in the DT–e.g., traffic, people, to assist in emergency response planning and intervention:

> 'We make various assumptions about people's behaviour, but the reality of people's behaviour is not necessarily the same [. . .] And there isn't really great evacuation data out there. So, [we would be interested in ways that] a digital twin could [predict] possible behaviour [during a flood event]' (I-4-ER1).

This would necessitate access to different types of social data to augment the environmental modelling of an integrated DT.

3.2.2 Preparation

Both asset management and performance/stress testing were key stakeholder concerns:

> 'there's also an asset management role [. . .] what happens if I hit the system with consecutive storms? How are my assets going to perform? What are the limits of it? What are some adjustments that we could make to manage these assets better?' (I-5-LG2).

> 'Because we've built a lot of the really big flood assets [. . .] that there's room for at the moment, we're in a mode of [. . .] transition over to [. . .] how can we improve [their] performance and function?' (I-5-LG2).

Stakeholders held differing opinions on the utility of an 'always on' set up of a DT system. One stakeholder flagged up that a key issue with DTs for FRM in the 'prepare' phase of the DRM cycle is irregular use, as extreme flood events are not daily occurrences, 'there's no familiarity there' (W-2-LG1-2). Most DTs in other settings are used operationally day to day. Operational nowcasting requires a DT to be running constantly in the background, providing flood alerts:

> 'I've just got this vision of [. . .] Google Maps, and you can just scroll into anything, zoom on anything, [. . .] but with [. . .] current real time flood extents on there [. . .] layers that you can tab on and off that's got all the sewer infrastructure on, you can click on a section of the sewer and it tells you what the level is in there [. . .] warnings that flash up to show that you've got floods [. . .] basically, it's a sort of GIS-type platform that has everything on there in real time.' (I-3-LG2).

While most stakeholders were concerned with identifying locations of water excess, local government stakeholders expressed an interest in tracking the *absence* of water as well as its presence. This included the notion of urban water catchments where flood flows could be diverted into zones of deficit.

Stakeholders also saw a possible use of DTs for adaptive planning engagements between professional stakeholders from different organisations, to work in a collective way to negotiate adaptive solutions. Gaming and testing decision making scenarios as a form of training could help with FRM decision making involving trade-offs: 'Some partners will win and lose together, so we'll try to balance that and help them understand. But for some partners, they will just be losing.' (I-4-ER1). These FRM trade-offs will interact with the high-level goals of each stakeholder organisation. Different organisations also have different risk aversion levels as they 'trade responsibility' amongst themselves and have different experiences of litigation.

3.2.3 Response

During workshops and interviews we explored the nature of communication between the wider group of stakeholders involved in emergency response:

> 'So, [it involves] our neighbouring local [government], [and] the local resilience forum, the police . . . the blue lights . . . [the environmental regulator]. But basically, we all get round the table, so whenever there're MET office warnings, we will convene [. . .] there's a flood cell, which is sort of all the responders, emergency responders and emergency planners, and that includes people like utilities as well and your health services and things, and it can include people like our housing

> colleagues so that everybody [. . .] knows what they're doing.' (I-1-LG1).

Discussion included the potential to use a DT for inter-organisational communication within an emergency situation room:

> 'I think the dream scenario [is that] somebody spins up a bronze command or something like that before a flood, and it would be so cool if there's a situation room and there's a big screen, and you throw up one of those models and you say, this is what we're projecting, we need to allocate resources in this manner. That's the dream, right?' (I-5-LG2).

Potential benefits expressed by stakeholders in the second workshop (environmental regulator-only) included: the near-real-time simulation and sharing information in a way that is useful for FRM partnership working. This involved a tool for coordinating operational response in an emergency, between blue light services (fire, ambulance, police), National Highways, local government and their road highways teams, the local resilience forum, Met Office, military, national health service, ports authorities, and rail network managers. It could include an illustrative function, using the DT for its visual, explanatory power whilst working with other agencies (I-4-ER1). These discussions also spoke to a wider issue of model and model output ownership. Notably that there were separate models run by the Environmental Regulatorfor River and Estuary flooding, and by the water utility for urban/sewage drainage/flooding. Access to outputs from both were controlled by the respective organisations.

3.2.4 Recovery

DTs could potentially support communication with the public, especially regarding near-miss flood events. A local government stakeholder envisaged:

> 'A digital twin that [. . .] we can point the public to and [say], "well, did you know this [near-miss] happened?" And they can go away and look at it, is probably a very good thing.' (I-4-ER1).

As the public have high expectations in terms of flood defence, one local government stakeholder expressed an interest in a using the DT to 're-run' the flood event of 2007, to demonstrate the benefits of the structural work done since then (I-3-LG2). This post-event communication with the public is also connected to explaining diverse stakeholder responsibilities for different flood types:

> 'How do you tell that story? This is what we had to do, and it is for the greater good [. . .] look what would have happened if we hadn't made this difficult, painful decision. And [this] also allows, hopefully, those [who] are the losers in that scenario to [. . .] advocate for themselves in a post-mortem situation.' (I-4-ER1).

