


Blueprint conceptualization for a river basin's digital twin

Debasish Pal ^{a,*}, Hannu Marttila^a, Pertti Ala-Aho^a, Eliisa Lotsari^b, Anna-Kaisa Ronkanen^c, Carlos Gonzales-Inca^d, Danny Croghan^e, Marie Korppoo^f, Maria Kämärif^f, Erik van Rooijen^b, Linnea Blåfield^d, Jari Silander^g, Aziza Baubekova^a, Joy Bhattacharjee^a, Ali Torabi Haghighi^a, Cintia Bertacchi Uvo^{f,h}, Harri Kaartinenⁱ, Mehdi Rasti^{a,j}, Björn Klöve^a and Petteri Alho^{d,i}

^a Water, Energy and Environmental Engineering Research Unit, Faculty of Technology, University of Oulu, Oulu 90570, Finland

^b Water and Environmental Engineering, Department of Built Environment, Aalto University, Aalto 00076, Finland

^c Marine and Freshwater Solutions, Finnish Environment Institute, Oulu 90014, Finland

^d Department of Geography and Geology, University of Turku, Turku 20014, Finland

^e Ecology and Genetics Research Unit, Faculty of Science, University of Oulu, Oulu 90014, Finland

^f Marine and Freshwater Solutions, Finnish Environment Institute, Helsinki 00790, Finland

^g Quality of Information, Finnish Environment Institute, Helsinki 00790, Finland

^h Water Resources Engineering, Lund University, Lund 22100, Sweden

ⁱ Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute FGI, National Land Survey of Finland, Espoo 02150, Finland

^j Centre for Wireless Communications, Faculty of Information Technology and Electrical Engineering, University of Oulu, Oulu 90570, Finland

*Corresponding author. E-mail: debasish.pal@oulu.fi; bestdebasish@gmail.com

 DP, 0000-0002-4851-1841

ABSTRACT

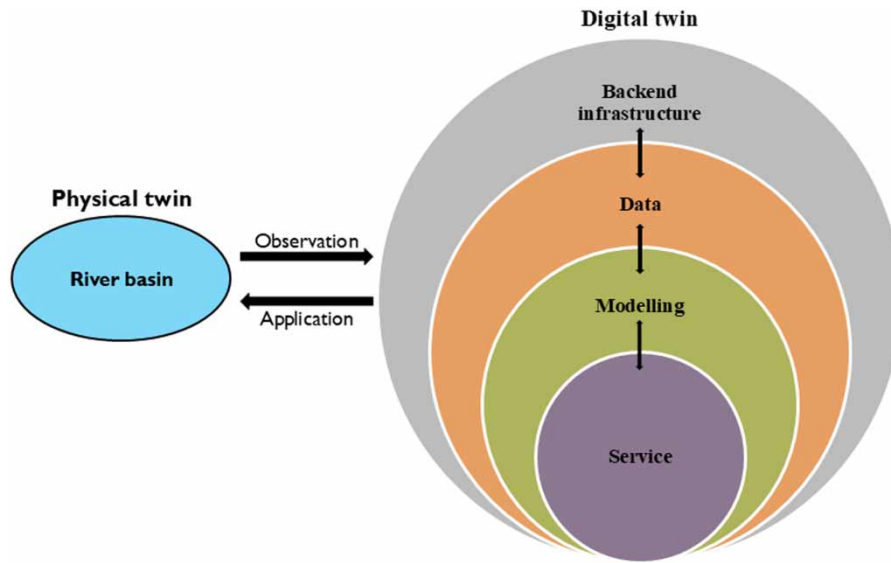
To achieve a good ecological status of water resources, we are exploring new frontiers by envisioning river basin planning through the newly promoted digital twin perspective. In river basin management, a digital twin is an innovative virtual paradigm – a holistic living replica of the river basin achieved by seamless integration of real-time monitoring, historical observations, data analytics, predictive modeling, and high-performance computing within a framework of interoperable software and scalable hardware – leveraging nuanced understanding of complex environmental, social, and economic interactions, discerning uncertainties, and bridging critical knowledge gaps for progressive improvement in system understanding, optimization of operational efficiency, and continuous advancements in decision-making. This perspective paper lays the groundwork in transforming the futuristic vision of a river basin's digital twin into reality. The proposed blueprint outlines the processes for integrating digital twin components, creating dynamic replicas of river basin systems, and conducting virtual what-if analyses. Aligning with digital transformation, this work segments the river basin into distinct systems to effectively manage diverse objectives and ensure adaptability across various river basin types with spatiotemporal scalability. Supporting sustainable management, the digital twin holds immense potential to surpass existing decision-support systems through continuous bi-directional feedback loops with the river basin.

Key words: data management, decision-making, digital twin, hybrid modeling, river basin management

HIGHLIGHTS

- Present a six-dimensional structural framework of the foundation of digital twins.
- Propose a comprehensive approach for deploying digital twins.
- Introduce various maturity levels of digital twins.
- Explain the application of digital twins in river basin planning.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Digitalization plays a key role in achieving the United Nations Sustainable Development Goals and moving toward a future resilient society (Mondejar *et al.* 2021; Arnell *et al.* 2023). Ongoing digital transformation anticipates previously unseen opportunities in water resource recovery, land management, food security, and energy production (Bauer *et al.* 2021). The rapid development of new measurement technologies such as satellite observations, unmanned aerial vehicles, point cloud, and high-frequency sensors, as well as analytical methods like artificial intelligence, big data analytics, and high-performance computing, has resulted in an inevitable trend of connecting the physical and virtual worlds through advanced digital tools like digital twins (Botín-Sanabria *et al.* 2022). The term digital twin initially appeared within the conceptual paradigm of product lifecycle management (Grieves 2014). In the current landscape, the pervasive influence of digitalization is transforming industries, resulting in the rapid rise of digital twin popularity driven by advancements in modern digitalization (Tao & Qi 2019). However, this surge in popularity has introduced challenges to achieving a consensus on digital twin definitions, as researchers often tailor their definitions based on their unique perspectives and fields of research (Singh *et al.* 2021). Despite the diversity in definitions, a shared understanding exists that a digital twin accurately mirrors the real-time state of its physical counterpart, and vice-versa, achieved through continuous bi-directional interactions and co-evolution (Qi *et al.* 2021). The application of digital twin technology in industrial production spans various aspects, including system design, enhancement of operational efficiencies, cost-effective asset management, mitigation of hazard risks, and implementation of control measures (Khallaf *et al.* 2022). Furthermore, the scope of the digital twin is expanding to represent the complexity of the human biological system, aiming to enhance life quality and well-being (El Saddik 2018). Beyond industrial and biological domains, the digital twin application to the natural environment, combining physics-based knowledge with data-driven insights, holds immense potential to address significant environmental challenges such as water quality deterioration, extreme hydrological events, geomorphological alteration, landscape instability, and biodiversity loss (Blair 2021).

Climate change, rising population, and economic expansion have intensified pressures on global river basins (Khedun *et al.* 2014), resulting in adverse effects on water resources, land-use, biodiversity, ecosystem services, and socioeconomic well-being (Mancosu *et al.* 2015; Swetapadma & Ojha 2017). This necessitates enhancements in environmental, social, economic, and political considerations within river basins (Wada *et al.* 2016), prompting a call for more responsive and holistic management approaches (Marttila *et al.* 2022). In response to a holistic perspective, the digital twin emerges as a transformative tool, serving as a comprehensive virtual replica of the river basin. Achieved through seamless integration of data analytics and predictive modeling in a scalable backend infrastructure, it leverages nuanced understanding of dynamic systems within the river basin to optimize operational efficiency and decision-making. The digital twin adeptly monitors human-induced

environmental changes, establishes correlations between natural resource consumption and socioeconomic factors, and forecasts the future evolution of river basins, enabling early adaptation strategies and comprehensive river basin management. Notably, it addresses challenges inherent in traditional river basin management, including irregular data collection, reliance on outdated information, limited stakeholder engagement, and a constrained understanding of system dynamics. Additionally, while river basin scale models provide a generic understanding of the physical counterpart and require new data for predictions, a digital twin can function as a self-evolving virtual tool, accurately predicting the physical river basin at any given time through data monitoring and dynamic simulations. The digital twin represents a paradigm shift toward more effective and adaptive river basin management in the face of complex and evolving environmental, social, and economic challenges.