However, FLOODTWIN stakeholders felt that a DT of Hull and the region would not be suitable for public or layperson use: 'I think it'd have to be so heavily refined [. . .] redacted, and [. . .] caveated that it might not be that useful.' (I-3-LG2). There was a clear point of agreement among the panel around restricting public access to any potential DT. Our participants suggested creating a heavily constrained or downgraded resolution version of the tool for educational or awareness-raising use within communities. Our data demonstrates a clear contradiction, sometimes expressed even by the same respondent, between wanting to use DTs to inform the public of near misses, but not trusting them with the data.

3.2.5 Potential contribution of DTs to DRM cycle

Stakeholders perceived that the functionality of DTs could potentially sit across different stages in the DRM cycle (Figure 4). Such an integrated approach to scoping emergent technology and lack of bounding of its application is both opportunity and challenge. Such cross-stage explorations could help with thinking afresh about how to develop a 'spiral' to increased resilience. However, these 'diffuse' use cases make it difficult to pin down what a DT is, and is for, during a co-creation process. The paper now progresses to consider the implications of these observations and learnings for a Research Planning Framework to support the set-up of a co-creation process with professional stakeholders.

4 Towards a research planning framework

The paper now considers the implications of this learning for how co-creation of Environmental DTs with professional stakeholders in complex risk settings might be navigated in future projects. We offer a detailed discussion on project set up from the lived experience of this research process, foregrounding stakeholder voices. This section is structured chronologically, considering each phase of the planning and delivery of co-design activities: 1) Project set up; 2) Negotiating data access and sharing; 3) Early brokering; and 4) the Co-creation process. Using observations from FLOODTWIN, we explore the necessary elements of such a process and consider potential problems and solutions. This culminates with a summary of the issues and concerns raised by the professional stakeholders (Table 2) and in the proposal of a potential framework for the front end of this process and a set of recommendations for future researchers. Project set up.

Defining the stakeholder group for co-creation activities in a complex risk setting involves careful consideration of which organisations should be involved and how to engage with horizon-scanning, strategic thinkers within each stakeholder organisation. Within FLOODTWIN, an additional consideration at this stage was the impact and dynamics of working with pre-existing groups. It is important to remember that the dynamic between stakeholders, even within the same organisation, will not represent a single viewpoint, and that levels of experience, seniority and personal compatibility will influence people's interactions during the process, both with their colleagues and with other members of the stakeholder panel.

Defining co-design at an early stage helps to structure the process. Careful planning is required to ensure that stakeholders are not merely selecting among options prepared for them to review but rather collaborating (both between themselves and with researchers) on the foundational definition of the problem or problems to be tackled, and generation of potential solutions. 'Meaningful participation' makes effective use of participants'

TABLE 2 Main issues and concerns raised by professional stakeholders as evidenced in the co-creation process.

Domain	Issue or concern
Definition of DT	• Differentiating DT from other forms of modelling
Stakeholder needs and uses	• Different organisations have different 'types' of problems, statutory responsibilities, priorities, needs for data and evidence, and relationships with technology • Work at differing temporal scales
Co-working in research process	• Prior relationships between those involved in co-creation process • Variable ability to prioritise time to contribute to co-creation process
Workplace norms	• How DT relates to existing modelling used by organisation • Perceived duplication of existing modelling efforts • Accuracy, credibility, cost and reliability of DT to run • Speed of analysis of DT cf. existing models • Computing power required for DT
Data sharing for DT development	• Quality and security of data used • Ownership of data • Potential for subsequent data manipulation by different users • Data subsequently feeding into AI
Prior experience of co-design	• Informs both research team and participants' attitudes towards co-design processes
Interacting with DT tool	• Preference for familiar interfaces rather than transformed design
Nature/frequency of use of DT	• DT would only be used in extreme situations (so running in background most of time)
Applications of DT	• Relationship of use cases to DRM spiral • Asset management and performance/stress testing • Use for managing water excess; use also for absence?
Determining spaces for innovation	• Operational or commissioning space of workplace cf. academic space and funding which encourages risk taking
Access to DT	• The agency and agendas of diverse users • Confusion if different 'truths' are shown in different modelling • How public/communities might interact with process/outputs
Legacy of DT development	• Contingent upon ongoing relevance/performance of DT • Defined by maintenance needs of the DT

time, and creates useful outputs (Pluchinotta et al., 2019: 341). This starts before the award of funding:

> 'Start at the beginning, I think if you're going to do this sort of bidding for a research project, you speak to us before you bid, so you actually put a bid in that [. . .] we all feel is a good investment of our time, effort, and money.' (I-2-ER1).

Busy stakeholder-users are not necessarily keen to engage with a full co-production process, which can be time-consuming:

> 'I think there's a need sometimes for somebody to be a bit paternalistic and step in and say, this is the product we're aiming for, this is the way we're going to achieve that [. . .] particularly on a project with as short a time horizon as this one, you don't have time to waste talking about how you're going to co-create something.' (I-5-LG2).

> 'I think there's value in saying, "We know this works, let's do this and pull the trigger and execute it."' (W-1-LG2).

This project focused on working with professional stakeholders; however, some stakeholders were influenced by their experience of co-working with other groups. For example, one stakeholder mentioned previous experiences of trying to conduct co-creation with publics:

> 'We really wanted to be able to co-create schemes with communities, but what we've realised is because flooding is so technical and quite complex, communities [are] not hydrologists so they can't tell us where they want things. Well, they can tell us where they want things but it's never where it actually has to go to have a benefit to get your funding.' (I-1-LG1).

The dynamics between different players in the interdisciplinary, multi-institution FLOODTWIN research team was further influenced by the different institutional cultures within which they worked. For instance, the difference in priorities between more experimental, emergent approaches taken by university researchers, versus a certain pragmatism from hybrid researcher-consultants at an ex-government environmental research organisation which operates more in the manner of a consultancy. The project's geo-informatics specialist, along with several of the stakeholder panel, wanted to move quickly to establish parameters for the DT's interface. Based on prior research experience of what makes a good spatial data platform, it was established early on that the interface would 'almost certainly

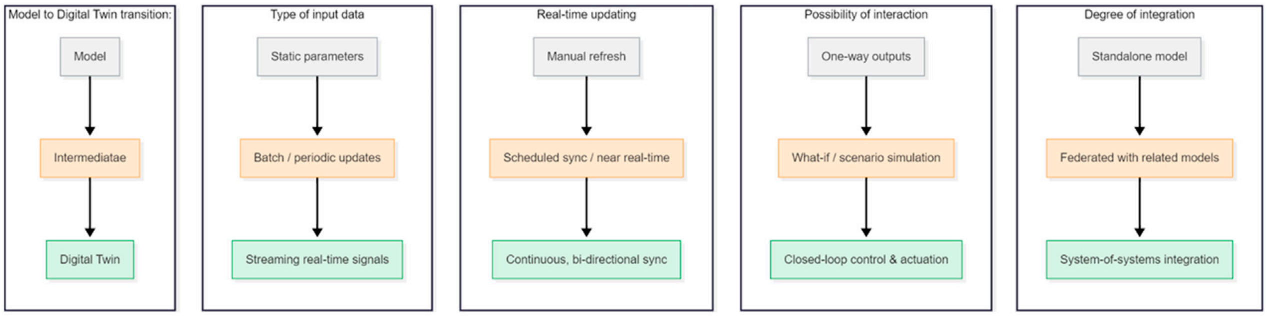

FIGURE 5
Diagram illustrating the key differences–and transition from a simulation model (top) to digital twin (bottom) according to factors such as input data, updating, interaction and integration.

feature' a map interface, some level of ability for users to select an asset and make changes to it, and a possible alert function.

Prior experience of co-design, or similar processes, will inform both the research team and the participants' attitudes towards these processes; it is here that the legacy–positive and less so - of previous projects can come into play. For those with prior experience of technological development, such as the commissioning of hydrological modelling, this may result in a preference for 'tried and tested' methods, and familiar interfaces, without appetite for exploring how tools and ways of working might be done differently. An early discussion around expectations and outcomes–for both researchers and participants–would be fruitful.

Initial brokering of research focus and terminology, though time-consuming, can help to avoid later confusion and repetition; this is particularly significant when differentiating between different emergent technologies. Within the FLOODTWIN project, we found an ongoing lack of clarity around the fundamental concept of DTs, particularly defining them in relation to existing numerical flood models and digital tools such as ArcGIS, and establishing their purpose, utility, and 'USP'[8]. This foregrounds the importance of taking time to ensure stakeholder and researcher understanding and 'alignment' on the meaning and potential of the term DT, and returning to this question at intervals through a co-creation process:

> 'I'm not a technical person at all, so for me [. . .] it was a fairly new concept [. . .] I understood the principle when you explained it to us, but before that, no, I didn't know what [a DT] was.' (I-1-LG1).

Crucially, many stakeholders questioned the difference between a DT and a model, echoing a wider discussion in this arena around the continuum between the two:

> 'I think it's just a shiny new name. Because I think actually when [the project] was first raised, I did say, "What is a Digital Twin? Is it just a posh name for a model?"' (I-2-ER1).

This imprecision marked the research team's - as well as the participants' - understandings of DTs, emphasising the need to build familiarity with, and shared understanding of, emerging technology and terminology early in the research process. We recommend establishing working understandings and shared definitions of terminology early in the process, particularly for emerging technologies such as DTs (see Figure 5). This can also be ameliorated by ensuring representation of all parts of DT development in all meetings and engagements with the stakeholder panel.