In recent years, the rapid deployment of digital twins across various sectors, such as aerospace, automobile, manufacturing, healthcare, and construction, has been well documented (Rasheed *et al.* 2020). Concurrently, a significant surge in interest among researchers has emerged regarding the application of digital twins in urban water distribution (Alzamora *et al.* 2021; Pedersen *et al.* 2021; Valverde-Pérez *et al.* 2021). Furthermore, a limited number of studies have directed their focus toward the deployment of digital twins in areas critical for water resources planning and management. Notably, these areas include terrestrial water cycle (Brocca *et al.* 2024), water resource recovery facility (Torfs *et al.* 2022), drainage system (Bartos & Kerkez 2021), flood risk mitigation (Tarpanelli *et al.* 2023), hydrological systems (Rigon *et al.* 2022), wastewater treatment (Johnson *et al.* 2021), land management (Park *et al.* 2023), land-use (Akroyd *et al.* 2022), dam operation (Park & You 2023), and nature-based solutions (Pillai *et al.* 2022). These examples highlight the observation that existing digital twin concepts and applications in water resources planning are often compartmentalized into subfields rather than approached with a unified perspective, especially in the context of a complex river basin system. Based on a recent study (Wenzheng 2022), the adoption of a digital twin for river basin management is recommended as a forward-thinking strategy. Our current understanding indicates a discernible gap in the conceptualization of a blueprint tailored specifically for a river basin's digital twin. Addressing this gap necessitates prioritizing a visionary framework over exhaustive technical intricacies. This strategic approach aids in understanding the fundamental aspects of a river basin's digital twin, encompassing its purpose, functionality, components, design principles, uncertainty handling, and potential applications. Moreover, it serves as a foundational point for stakeholders to initiate more detailed planning and development initiatives toward the implementation of the digital twin for a river basin.

A seminal paper published in the late 1960s, at the dawn of computer technology availability, proposed a blueprint for developing a physics-based hydrologic response model through digital simulations (Freeze & Harlan 1969). To date, numerous hydrological modeling schemes have put their visionary ideas into action (Simmons *et al.* 2020). In this paper, we take a similar leap of faith by providing a blueprint for a river basin's digital twin. We strive to provide an in-depth understanding of the methodology involved in creating the river basin's digital twin. The methodology begins by describing the conceptualization of a river basin's digital twin, outlining the fundamental principles and vision behind this innovative approach. Following this, the structural framework is presented, establishing the foundational architecture that supports the digital twin. The methodology then delves into the design implementation, detailing how the structural framework and its components are realized to ensure functionality and scalability. Subsequently, we address data measurement and modeling simulations, which constitute the core operational elements of the digital twin, driving its analytical and predictive capabilities. The decision-making workflow highlights the processes by which the digital twin supports stakeholders in managing the river basin. The methodology also explores the maturity spectrum, showcasing the progressive development stages of the digital twin, and how it evolves to achieve higher levels of integration and sophistication. Furthermore, we discuss approaches for overcoming challenges encountered during development and deployment, as well as the potential applications of the digital twin, demonstrating its versatility in addressing critical issues in river basin management.

2. METHODOLOGY

2.1. Conceptualization

A digital twin of a river basin has the potential to serve as a dynamic and holistic virtual counterpart, forming a robust and evolving basis for informed river basin management. The core objectives of the digital twin include optimizing operational efficiency, identifying uncertainties, bridging crucial knowledge gaps, and perpetually advancing decision-making processes within the river basin. Functioning within a framework of interoperable software and scalable hardware, the digital twin

seamlessly integrates real-time monitoring, historical observations, data analytics, and predictive modeling. This integration leverages a nuanced understanding of the intricate environmental, social, and economic interactions occurring within the river basin. The observation and application of the digital twin on the river basin is an ongoing process, facilitated by a structural framework involving backend infrastructure, data, modeling, services, and connection components.

The ownership and governance of a river basin's digital twin involve multiple stakeholders, including river basin authorities, governmental bodies, regional administrations, industry representatives, academic institutions, policymakers, funding bodies, non-governmental organizations, and local communities. These stakeholders have diverse interests, leading to a wide range of objectives, such as flood risk management, water supply optimization, agricultural productivity, environmental conservation, and economic development. A robust governance framework must balance these varied interests while ensuring fairness, transparency, and accountability. This could be achieved through a hybrid governance model that integrates a centralized administrative body – tasked with mediating stakeholder interests, defining shared objectives, and implementing standardized rules – with a distributed ownership framework that allocates responsibilities to stakeholders based on their expertise in the digital twin's development and maintenance, while preventing exclusive claims over any specific part of it. Clear protocols for collaboration and conflict resolution would further support this hybrid governance model.

The sustainability and effective implementation of the digital twin depend on stakeholders' funding commitment, resource allocation, regular communication, data-sharing agreements, and well-defined responsibilities. Data standardization, reliability, and provision are critical components, overseen by the centralized administrative body in collaboration with technical experts and stakeholders. Decisions regarding the accuracy, timeliness, and frequency of data collection must align with the digital twin's objectives – be it real-time applications for flood prediction, periodic updates for infrastructure planning, or long-term trend analysis for climate adaptation. Evolutions of the river basin are simulated using integrated modeling approaches, including structural, data-driven, and physics-based methods, combined with real-time and historical data. Clear guidelines outlining data collection, modeling techniques, system validation, and information-sharing protocols, supported by periodic reviews involving all stakeholders, further enhance collaboration. Regular engagement sessions and updates foster alignment of expectations and ensure that the digital twin remains responsive to emerging challenges in river basin management.

Both digital twins and decision-support systems serve important roles in river basin management (Blair 2021). A decision-support system, which provides analytical capabilities for simulating specific outputs and aiding decision-making across various river basins, can also be considered a component of a digital twin. However, a digital twin surpasses the scope of a decision-support system by integrating bi-directional communication and offering the flexibility to dynamically adapt its objectives to evolving conditions within a specific river basin. Unlike decision-support systems, which typically operate within a fixed framework and focus primarily on uncertainties that can be reduced using techniques like data assimilation (Alfieri *et al.* 2022), digital twins handle a broader range of uncertainties. By continuously integrating real-time data, digital twins not only address reducible uncertainties but also adapt to irreducible and critical uncertainties arising from natural variability or factors that significantly influence decision-making. Digital twins achieve this dynamic adaptation through continuous feedback, pattern recognition, and advanced modeling techniques such as stochastic prediction, scenario simulation, and ensemble modeling. These capabilities enable digital twins to iteratively refine their underlying frameworks, ensuring greater predictive accuracy and operational relevance. Furthermore, digital twins incorporate multidisciplinary hybrid modeling, where data-driven insights complement untheorized gaps in physics-based simulations, effectively overcoming limitations often encountered in single-discipline decision-support system implementations. By combining advanced modeling techniques, robust infrastructure, stakeholder collaboration, and dynamic adaptability, a digital twin emerges as a comprehensive tool for river basin management, representing a transformative evolution in decision-making frameworks. The digital twin can further help attain a sustainable future and meet the United Nations Sustainable Development Goals by supporting policy analysis, risk assessment, and mitigation strategies (Favre *et al.* 2017).

2.2. Structural framework

To create the river basin's digital twin, we propose a six-dimensional structural framework. The dimensions are physical river basin, backend infrastructure, data, modeling, service, and connectivity. The backend infrastructure serves as the backbone of the digital twin, supporting data storage, model simulation, and decision-making services for stakeholders. Data is the essential fuel of the digital twin, providing the raw input needed to monitor river basin dynamics. Modeling acts as the driver of the

digital twin, using data to simulate future scenarios within the river basin. Service represents the tangible outcomes of the digital twin, delivering predictions and actionable information to stakeholders. Finally, connectivity ensures seamless integration among all dimensions, enabling efficient communication and coordination within the digital twin. A conceptual representation of the dimension relationships and their dominant features is shown in Figure 1.

The creation of a digital twin is imperative for the river basin dimension, which is a physical system characterized by complex interactions between natural resources, environmental phenomena, and socioeconomic functions. Climate conditions, water, geodiversity, land cover, and biodiversity are examples of natural resources, whereas environmental phenomena emerge from hydrological, morphological, and biogeochemical functions. Socioeconomic functions such as urbanization, agriculture, and industrialization, are the primary causes of natural resource depletion and environmental degradation, having a direct impact on stakeholder concerns like water quality, soil fertility, and natural hazard risk mitigation. The real-world dynamics of the physical river basin and its continuous management are mirrored in virtual representations, supported by the backend infrastructure, data, modeling, service, and connectivity dimensions.