A significant issue in the development of this emerging technology is the management of participants' expectations of what can be seen as an over-hyped term or cliché (Batty, 2018) or a 'fashionable buzzword' (Tomko and Winter, 2019: 395). Uptake and enthusiasm for DTs, and related developments including AI and Machine Learning, may call on researchers' skills to address a mixed crowd: 'Bridging the gap between enthusiastic and pessimistic stakeholders is required' (Kober et al., 2024: 6). Before they can input thoughts on their necessary features and function, participants need to understand first what a DT is and what it can offer. Within our stakeholder panel, we noted the early desire to hear background information from other examples of the development and application of DT in water resource management in other countries and circumstances and supported this in our knowledge sharing.

Arguably, academic space, and funding that encourages risk taking, allows more latitude for innovation than the operational or commissioning space of discussions in stakeholders' day-to-day work. For a minority of our stakeholders, research-led DT studies offered the opportunity for 'blue-sky' experimentation:

> 'It's great that the university are our [. . .] academic partner in Living with Water, because they're able to do things that we probably wouldn't have the time or the money to do on our own. [. . .] [which] helps us with lobbying government for policy change, it helps us potentially get investment because [we can

8 This is not a problem unique to stakeholders, but is represented in academic and industry discussions around DTs: '[A] problem that has arisen due to the growing popularity of DT is a lack of consensus on the description of DT as well as so many different types of DT, which adds to the confusion' (Singh et al., 2021: np).

> show that] we're trying all these new things, [. . .] and hopefully that leads to people then wanting to invest.' (I-1-LG1).

Some stakeholders expressed that they would have preferred something more 'challenging and provocative' from the first workshop (see Supplementary Appendix B for contents); most, however, remained tied to the immediacy of needs of the workplace.

A stakeholder from the environmental regulator encouraged researchers to work more face to face, 'where some of the nitty-gritty, really tricky issues would have come out', and to try novel things, to be more controversial and 'to push stakeholders a bit' as this will offer more learnings for stakeholders to take back to their own work (I-4-ER1).

4.1 Negotiating data: availability, reliability and ease of access

4.1.1 Accessing data

The creation of a DT for FRM requires shared, open data, from diverse sources and of many types, which may include earth observation data, data from sensor networks and numerical hydrological models, mapping data including infrastructure plans, and more. This data must be made interoperable within a federated architecture that populates an interface with the potential for interaction, according to the need for visualisation and functionality established through consultation with end users. The creation of a combined surface water model drawing on different data sources requires the use of APIs (application programming interfaces). The United Kingdom Met Office has its own API that generates rainfall data, outputs of which can be fed into a partially working version of the FLOODTWIN DT for participants to interact with. The availability of–and conditions for the use of–relevant data and APIs is complex and dynamic. Part of the work of co-creating DTs with user stakeholders needs to be an element of un-black-boxing of technology–communicating the complexity of the design of digital tools, and the realities of data sharing that go into them:

> 'Particularly in today's environment where you have products like ChatGPT that produce these amazing written summaries [. . .] I think [. . .] [people] just implicitly trust them without understanding the *why* behind them. And I think that's particularly true with flood modelling, and with people who don't deal with models day in and day out.' (I-5-LG2).

Stakeholders expressed concern around data security, trustworthiness, and validation thresholds. In some cases, stakeholder organisations were unwilling to share data with the research team, as well as with other organisational partners:

> 'The biggest constraint, and I'm sure you guys have faced a little bit, is you cannot get an accurate picture for a model without knowing [organisation name redacted] network. And they are - I understand why to a degree - but they are very covetous over their data' (I-5-LG2).

Gatekeeping of data by stakeholder organisations requires careful negotiation and can impede research into DTs. The validation of a numerical hydrological model can be a long and complex process requiring scrutiny from each organisation; participants felt that this would be yet more elaborate for a DT:

> 'Things like the Living With Water integrated model, it's had to go through a [long] period where it's been validated by [the water supply company's] modellers, it's gone to the [environmental regulator] because we've used it for investment bids and things like that. So, it's gone through a lot of scrutiny' (I-1-LG1)

Concerns about quality and security of data expressed by stakeholders run in multiple directions: can you trust that the accuracy of data, was it legally obtained, does its use compromise your organisation's public values or image, and does it need to be protected from further, potentially illegal or even nefarious use–for instance by Big Tech companies scraping data from the web to feed their own AI systems:

> 'How you know whether actually you even had the copyright for some of the stuff that's harvested it, that created it, and so do we really have the IPR to use what we've done or will that be challenged down the line? I've no idea.' (I-4-ER1).

This is also of concern in terms of the development of digital tools by organisations such as the environmental regulator using their own data, that this needs to be protected from being 'fed' to AI that is beyond their organisational control:

> 'Some of our data is sensitive - if you took reservoir data which is classed as official sensitive, and actually if some of that got in the wrong hands there's the potential there to cause widespread spread impacts to UK Plc. So yeah, we take cybersecurity very seriously in that respect.' (I-4-ER1).

AI and Machine Learning data sources pose further challenges in relation to IP law, data ownership, particularly for arms-length government organisations such as the environmental regulator, due to implications for public trust and reputation management, including not breaking GDPR:

> 'We have loads of issues with cyber security and approvals, and data ownership [. . .] we have to jump through a lot of hoops if we want to use technology in terms of where it will be hosted and what those pathways are to access data [. . .] that comes with its own challenges because then we actually need to be able to make sure we can meet those cyber security needs if we want to host it ourselves, and digital twins are very resource intensive' (I-4-ER1).

4.2 Early brokering

In our early brokering engagements with stakeholders (see Figure 3), they asked background questions about DTs including:

what are they, who is developing them, where are they used and by whom, and what place they have in managing environmental systems?

Defining the user and audience, during early brokering, improves the likelihood of asking the right questions and receiving valuable answers and data from stakeholders. This will include discussing who the DT is for, which professional and/or wider communities should be able to input into its functionality, and establishing the real-world problem(s) to be solved. Additionally, we debated the level of understanding and expertise required of a user, and how much they need to know to assess a DT's capabilities and credibility as an evidence source for decision making. One participant, representing a drainage board, cautioned that for him, 'lay people' include those working for the police and fire service, and he 'wouldn't want to leave them to interpret' a hydrological model without support or, by extension, a DT if one were available (I-8-DB2). This expert cited his own recent experience of flood false alarms arising from technical confusion over measurement conventions, leading some partners to assume that flooding was imminent when in fact no threat was posed:

> 'We're already doing modelling as a sector, huge amounts of modelling. [. . .] And it gets more and more sophisticated. If you said to me, you know, "The government's given me a pile of money, what would be the most useful tool you could develop for our sector?" I would saying having some web-based GIS thing with multiple layers on, but I would want that to be driven by flood risk practitioners, for the benefit of decision-makers. If they could just access it and click on lots of layers themselves, they might not know what it means. More dangerously, they might misinterpret it.' (I-8-DB2).

These discussions raise important questions for co-creation and co-design processes: What are the implications of different levels of 'science capital' and prior science and technical knowledge among stakeholders (Archer et al., 2015)? Who is the end user? Is there a requirement for diverse expertise within user teams, rather than one 'super user' individual? Building an Environmental DT requires multidisciplinary data and, therefore, a multidisciplinary team; does it also follow that the users of such a DT will be multidisciplinary?

Stakeholders expressed another concern around the potential for data manipulation by different users; envisaging a scenario in which each user 'tweaks' the model to generate outputs that show what they want to show (e.g., developers, local council, insurers). This concern with the agency and agenda of diverse users reminds us that a model or DT is neither neutral nor impartial. Unmonitored use of an emergent technology like a DT contains the possibility for unintended outcomes, for instance that a potential DT may be used to justify a rise in insurance premiums:

> 'So, for developers, it's usually they tweak [a] model to make sure it shows less risk [. . .] so that they can continue to build their houses. For schemes, we'll show it at more risk so [the local council] can get the investment to build the schemes. So, I must admit, I am quite distrustful [. . .]' (I-1-LG1).

These concerns exemplify the delicacy (and politics) of representing flood risk in Hull, as a particularly sensitive (in both socio-political and hydrological senses) and complex catchment:

> 'It's just the politics [. . .] working out where the most beneficial areas are to store the water [. . .] a lot of times, it's not very popular because it might be where people's existing houses are [. . .] You might even be talking about demolition of existing development and relocating to make space for water.' (I-1-LG1).

Potential exists also for confusion if different 'truths' are shown in different modelling:

> 'So, we publish our flood risk maps, [the Local Government] will have the SFRA maps, Strategic Flood Risk Assessment Maps, I think we've just got to be careful that there aren't different versions of the truth out there.' (I-2-ER1).

> 'In terms of the digital twin, I'm guessing it will have used the best available information that's probably gone through the validation periods of each individual authorities [. . .] So, it's not using any new data necessarily that hasn't been validated [. . .] I suppose I just want whatever comes out for the partners, the *Living with Water* partners, to be comfortable with it so we all are singing from the same hymn sheet' (I-1-LG1).

This emphasises the importance of cross-organisational working in FRM, and in the potential use of a DT.

4.2.1 Understanding existing tools and operational needs

We noted early on that participants had difficulty in parsing our questions about use cases, functionality and interface preferences, given that they had not had the chance to interact with a working DT. How do we talk about emerging technologies, such as DTs, when they may not yet exist in their full, potential form? This causality dilemma sparked a debate around the relationship between research, innovation, and change within organisations, relating to their ongoing working practices, established staff, and institutional knowledge. FLOODTWIN's stakeholders expressed concerns around duplication of existing modelling efforts:

> 'I expressed concern as to what you're doing, [. . .] whether you were adding value to the [. . .] existing knowledge base or just duplicating something that was already in place.' (I-2-ER1).