The backend infrastructure dimension encompasses instrumentation, storage, computational scalability, and Internet of Things, ensuring the seamless operation of the digital twin. The instrumentation of the digital twin, driven by remote and direct sensing devices, produces substantial volumes of climatological, environmental, and socioeconomic data. This data is stored either in strategically positioned edge servers near the data source within local networks or cloud storage platforms, based on the preference for decentralized or centralized data storage. Proprietary data is managed through a hierarchical access control system overseen by the administrative body in collaboration with key stakeholders. Access levels, defined by stakeholder roles such as researchers, policymakers, and operational managers, are secured by encrypted transmission protocols to ensure privacy and compliance with regulatory frameworks. Data security and traceability are further strengthened through regular audits and access log monitoring. To simulate models at the river basin scale, computational scalability can be addressed through the application of edge, grid, and cluster computing techniques, each catering to specific needs.

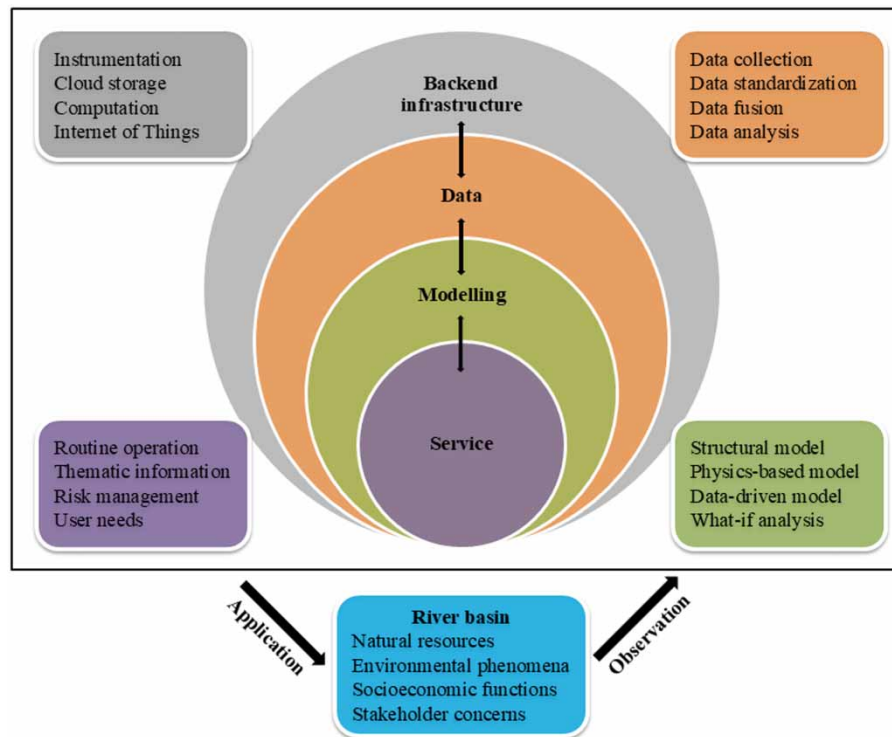


Figure 1 | A graphical abstract illustrating the six-dimensional framework of the digital twin concept applied to a river basin. The dimensions include the river basin, backend infrastructure, data, modeling, service, and connectivity. The dominant features of each dimension are represented by corresponding colored rectangular shapes. Arrows depict one-directional connectivity between the river basin and the four hierarchical dimensions – backend infrastructure, data, modeling, and service – which are also interlinked through bi-directional relationships.

Edge computing processes data close to its source, reducing latency and enhancing response times. Grid computing employs distributed networks for parallel processing of large-scale simulations. Cluster computing integrates tightly coupled systems to deliver high-performance computational capabilities. Modern communication technologies, such as Internet of Things, enhance system connectivity, while robust encryption and cybersecurity protocols mitigate risks, ensuring secure and reliable operations across all dimensions.

The data dimension manages all aspects of data flow, including collection, standardization, fusion, and analysis. Continuous collection from various spatial and temporal scales across climate, water, land, social, and economic domains is done from the instrumentation of the backend infrastructure dimension. Heterogeneous data from diverse sources is standardized to ensure interoperability, including consistent formats, harmonized metadata, error correction, gap-filling, and reliability checks. The administrative body, in collaboration with stakeholders, approves consensus on data standardization practices. This is achieved through workshops, discussions, and conflict-resolution mechanisms, emphasizing the shared benefits of improved data interoperability. Privacy-preserving techniques, such as anonymization and encryption, balance accessibility and confidentiality, while collaboratively developed data-sharing policies define access conditions, licensing agreements, and sharing protocols in line with legal and regulatory requirements. Data quality is continuously monitored by technical experts, with periodic stakeholder reviews to address emerging challenges. The data dimension ensures that data remains high-quality, accessible, compliant, private, and secure. Data fusion integrates heterogeneous datasets, enhancing the value of individual datasets and synthesizing complementary information to provide a holistic view of the river basin system. Analysis of standardized and unified data supports comprehensive assessments of river basin dynamics, identifying hydro-morphological and anthropogenic pressures that contribute to natural resource depletion and environmental degradation, thereby facilitating informed decision-making.

The modeling dimension endeavors to project the evolution of river basins across diverse temporal scales while preserving local-level phenomena through a modular and hierarchical framework. This framework accommodates the diverse objectives of the digital twin by segmenting models into self-contained units integrated into a shared ecosystem, ensuring alignment with broader goals. Each model is developed with a clearly defined purpose to address specific river basin objectives. A model management committee, composed of scientists, policymakers, and technical experts, oversees the interoperability, updates, and calibration of models to maintain consistency in outputs, support emerging modeling needs, and enable cohesive operation. The modeling dimension employs a synergy of structural, physics-based, data-driven, and what-if approaches to simulate river basin dynamics. Structural modeling captures the geometric and static features of the river basin, including infrastructure such as dams, reservoirs, and levees, and helps in understanding how physical elements of the river basin interact with natural processes. Physics-based modeling represents environmental processes, including hydrological flow, stream hydrodynamics, soil erosion, and sediment transport, based on scientific principles. Data-driven modeling complements these approaches by identifying patterns in environmental stochasticity, such as precipitation variations and evapotranspiration, alongside socioeconomic factors, including crop production and water contamination. Continuous calibration and validation ensure the accuracy and relevance of models, considering key factors such as parameter complexity, data variability, computational cost, and model performance metrics. What-if analyses are conducted using loosely and tightly coupled models, enabling stakeholders to explore strategies that optimize resource use, environmental sustainability, and socioeconomic growth without affecting the physical river basin. Emerging hybrid modeling techniques, combining the interpretability of physics-based models with the efficiency of data-driven approaches, enhance the modeling dimension's ability to generate actionable insights for river basin management.

The service dimension contributes to routine operations, thematic information, and risk management within the river basin, while also addressing user needs. The data analysis and model simulations of the digital twin calculate the river basin's parameters, assisting stakeholders in deciding routine operations. This dimension further supports regional authorities in implementing proactive measures to uphold the environmental standards of the river basin. By providing thematic information in disciplines such as hydrology, geomorphology, and biogeochemistry, the service dimension empowers administrators to take strategic actions. Moreover, risk management is facilitated by assessing the impact of optimal management strategies on potential future risks, which are evaluated through the what-if analyses in the modeling dimension, ensuring the sustainability of the river basin. User needs, including data accessibility, interactive analysis, remote simulation, and application programming interfaces, are comprehensively addressed within this dimension. The application programming interfaces, in particular, enable stakeholders to develop interoperable applications for hindcasting, nowcasting, and forecasting diverse river basin scenarios, fostering innovation and adaptability in management practices.

The connectivity dimension promotes collaboration among the other dimensions. The connectivity between the river basin and the four dimensions represents an iterative process that begins by accounting for the current state of the river basin and ends with strategic actions for plausible vulnerability in the river basin. Among the four dimensions, the backend infrastructure underpins data, modeling, and service, reflecting a hierarchical yet bi-directional connectivity. The service dimension receives outputs from the data and modeling dimensions, which in turn rely on the backend infrastructure. New services requested by stakeholders necessitate changes in the modeling, data, and backend infrastructure dimensions. The expansion of the backend infrastructure depends on data volume, computational scalability, and increased stakeholder services. The processes in the data, modeling, and service dimensions are managed within the backend infrastructure, ensuring seamless integration and efficient operation of the digital twin as it interacts with the physical river basin.