This is a particular challenge to the research process when existing models, which are perceived to work well, are already in use professionally by stakeholders. Awareness of the complexity of existing models also made some participants cynical about the potential to represent the full hydraulic system within a DT:

> 'On the face of it, it sounds really exciting [. . .] I'd love it if it worked, but I would be lying if I said I wasn't slightly sceptical about it being a viable thing to achieve, but if it did work, it would make my life easier.' (I-3-LG2).

In workshops and interviews, participants' answers to our questions often returned to modelling, and the question of how to improve it. This reinforces the need for the 'back engine' of a DT development project (i.e., advances in modelling) are represented within its stakeholder contact activities. Within the context of our case study catchment, ongoing modelling work included the concurrent development of the LWW partnership model (focused on the city of Hull, 'a very urbanised, pipe-driven model' (I-2-ER1)) and the environmental regulator's wider catchment model of the flatlands surrounding Hull ('a much bigger model in terms of geography for the rest of the catchment going into the chalk streams' (I-2-ER1)). In addition, an environmental consultancy company had recently been awarded a circa £1 m contract to improve the River Hull model (adding to over 35 years' previous work on this):

> 'We've spent about a million pounds improving that model [. . .] that's the level of investment that we feel is necessary to produce a model [or] Digital Twin to be credible for our uses.' (I-2-ER1).

Therefore, as well as competition with existing platforms in use by stakeholder organisations, researcher-led co-creation processes may also be running in parallel with commissioned development of digital tools with contractors. Working with multi-organisational stakeholders to inform the development of an environmental DT presents significant additional challenges for researchers in comparison to either the in-house development (e.g., by a manufacturer) or commission of such a tool by a single organisation engaging external contractors. These challenges include fears around data sharing (see Section 4.2), and the level of transparency inherent in the DT development and after. This encompasses whether the DT will be widely or publicly accessible, and who will have access to it.

Stakeholders shared that their concerns for models are their accuracy, credibility, cost and reliability to run, time to run, and computing power required; with one saying of the LWW model that, 'it's not very reliable [. . .] because [. . .] the more high resolution you get in it, the more it crashes, and the longer it takes' (I-7-LG1). Our data highlights that the status of the research challenge and innovation must be balanced with current organisational practices and perceived need in the workplace. The adoption of innovative tools such as DTs in FRM requires the winning of hearts and minds, as well as more pragmatic sharing; co-design can play an important role in this process.

4.3 Co-creation process

4.3.1 Generating buy-in and maintaining enthusiasm

FLOODTWIN was a time restricted project, dictated by the wider funding scheme which supported it. A longer engagement would be required for the satisfactory completion - from a researcher perspective - of a full co-creation process. Although the process received strong buy-in from senior representatives of each stakeholder organisation, this resulted in the additional logistical difficulty of coordinating busy diaries. Future projects may wish to consider reinforcing this early organisational "buy-in" to extend to the allocation of staff time and resources to the co-creation process, which can be time consuming. Researchers' access to institutional memory and expertise in FRM is largely dictated by the availability of senior professionals to participate in a longitudinal process of co-creation and co-design. Flood Risk Management necessitates a deep understanding of place and an integrated approach to data and cross-disciplinary collaboration, an understanding of dynamic risk profiles along with the ability to reckon with significant uncertainty and make decisions based on probability of expected outcomes. However, those with the longest-lived organisational knowledge are likely to be the least accessible due to their workplace seniority and demands on their time. Nonetheless, this individual experiential knowledge and institutional memory (cf. Haughton et al., 2015), bringing together numerical hydrological modelling and local/expert knowledge, is vital in effective FRM. This lived expertise is required to interpret any digital tool, including DTs:

> 'I don't know everything, but I've been taught well by my predecessors' (I-2-ER1).

> 'I work . . . I deal with expert modellers, who support me in my lack of technical knowledge. All I've got is what I've picked up off them over the years.' (I-2-ER1).

A critical concern is how to manage SH expectations whilst also generating interest ahead of a workshop. Here some sort of prototyping is important to test and validate the usefulness of a digital tool:

> 'I would have been excited to see [an] all singing, all dancing model, just to have a play around with [. . .] But yeah, I think [it is hard to reply to the question] without something tangible to work with . . . ' (I-3-LG2).

Stakeholders' level of buy-in and time allocation to FLOODTWIN contrasted to that with LWW with strong top-down commitment to institutional participation:

> 'Because ultimately, you know, if you go into other departments saying, can you put time and resource to this partnership, if you don't have that top-down pressure, then they . . . it's quite easy for people to say no when, you know, people have got a lot of things on.' (I-3-LG2).

In complex stakeholder engagement, it is important to have multi-organisational input in workshops (requiring both enthusiasm for the work, and attendance at sessions); in our case, the second workshop was a pivotal, but restricting, moment, as it was only attended by a single organisation, despite anticipated attendance from partners from three other organisations. Although multiple colleagues attended and participated fully, this was demotivating to some project team members. Researchers with delivery deadlines can be quick to make assessments (e.g., of likely use cases) based on a limited pool of stakeholders and thus may throw a co-creation process off course.

4.3.2 Perceptions of usability

The success of a DT co-creation or co-design process will depend on participants' willingness to move beyond familiar interface norms; this applies to both participants and researchers, particularly geoinformatics specialists who may have predetermined ideas of 'what works' in such a platform that is sharing spatial data,

TABLE 3 A research planning framework for co-design of environmental digital twins in complex risk settings.

Research stage	Activities and priorities	Operational prompts to thinking
Project set up (4.1)	Defining the stakeholder group	- To what extent are you working with a pre-existing group? - What knowledge and experience does each individual bring to the co-creation process?
	Defining co-design	- Have you identified likely stakeholder needs? - Are there different attitudes to co-creation within the stakeholder group? - What prior experiences do both stakeholders and researchers have of co-design processes?
	Initial brokering of research focus and terminology	- Have you worked with the stakeholders to gather their understandings of the purpose of a DT? - Have you discussed differentiation of DTs from existing tools used in the workplace (e.g., numerical models)?
Negotiating data: availability, reliability and ease of access (4.2)	Accessing data	- Are partner organisations wary or unwilling to share data; if so, why? - Do they have concerns around IP law, data ownership, cyber security? - Have you discussed access to and use of APIs to integrate data?
Early brokering (4.3)	Defining the user and audience	- Who is the DT for, and who should be able to access it? - What level of user expertise should be required to use it? - Are stakeholders concerned about potential data manipulation by external users?
	Understanding existing tools and operational needs	- What existing tools are in operational use among your stakeholders? - How does a DT differ and/or what would it add? - What experience do the stakeholders have of working with contractors/consultants, and academic researchers? How does this impact on the co-design process?
Co-creation process (4.4)	Generating buy-in and maintaining enthusiasm	- What are stakeholder expectations from both a DT and the co-design process? - What are researcher expectations from both a DT and the co-design process?
	Perceptions of usability	- To what extent are stakeholders attached to familiar interface norms? - What level of familiarity is required to understand and operate the DT?
	Navigating outputs and project legacy	- Are you limited by a restricted research project lifecycle? - [If a DT is produced] what plans are in place for the future maintenance of the tool?

based on prior experiences of research projects and available best practice guidance (UK Government Digital Service Geospatial Commission, 2022). A stakeholder from the drainage board explained that his organisation already uses GIS systems to explain and demonstrate during inter-agency working; he appraised that this 'works pretty well' and therefore stated he had little motivation to explore alternatives. Given the increasing sophistication of numerical modelling, he expressed a wish for 'a web-based GIS with multiple layers driven by flood risk practitioners for the benefit of decision makers' (I-8-DB2). A second stakeholder from local government also mentioned a preference to use an interface familiar from existing tools:

> 'You want it to be technical enough to be useful, but you want the UI to be dumb enough that more people can use it [. . .] making it as much like ArcGIS as possible is probably the right call.' (I-5-LG2).

However, they explained that this approach could be limited by software licencing:

> 'I've been trying to make a flooding emergency management ArcGIS portal, because we just have so much spatial data, that would be so useful for emergency planning purposes and during a response, but the LRF [Local Resilience Forum] doesn't even have an ArcGIS licence, [. . .] so there are these very fundamental, very basic barriers' (I-5-LG2).

The city council are trialling the use of a commercial platform (*Connexin*) to bring together open source FRM data:

> 'I'm working on [. . .] a Smart Cities platform [. . .] where we're going to try and centralise and bring all of our flood risk management information into one screen, [. . .] it's got a map on it, and then, it'll have the rain gauge information, river level data, flood warnings, [. . .] as long as we've got the input information.' (I-7-LG1).

In these discussions around transformation versus adaptation, it is important to establish a clear need for the development of a new tool, versus the improvement of existing resources (e.g., hydrological model, GIS).

4.3.3 Navigating outputs and project legacy

Given the limited lifecycle of research project funding, it is vital to consider what a DT research demonstrator project can reasonably expect to deliver, as well as what outputs are viable, accessible and valuable for stakeholders and researchers.

Furthermore, and perhaps most importantly, the legacy of a DT is contingent upon its ongoing relevance and performance. This, in turn, is defined by the maintenance of the DT. Running a DT requires power, and ongoing hosting on a server and an important consideration is whether this is maintained beyond the scope of a research project time frame. Whilst running, the reliability of the DT is dependent upon the performance of both the software and the data driving the DT. For example, the DT itself must be robust enough to be able to cope with unusual or spurious entries or operation. Additionally, data used to drive DTs, such as river flow data in our example, is frequently in the format of API (application programming interface[9]) data where the information is collated and hosted by a different organisation and harvested/used by the DT. If the format of the API is changed, or the data is absent (no data values) or unreliable, this all has a potential impact on the performance of the DT. This would require a human intervention in the form of re-coding and/or quality checking the data. Whilst many tasks can be automated, there is a surprising amount of 'maintenance' required in upkeeping a DT, with impacts for longevity and legacy. Further, comments in 4.2 revealed concerns about methodological rigor of DT modelling frameworks, illustrating how important it is for stakeholders to have confidence in the performance and predictions of a DT.