2.3. Design implementation

This section outlines the design and implementation process for a river basin's digital twin, structured according to the hierarchical framework proposed for smart manufacturing digital twins (Tao *et al.* 2019). To facilitate understanding, a schematic illustration is provided in Figure 2, offering a visual aid to better understand the intricacies of the design implementation. The implementation unfolds through three progressive phases: Unit, System, and System of Systems (SoS). At the System of Systems (SoS) phase, the river basin is viewed as an interconnected network of multiple systems, including climatological, hydrological, fluvial, geomorphological, infrastructural, environmental, social, economic, and governance systems. However, the administrative body, in collaboration with stakeholders, retains the flexibility to further classify these systems based on the specific goals of the digital twin. The progression through the Unit, System, and SoS phases represents increasing levels of complexity and integration: mild, moderate, and intense, respectively. Each phase addresses different decision-making aspects. The Unit phase focuses on localized, routine decisions, such as daily water usage or flood management. The System phase addresses more integrated decisions, such as resource allocation across the hydrological system. The SoS phase oversees overarching decisions for the entire river basin, integrating multiple systems into a cohesive framework. Each of these phases also aligns with distinct types of uncertainty. The Unit phase primarily deals with reducible uncertainties, such as real-time water flow data, which can be improved through data assimilation. The System phase addresses irreducible uncertainties, such as rainfall pattern variability that cannot be fully predicted. In contrast, the SoS phase tackles critical uncertainties, such as social or political factors that significantly affect long-term planning for the river basin. These

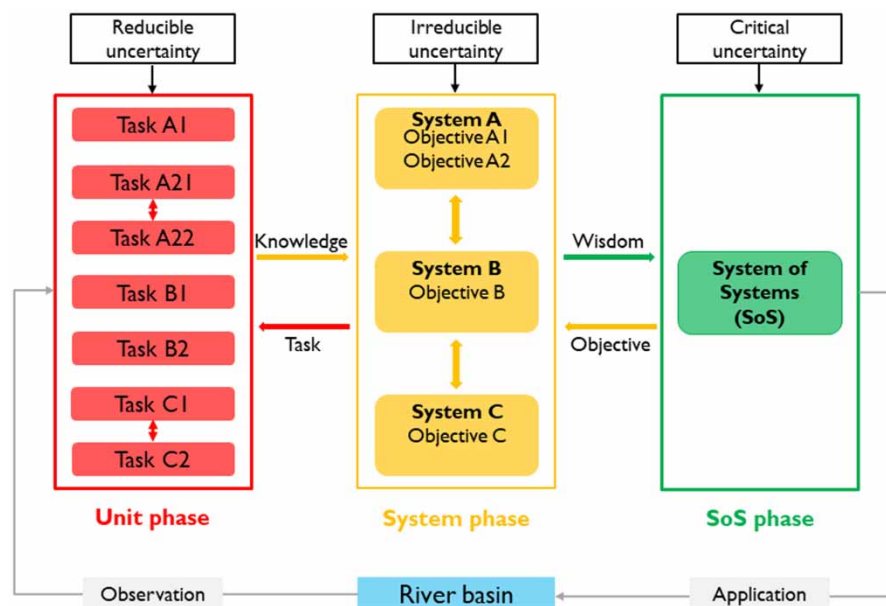


Figure 2 | A schematic representation of the river basin's digital twin design implementation, which progresses through three phases: Unit, System, and System of Systems (SoS). Unit phase tasks A21 and A22 correspond to System phase objective A2, tasks B1 and B2 correspond to System phase objective B, and so on. The Unit, System, and SoS phases mitigate reducible, irreducible, and critical uncertainties, respectively. Red, yellow, and green colors denote mild, moderate, and intense progress in the digital twin implementation.

uncertainties are managed using different modeling techniques and stakeholder interactions, ensuring well-informed short-term operational decisions and long-term strategic planning.

Although the implementation of the digital twin follows three progressive phases – Unit, System, and SoS – the planning process begins in reverse, starting with the long-term sustainable goals of the SoS phase. These goals must align with the diverse interests of stakeholders, including water resources planning, resilient ecosystem services, and sustainable socio-economic conditions. To ensure effective communication among stakeholders, the administrative body adopts standardized technical and scientific terminology, facilitating clarity and minimizing ambiguities during discussions. Guided by stakeholders' concerns, perspectives, and expertise, the digital twin management team – including scientists, engineers, policymakers, and river basin managers – systematically categorizes the goals identified at the SoS phase into actionable objectives for the System phase. These objectives must address key issues, establish a clear decision-making framework, and align with expected outcomes. Stakeholder approval ensures that the objectives reflect shared priorities and are feasible within the available resources and constraints. Each System phase objective undergoes further subdivision into specific Unit phase tasks, enabling measurable achievement within a predefined timeframe. For instance, within the environmental system objective of water quality improvement, a specific task might involve achieving a 20% reduction in nutrient levels within a year.

After the planning phase, the administrative body shifts focus to executing Unit phase tasks by addressing critical factors such as budget allocation, expert team formation, and regulatory compliance. The expert team adopts a systematic approach to the assigned tasks, encompassing the monitoring of features, development of data collection strategies, selection of appropriate modeling techniques, adoption of standardized data formats, assessment of cybersecurity threats, identification of decision variables, and anticipation of potential challenges. Upon finalizing these aspects, strategic deployment of devices and sensors ensures continuous data monitoring. Model simulations are conducted using test data, followed by calibration with real-time data, while accounting for reducible uncertainties such as data gaps and parameter sensitivity. Unit phase tasks play a crucial role in extracting scientific knowledge, encompassing both quantitative and qualitative aspects, from the river basin information. This knowledge serves as input for the System phase implementation. Throughout this process, technical interoperability is prioritized to facilitate seamless cross-platform integration across all implementation phases.

Depending on specific requirements, each Unit phase task within the System phase objective can be executed independently or integrated with other tasks, utilizing loose or tight coupling techniques. Ensuring precise coupling requires validating the simulated outcomes of the coupled Unit phase tasks against benchmark scenarios specific to the river basin processes. After validating all Unit phase tasks, each System phase objective undergoes a comprehensive analysis to identify existing pressures and discern their driving forces. Leveraging these driving forces and pressures, each System phase objective conducts what-if scenarios to account for irreducible uncertainties inherent in river basin processes. For example, this involves evaluating the dynamics of surface water-groundwater interactions in the hydrological system while considering inherent variations in precipitation. System phase objectives interact with one another, and the collective wisdom from these interactions serves as input for the SoS phase.

The SoS phase involves coupling System phase objectives, undergoing validation against benchmark scenarios tailored to the river basin. The SoS phase enhances the understanding of the interdependencies and trade-offs between System phase objectives. This holistic perspective enables a comprehensive grasp of the river basin's current state and anticipated future impact. To address future impacts, the SoS phase conducts what-if scenarios for risk mitigation planning, considering critical uncertainties such as the impact of climate change on precipitation patterns. The SoS phase engages in multi-criteria decision-making, considering Unit phase knowledge, System phase wisdom, and optimal solutions derived from SoS phase what-if scenarios. This process aids in making synergized decisions for routine operation measures and long-term strategic actions for restoration management in the river basin. The implementation of the digital twin reaches its conclusion when the SoS phase is connected to the river basin, enabling the application of actionable decision-making derived from the digital twin. Following the execution of these measures and actions, evolving conditions within the river basin may necessitate revisions to the Unit, System, and SoS phases. Such changes could lead to the introduction of new goals, objectives, and tasks tailored to address the updated river basin dynamics. The flexible design framework of the digital twin can integrate these revisions, facilitating the inclusion of new technologies and modeling features. For instance, advanced hydrological sensors integrated with machine learning models can be incorporated into the Unit phase, significantly improving the accuracy and efficiency of data collection and analysis. Similarly, the System phase can integrate advanced water resource management practices, while the SoS phase can include new governance models or innovative restoration strategies informed by

multidisciplinary research. This flexibility ensures that the digital twin remains a forward-looking tool, capable of addressing both current challenges and future demands, while consistently refining its predictive accuracy and operational relevance.