Table 2 provides a summary of the issues and concerns raised by the professional stakeholders.

4.4 Towards a research planning framework for the initiation of DT co-creation

In this section, we propose a research planning framework (Table 3), based on our learning from the FLOODTWIN project (Sections 3 and 4). This is intended as a living document for reworking and amendment considering future work.

5 Conclusion

Our research insights are relevant for researchers pursuing the future development of DTs in collaboration with stakeholders, particularly for environmental DTs and other tools for decision making in complex risk environments. Returning to our research questions, we have evidenced that professional stakeholder voices can be foundational to the development of DTs, and that this offers opportunities to better understand user needs and contexts for decision making (Q1). The project developed a bottom-up, emergent participatory co-design process, which was able to capture a broad evidence base rooted in a diverse range of stakeholder perspectives on the development of DTs. This contrasts strongly with top-down, technology driven approaches that seem to dominate existing DT development–as evidenced by stakeholder comments surrounding the need (or not) for another model. This paper has reflected on what a good co-design process might look like both conceptually and logistically (Q2) and presented a proposed research planning framework for the set-up of co-created research on Environmental Digital Twins in complex risk settings (Q3). In so doing, the paper also illustrates ways in which sub-optimal water risk management is socially constructed, and not merely a technical challenge to be surmounted.

Based on our research, use cases for DTs are clearly still being defined within hydrology (Q4). Our exploration of some potential use cases for the DT with FRM stakeholders generated a hybridity in possibilities that could be overlaid across all phases of the DRM cycle (Figure 4). Such cross-stage explorations could be useful for individual, inter-organisational, or multi-organisation working, particularly in supporting fresh thinking, through using emergent technologies, to develop a 'spiral' towards improved resilience (Q5). Our research evidences that DTs hold the potential to help stakeholders with decision making in all phases of the DRM cycle. Specific use cases by phase include: *Preparation*–asset management, stress testing, nowcasting; *Mitigation and Prevention*–optioneering, proactive emergency planning and managing trade-offs; *Response*–emergency response, situation room; *Recovery*–communications (Q6). However, this potential hybridity also leads to challenges in defining what a DT is or could be.

Many useful provocations for research reflection arose from the stakeholder input to this project, particularly due to the intersection of different organisational cultures and priorities within FRM: most significantly, discussions around the continuum between models and DTs, and how to negotiate access to data that is owned by different organisations. It raises important questions around the development of digital tools for decision making (including DTs), for example,: who commissions digital tools, who designs them, who understands them, and can comment on their potential use and development? This involves considering different organisational cultures in the development of new technological resources, for instance organisational histories and structures that encourage the outsourcing of specialist tasks. We encourage future researchers to reflect on the role of academic input to these conversations; does a project such as FLOODTWIN *shape* the development of DTs, or *reflect* on it? It is also worth considering the ways in which the research process differs from stakeholder organisations' outsourcing of modelling and other digital development to private contractors; researchers have the 'permission' for experimentation and risk-taking, in a way consultants may not.

This paper points to a wider discussion on the challenges of engaging with emergent technologies, both for stakeholders, as well as researchers. This included defining terms and clarifying boundaries between different types of modelling. These discussions pose further questions about how critical it is to put boundaries around technology–or not. Boundaries can help with gaining practical and operational insights for the design of an interface. Yet, given the increasing hybridity in technology and the rapid pace of change, does creating such boundaries limit the possibilities offered by the technology? Is the notion of such bounding obstructive and retrograde? To conclude with one of the voices of our stakeholders:

> 'The scale of the challenges that we've got to face in response to climate change are so big that [. . .] We're not going to be able to solve them operating inside our little box and our comfort zone of what we've always done. So actually being able to try novel

9 https://www.ibm.com/think/topics/api#:~:text=An%20API%2C%20or%20application%20programming,the%20integrity%20of%20system%20security.

> things, or push people and things, is where I see the real value of [this type of project]' (I-4-ER1).

Data availability statement

The datasets presented in this article are not readily available because The data supporting this article (interview material) is not uploaded as a dataset to protect the anonymity of participants. Requests to access the datasets should be directed to LM: Lindsey.Mcewen@uwe.ac.uk.

Ethics statement

The studies involving humans were approved by University of the West of England (UWE) Bristol. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HU: Conceptualization, Data curation, Methodology, Visualization, Project administration, Formal Analysis, Investigation, Writing – review and editing, Writing – original draft. LM: Supervision, Investigation, Conceptualization, Writing – review and editing, Methodology, Funding acquisition, Writing – original draft. TC: Conceptualization, Funding acquisition, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1724250/full#supplementary-material

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