2.4. Data measurement and model simulations

Modern data instrumentation monitors terrain and environment data in the river basin at high spatiotemporal resolutions. Remote sensing techniques, including Aerial Photogrammetry, Synthetic Aperture Radar, Light Detection and Ranging, Moderate Resolution Imaging Spectroradiometer, and Passive Microwave Radiometry, facilitates the mapping of topography (Okolie & Smit 2022), land cover classification (Teo & Wu 2017), and snow cover (Xue *et al.* 2019), as well as surface water storage in rivers, wetlands, and lakes (Papa & Frappart 2021). To capture three-dimensional water flow velocity, sediment transport, and hydro-morphological changes, various methods are employed, including the Acoustic Doppler Velocimeter and video frames from close-range time-lapse cameras or drones (Eltner *et al.* 2021; Lotsari *et al.* 2022). Water quality is represented through several parameters that are measured using remote sensing and in-situ measurements (O'Grady *et al.* 2021). Some water quality parameters, such as nitrogen, phosphorus, and chemical oxygen demand, can be used as proxies to assess socioeconomic activities such as crop production and industrial development (Duan *et al.* 2022). Other socioeconomic indicators, such as population density and average monthly income, are available from national organizations concerned with social welfare and economic affairs (Malik & Bhat 2014). The operational efficiency of the digital twin relies on flexible data collection frequencies. For instance, streamflow velocity and water quality are monitored at high frequencies such as every second, minute, hour, or day, while wildlife habitat, crop production, and employment rates are tracked less frequently, such as monthly, quarterly, or yearly. Spatial resolutions are similarly tailored to monitoring needs: 1–5 meters for topography, 10–50 meters for land cover classes, 100–500 meters for average meteorological variables, and 1,000–10,000 meters for population density and economic activities. This adaptive approach ensures optimal data granularity, aligning with diverse monitoring objectives. To address potential challenges of over data collection, the centralized body implements a hierarchical data prioritization mechanism guided by stakeholder requirements in the data collection framework of the digital twin. Data relevance, frequency of updates, and operational objectives are key determinants of prioritization. High-priority data, such as real-time streamflow and water quality, are monitored with finer granularity and greater frequency, while low-priority data are collected less often or at coarser resolutions. Advanced data compression and storage techniques optimize the management of large datasets, while redundant or less informative data is either filtered out or archived for potential future use. These measures ensure efficient system performance, cost-effectiveness, and alignment with the operational objectives of the digital twin.

In the digital twin, diverse models, such as hydrological, hydrodynamic, land management, ecosystem service, social, and economic models, are employed to predict and forecast the river basin status. These models can be broadly categorized as structural, physics-based mechanistic, and data-driven machine learning approaches. Structural models assess the impact of physical infrastructure – such as dams, levees, reservoirs, and bridges – on river basin dynamics, including water flow, sediment transport, and land erosion. Mechanistic models translate hydrological, morphological, and biogeochemical processes into mathematical equations, offering interpretability and the ability to extrapolate values across spatiotemporal scales (Kuffour *et al.* 2020). However, they often involve high computational costs and struggle to predict phenomena not adequately captured by their predefined mathematical formulations. Machine learning models, by contrast, excel at uncovering stochastic relationships between environmental variables and socioeconomic functions, effectively handling large datasets with lower computational costs (Carozza & Boudreault 2021). Despite their efficiency and ability to identify unknown patterns, machine learning models lack interpretability and are constrained by the boundaries of their training data, limiting their extrapolation capabilities. Given that a digital twin serves as a comprehensive platform for data integration and multidisciplinary modeling, hybrid modeling holds significant potential as a promising approach, combining the strengths of both mechanistic and machine learning models. By leveraging the interpretability of mechanistic models and the pattern recognition capabilities of machine learning models, hybrid models improve prediction accuracy, interpretability, and extrapolation potential (Gonzales-Inca *et al.* 2022). Recent studies in river basin management have demonstrated that hybrid models can outperform traditional physics-based and data-driven approaches (Kumar *et al.* 2024; Li *et al.* 2024). While traditional approaches retain significant value, hybrid modeling represents the future of river basin management. With advances in machine learning techniques and high-performance computing, hybrid models are uniquely positioned to address complex challenges within a digital twin, offering enhanced predictive accuracy and decision-making capabilities.

2.5. Decision-making workflow

In Figure 3, we present the decision-making workflow for the river basin’s digital twin. The initial step involves collecting data from the river basin, which is processed by embedded data analysis algorithms into a predetermined format approved by the administrative body before being stored in the database. The processed data is then utilized by the digital twin for data fusion and model simulations. The outcomes of data fusion, model simulations, and calibrated parameters are stored in the database, enabling revisitation of historical conditions as needed. Leveraging these capabilities, the digital twin can nowcast environmental phenomena and socioeconomic activities, integrating past river basin conditions. The accuracy of nowcasting and overall prediction reliability is assessed by comparing nowcasted results with actual events. The more accurate the digital twin projections, the more valuable they become for decision-making regarding routine operational measures such as sectoral water distribution and flood control. The domain expert team among the stakeholders is notified of newly generated data and nowcasted events through the digital twin’s user interface. This interface ensures secure and transparent sharing of information while safeguarding sensitive data. The domain expert team is responsible for interpreting and applying this information in various areas, including policy planning, law enforcement, and short-term restoration measures. Established protocols govern data access and utilization, fostering collaborative decision-making among stakeholders.

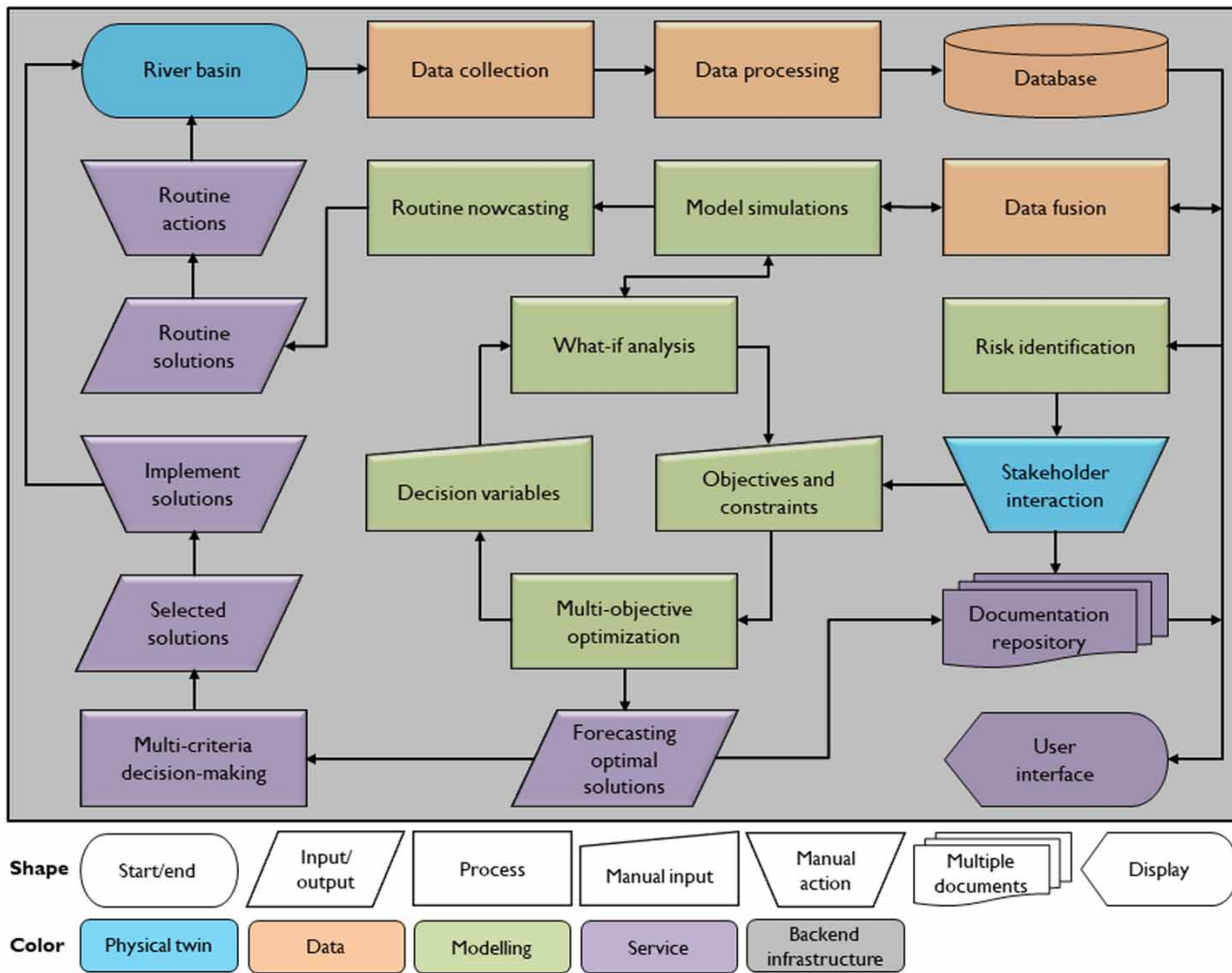


Figure 3 | An illustrative representation of the decision-making workflow within the digital twin to support river basin management. The color legends highlight the sequence of processes and their interdependencies, aligning with the backend infrastructure, data, modeling, and service dimensions outlined in Figure 1.

Beyond nowcasting, the digital twin can estimate future risks through a combination of structural alteration, data-driven pattern, and physics-based interpretation. Examples of risks include water contamination, soil fertility deterioration, ecosystem service degradation, and hydrological extreme events. While data-driven models leverage historical and real-time data for pattern recognition, physics-based models estimate risks by simulating system behavior under given conditions. Both approaches are integral to the digital twin, ensuring robust risk estimation when used with accurate inputs. By communicating the underlying causes of risks, the digital twin can assist stakeholders in risk mitigation planning. The domain expert team define objectives, decision variables, and constraints in planning exercises. This information enables the digital twin to employ what-if analysis and multi-objective optimization to forecast optimal solutions in the virtual river basin without affecting the physical river basin. The multi-criteria decision-making system, which combines quantitative metrics and stakeholder-defined priorities, aids in evaluating trade-offs among competing objectives such as cost, environmental sustainability, and reliability. This ensures stakeholders are equipped to select the most suitable solutions for the river basin.

While the digital twin is vital in recommending optimal solutions, it is imperative to highlight, especially at the initial stage of its operation, that manual cross-verification is a prerequisite before implementing optimal solutions in the physical river basin. Relying solely on the digital twin's recommendations without manual cross-checking poses potential risks until the digital twin attains a satisfactory level of prediction accuracy over time. Once optimal solutions for risk mitigation are finalized, the domain expert team oversees their implementation in the river basin. The digital twin is then employed to monitor the performance of these solutions using key indicators such as the comparison of projected versus actual outcomes, adherence to project timelines, consistent performance under varying conditions, adaptability to stressors, and efficient resource utilization relative to benefits. If the performance is deemed unsatisfactory, the digital twin facilitates revisions to the implementation plan to achieve the desired outcomes. Its documentation repository serves as a centralized storage space for revisiting prior optimization approaches to tackle historical river basin conditions. This repository provides valuable scientific insights for designing future planning measures and ensuring sustainable management practices.

2.6. Maturity spectrum of digital twin

We present a five-level maturity spectrum for the digital twin of a river basin, drawing on prior research (Evans *et al.* 2019). In Figure 4, each maturity level is represented as a digital twin, progressing through fact, question, intuition, exploration, and self-governance in the what-if simulations. This sequential advancement aims to enhance stakeholders' decision-making capabilities. However, the increasing complexity arises from additional technical integration within the digital twin's five core components – backend infrastructure, data, modeling, service, and connectivity – designed to mirror the physical river basin. This complexity grows exponentially due to heightened randomness in environmental, social, and economic variables, uncertainties, variations in input data, and incomplete information on various factors.

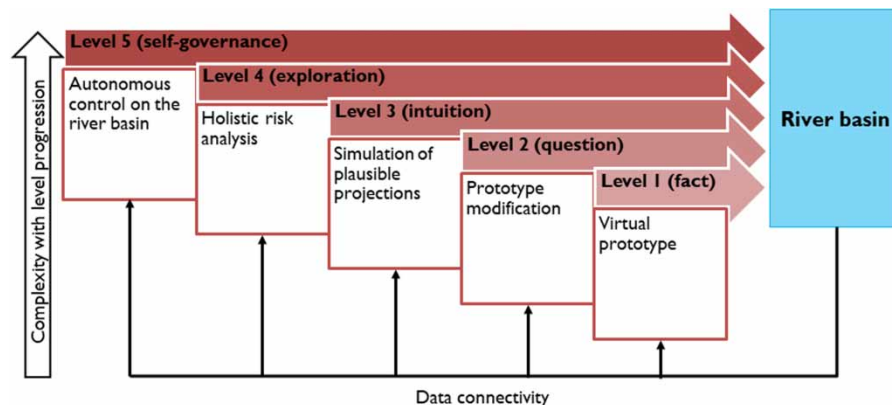


Figure 4 | A schematic representation illustrating the progression of the digital twin's maturity level. Each level encompasses all lower levels. The complexity associated with additional technical integration in the digital twin's five core components – backend infrastructure, data, modeling, service, and connectivity – exponentially increases with each advancing level.

Level 1 represents the foundational digital twin, constructing a virtual prototype of the river basin through real-time data connectivity. Historical events validate this level, empowering stakeholders to identify potential threats and craft risk mitigation plans based on the existing conditions of the river basin. Progressing to level 2 marks the initiation of prototype modification, allowing stakeholders to virtually question the river basin's adaptability to specific future events. Level 3 introduces multi-dimensional flexible simulations with diverse intuitive projections of the river basin's future state, empowering stakeholders to access previously untapped knowledge for effective risk management. Level 4 explores a comprehensive analysis to minimize unknown risks while contributing to robust optimization, aiming to maximize stakeholder benefits and fortify the river basin's resilience against future vulnerabilities. Reaching the pinnacle of level 5 would signify a significant accomplishment. At this stage, the digital twin learns from its own experiences, automates major operations, and proactively takes actions to manage and optimize the river basin.

2.7. Overcoming challenges

Theoretically, crafting a digital twin for any river basin is feasible using cutting-edge technologies; nevertheless, numerous challenges must be addressed during practical implementation. Substantial investment is requisite for constructing a digital twin. To navigate funding issues, stakeholders must outline their contributions and ownership responsibilities in the operation and maintenance of the digital twin, evaluating the value contributed by the digital twin against their interests. Conducting a comprehensive analysis of the potential of the digital twin's data and services in creating new business opportunities can mitigate the challenges associated with the long-term maintenance cost of the digital twin. In this context, a dedicated team of domain experts assumes a pivotal role in understanding both technical and practical challenges in the early stages, thereby enabling timely solutions and averting unnecessary delays in the implementation progress.

Establishing adaptive policies related to the privacy, confidentiality, and ownership of data is paramount before digital twin implementation, given the pivotal role of data sharing. Overcoming the initial challenge of capturing river basin characteristics can be achieved by installing reasonably priced smart sensors equipped with advanced monitoring techniques (Zhang *et al.* 2019). Implementing regular maintenance schedules for these sensors can effectively address issues related to the quality and reliability of the obtained data. Addressing the challenge of sensor installation in hard-to-reach areas is possible by leveraging satellite remote sensing data as a proxy for the variables of interest. In managing multiple real-time processes within the digital twin, ensuring computational scalability is crucial and can be achieved using low-cost edge, cluster, and grid computing techniques.

Continuous collaboration among digital twin team members promotes cross-domain learning, aiding in the alignment of scientific knowledge when attempting to understand interrelated processes. Coupling methods can be used to integrate digital twin models wherever possible to reduce predictive errors, resulting in ease of uncertainty handling. Stakeholders may use insights from digital twin data to translate complex events, such as social sentiment and political discussion, into quantitative forms, strengthening the validity of what-if analysis. Adopting preferred data formats, international units, and interoperable open-source software can alleviate the standardization challenge in digital twin implementation. Given the absence of a specific lifecycle time for a river basin and the rapid evolution of modern technologies, commencing with the latest version of backend infrastructure minimizes the risk of early obsolescence. In cases where a river basin extends across national borders, coordinated planning among international agencies is essential for the successful implementation of the digital twin, taking into account potential future political conflicts.

2.8. Potential applications

The application of a digital twin holds significant potential across various sectors of river basin planning. Examples encompass optimal water distribution, reservoir operations, groundwater monitoring, flood prediction, drought control, soil erosion mitigation, urban planning, infrastructure development, vegetation management, sustainable land-use, ecosystem service enhancement, wetland restoration, biodiversity protection, policy awareness, and collaborative decision-making. Through cross-domain linking of data analysis and model simulations, the digital twin facilitates river basin planning as an optimized system for increasing environmental, social, and economic benefits. By providing detailed insights into how environmental and socioeconomic functions influence the flow connectivity of water-soil-sediment-nutrient, the digital twin enables stakeholders to design nature-based solutions in high-risk areas of water scarcity, flooding, biodiversity loss, and environmental degradation. The digital twin can shed light on the synergy of various nature-based solutions, allowing for more cost-effective future interventions. Sectoral departments, such as agriculture and forestry, can use the digital twin outputs to design better

management practices. To achieve river basin sustainability with resilience to future vulnerability, the digital twin aids in comprehensive risk analysis, multi-level holistic decision-making, and faster adaptive management.

Developed and maintained by a consortium of partners from academia, industry, and government, the digital twin fosters collaboration and innovation in river basin research. Its database and modeling platform reduce the cost of data collection and model computation for other projects within the same river basin. The digital twin provides critical information on hydro-morphological and anthropogenic impacts on river basins, laying the groundwork for future research and generating new questions. It helps in bridging the knowledge gap between scientific research and management practices, offering valuable insights that inform better river basin management. As the digital twin technology matures, it has the potential to enhance river basin management across various levels of stakeholders, including river basin managers, scientists, regulators, policymakers, industrial partners, and funding agencies. River basin managers can integrate scientific insights into their operational strategies, adapting management approaches to address both current and emerging challenges. Scientific researchers can refine their hypotheses and recommendations by incorporating real-world management experiences, enabling more effective and relevant studies. Regulators can evaluate the effectiveness of existing policies at both local and river basin scales, identifying areas for improvement. Policymakers can gain insights to design and update policies that adapt to the evolving conditions of the river basin, ensuring resilience to environmental and socioeconomic changes. Funding agencies can use the data and insights provided by the digital twin to conduct comprehensive cost-benefit analyses, helping to prioritize and allocate resources effectively for upcoming projects and interventions. Industrial partners can leverage the digital twin to identify business opportunities for developing new technologies and services tailored to river basin management. Students can engage with the digital twin through academic projects or internships, gaining hands-on experience by analyzing data or contributing to specific aspects of the digital twin's development. This involvement helps to bridge the gap between academic learning and real-world river basin management, fostering the next generation of professionals.

3. CONCLUSION

The blueprint conceptualization we propose can be used as a generalized starting point for developing a river basin's digital twin. Though general guidelines for all types of river basins are provided here, the digital twin can be customized to manage an individual river basin's dominant factors, such as forest cover, urbanization, and agriculture. This is an ideal time to create the digital twin because of significant technological advancements in cloud data storage, machine learning tools, and high-performance computing; however, significant efforts are required to overcome several challenges, such as technical standardization, cross-domain collaboration, funding, and legislation. Though the digital twin's quantifiable benefits can only be realized after it is created, we are confident that it will serve as a positive catalyst in river basin planning through its support in discovering new scientific and technical approaches. Investment in digital twin development is worthwhile because it has the potential to generate new business opportunities such as natural resource recycling, alternative grey-water infrastructure, and the commercial use of river basin data. We are seeing growing societal interest in the digitization of water distribution, drainage systems, land-use planning, and nature-based solutions that are part of a river basin. This indicates that the journey toward the creation of a digital twin for an entire river basin is being taken in small steps, with the convergence of insights gained from the steps guiding digital twin development.

ACKNOWLEDGEMENTS

This research is part of the Green-Digi-Basin project, which was funded by the European Union – Next Generation EU Recovery and Resilience Facility through the Research Council of Finland (RCF), and the DefrostingRivers project, which was funded by RCF. Debasish Pal and Joy Bhattacharjee received funding through the University of Oulu (Green-Digi-Basin, grant number 347704). Anna-Kaisa Ronkanen, Marie Korppoo, Maria Kämäri, Jari Silander, and Cintia Bertacchi Uvo received funding through the Finnish Environment Institute (Green-Digi-Basin, grant number 348022). Eliisa Lotsari received funding through the Aalto University (DefrostingRivers project, grant number 338480). Erik van Rooijen received funding through the Aalto University (Green-Digi-Basin, grant number 347703). Linnea Blåfield received funding from the University of Turku through the Green-Digi-Basin project (grant number 347701) and the Kone Foundation (grant number 202104246). Danny Croghan received funding from the Maa- ja Vesitekniikan Tuki Ry (grant number 4651). Mehdi Rasti received funding from the University of Oulu (Profif6, grant number 336449) and the Business Finland (DigiPave, project number

3992/31/2023). Harri Kaartinen received funding through the Finnish Geospatial Research Institute FGI (Green-Digi-Basin, grant number 347702). Finally, we acknowledge the consortium of DIWA (Digital Waters flagship), funded by the Research Council of Finland, for contributing to the brainstorming of the river basin's digital twin concept, as well as two anonymous reviewers for their valuable comments in improving the manuscript.

AUTHOR CONTRIBUTIONS

D.P. contributed to conceptualization, methodology, visualization, writing – original draft, writing – review & editing. P.A.-A., C.G.-I., D.C., M.K., E.v.R., L.B., J.S., A.B., J.B., A.T.H., C.B.U., M.R., B.K. contributed to writing – review & editing. E.L., H.K., A.-K.R., P.A., H.M. contributed to writing – review & editing, funding acquisition, supervision, project administration.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Akroyd, J., Harper, Z., Soutar, D., Farazi, F., Bhave, A., Mosbach, S. & Kraft, M. (2022) [Universal digital twin: land use](#), *Data-Centric Engineering*, **3**, e3.
- Alfieri, L., Avanzi, F., Delogu, F., Gabellani, S., Bruno, G., Campo, L., Libertino, A., Massari, C., Tarpanelli, A., Rains, D., Miralles, D. G., Quast, R., Vreugdenhil, M., Wu, H. & Brocca, L. (2022) [High resolution satellite products improve hydrological modeling in Northern Italy](#), *Hydrology and Earth System Sciences*, **26** (14), 3921–3939.
- Alzamora, F. M., Conejos, P., Castro-Gama, M. & Vertommen, I. (2021) Digital twins-a new paradigm for water supply and distribution networks, *HydroLink Magazine*, **2**, 48–54.
- Arnell, M., Miltell, M. & Olsson, G. (2023) [Making waves: a vision for digital water utilities](#), *Water Research X*, **19**, 100170.
- Bartos, M. & Kerkez, B. (2021) [Pipedream: an interactive digital twin model for natural and urban drainage systems](#), *Environmental Modelling & Software*, **144**, 105120.
- Bauer, P., Stevens, B. & Hazeleger, W. (2021) [A digital twin of earth for the green transition](#), *Nature Climate Change*, **11** (2), 80–83.
- Blair, G. S. (2021) [Digital twins of the natural environment](#), *Patterns*, **2** (10), 100359.
- Botín-Sanabria, D. M., Mihaita, A.-S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A. & Lozoya-Santos, J. d. J. (2022) [Digital twin technology challenges and applications: a comprehensive review](#), *Remote Sensing*, **14** (6), 1335.
- Brocca, L., Barbetta, S., Camici, S., Ciabatta, L., Dari, J., Filippucci, P., Massari, C., Modanesi, S., Tarpanelli, A., Bonaccorsi, B., Mosaffa, H., Wagner, W., Vreugdenhil, M., Quast, R., Alfieri, L., Gabellani, S., Avanzi, F., Rains, D., Miralles, D. G., Mantovani, S., Briese, C., Domeneghetti, A., Jacob, A., Castelli, M., Camps-Valls, G., Volden, E. & Fernandez, D. (2024) [Digital twin of the terrestrial water cycle: a glimpse into the future through high-resolution earth observations](#), *Frontiers in Science*, **1**, 1190191.
- Carozza, D. A. & Boudreault, M. (2021) [A global flood risk modeling framework built with climate models and machine learning](#), *Journal of Advances in Modeling Earth Systems*, **13** (4), e2020MS002221.
- Duan, T., Feng, J., Chang, X. & Li, Y. (2022) [Watershed health assessment using the coupled integrated multistatistic analyses and PSIR framework](#), *Science of The Total Environment*, **847**, 157523.
- El Saddik, A. (2018) [Digital twins: the convergence of multimedia technologies](#), *IEEE Multimedia*, **25** (2), 87–92.
- Eltner, A., Bertalan, L., Grundmann, J., Perks, M. T. & Lotsari, E. (2021) [Hydro-morphological mapping of river reaches using videos captured with UAS](#), *Earth Surface Processes and Landforms*, **46** (14), 2773–2787.
- Evans, S., Savian, C., Burns, A. & Cooper, C. (2019) *Digital Twins for the Built Environment: an Introduction to the Opportunities, Benefits, Challenges and Risks*. s.l: The Institution of Engineering and Technology.
- Faivre, N., Fritz, M., Freitas, T., Boissezon, B. d. & Vandewoestijne, S. (2017) [Nature-Based solutions in the EU: innovating with nature to address social, economic and environmental challenges](#), *Environmental Research*, **159**, 509–519.
- Freeze, R. A. & Harlan, R. L. (1969) [Blueprint for a physically-based, digitally-simulated hydrologic response model](#), *Journal of Hydrology*, **9**, 237–258.
- Gonzales-Inca, C., Calle, M., Croghan, D., Haghighi, A. T., Marttila, H., Silander, J. & Alho, P. (2022) [Geospatial Artificial Intelligence \(GeoAI\) in the integrated hydrological and fluvial systems modeling: review of current applications and trends](#), *Water*, **14** (14), 2211.
- Grieves, M. (2014) Digital twin: manufacturing excellence through virtual factory replication, *White Paper*, **1**, 1–7.
- Johnson, B. R., Kadiyala, R., Owens, G., Mak, Y. P., Grace, P., Newbery, C., Sing, S., Saxena, A. & Green, J. (2021) *Water Reuse and Recovery Facility Connected Digital Twin Case Study: Singapore PUB's Changi WRP Process, Control, and Hydraulics Digital Twin*. Chicago, USA: WEFTEC.
- Khallaf, R., Khallaf, L., Anumba, C. J. & Madubuike, O. C. (2022) [Review of digital twins for constructed facilities](#), *Buildings*, **12** (11), 2029.

- Khedun, C. P., Flores, R. S., Rughoonundun, H. & Kaiser, R. A. (2014) World water supply and use: challenges for the future. In Van Alfen, N. K. (Eds.): *Encyclopedia of Agriculture and Food Systems*, Amsterdam: Elsevier, pp. 450–465.
- Kuffour, B. N. O., Engdahl, N. B., Woodward, C. S., Condon, L. E., Kollet, S. & Maxwell, R. M. (2020) Simulating coupled surface–subsurface flows with ParFlow v3. 5.0: capabilities, applications, and ongoing development of an open-source, massively parallel, integrated hydrologic model, *Geoscientific Model Development*, **13** (3), 1373–1397.
- Kumar, S., Choudhary, M. K. & Thomas, T. (2024) A hybrid technique to enhance the rainfall-runoff prediction of physical and data-driven model: a case study of Upper Narmada River Sub-basin, India, *Scientific Reports*, **14** (1), 26263.
- Li, B., Sun, T., Tian, F., Tudaji, M., Qin, L. & Ni, G. (2024) Hybrid hydrological modeling for large alpine basins: a semi-distributed approach, *Hydrology and Earth System Sciences*, **28** (20), 4521–4538.
- Lotsari, E., Lintunen, K., Kasvi, E., Alho, P. & Blåfield, L. (2022) The impacts of near-bed flow characteristics on river bed sediment transport under ice-covered conditions in 2016–2021, *Journal of Hydrology*, **615**, 128610.
- Malik, M. I. & Bhat, M. S. (2014) Integrated approach for prioritizing watersheds for management: a study of Lidder catchment of Kashmir Himalayas, *Environmental Management*, **54**, 1267–1287.
- Mancosu, N., Snyder, R. L., Kyriakakis, G. & Spano, D. (2015) Water scarcity and future challenges for food production, *Water*, **7** (3), 975–992.
- Marttila, H., Laudon, H., Tallaksen, L. M., Jaramillo, F., Alfredsen, K., Ronkanen, A.-K., Kronvangh, B., Lotsari, E., Kämäri, M., Ala-Ahoa, P., Nousu, J., Silander, J., Koivusalo, H. & Kløve, B. (2022) Nordic hydrological frontier in the 21st century, *Hydrology Research*, **53** (5), 700–715.
- Mondejar, M. E., Avtar, R., Diaz, H. L. B., Dubey, R. K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbungu, N. T., Okolo, C. C., Prasad, K. A., She, Q. & Garcia-Segura, S. (2021) Digitalization to achieve sustainable development goals: steps towards a Smart Green Planet, *Science of the Total Environment*, **794**, 148539.
- O’Grady, J., Zhang, D., O’Connor, N. & Regan, F. (2021) A comprehensive review of catchment water quality monitoring using a tiered framework of integrated sensing technologies, *Science of The Total Environment*, **765**, 142766.
- Okolie, C. J. & Smit, J. L. (2022) A systematic review and meta-analysis of Digital elevation model (DEM) fusion: pre-processing, methods and applications, *ISPRS Journal of Photogrammetry and Remote Sensing*, **188**, 1–29.
- Papa, F. & Frappart, F. (2021) Surface water storage in rivers and wetlands derived from satellite observations: a review of current advances and future opportunities for hydrological sciences, *Remote Sensing*, **13** (20), 4160.
- Park, D. & You, H. (2023) A digital twin dam and watershed management platform, *Water*, **15** (11), 2106.
- Park, J., Choi, W., Jeong, T. & Seo, J. (2023) Digital twins and land management in South Korea, *Land Use Policy*, **124**, 106442.
- Pedersen, A. N., Borup, M., Brink-Kjær, A., Christiansen, L. E. & Mikkelsen, P. S. (2021) Living and prototyping digital twins for urban water systems: towards multi-purpose value creation using models and sensors, *Water*, **13** (5), 592.
- Pillai, U. P., Pinaridi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., Valentini, A. & Staneva, J. (2022) A digital twin modelling framework for the assessment of seagrass nature based solutions against storm surges, *Science of The Total Environment*, **847**, 157603.
- Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L. & Nee, A. Y. (2021) Enabling technologies and tools for digital twin, *Journal of Manufacturing Systems*, **58**, 3–21.
- Rasheed, A., San, O. & Kvamsdal, T. (2020) Digital twin: values, challenges and enablers from a modeling perspective, *IEEE Access*, **8**, 21980–22012.
- Rigon, R., Formetta, G., Bancheri, M., Tubini, N., D’Amato, C., David, O. & Massari, C. (2022) HESS opinions: participatory Digital eARth Twin Hydrology systems (DARTHs) for everyone—a blueprint for hydrologist, *Hydrology and Earth System Sciences*, **26** (18), 4773–4800.
- Simmons, C. T., Brunner, P., Therrien, R. & Sudicky, E. A. (2020) Commemorating the 50th anniversary of the Freeze and Harlan (1969) blueprint for a physically-based, digitally-simulated hydrologic response model, *Journal of Hydrology*, **584**, 124309.
- Singh, M., Fuenmayor, E., Hinchy, E. P., Qiao, Y., Murray, N. & Devine, D. (2021) Digital twin: origin to future, *Applied System Innovation*, **4** (2), 36.
- Swetapadma, S. & Ojha, C. S. P. (2017) Sustainable river basin management planning: a holistic approach, *Earth Science India*, **10** (4), 126–152.
- Tao, F. & Qi, Q. (2019) Make more digital twins, *Nature*, **573** (7775), 490–491.
- Tao, F., Qi, Q., Wang, L. & Nee, A. Y. C. (2019) Digital twins and cyber-physical systems toward smart manufacturing and industry 4.0: correlation and comparison, *Engineering*, **5** (4), 653–661.
- Tarpanelli, A., Bonaccorsi, B., Sinagra, M., Domeneghetti, A., Brocca, L. & Barbetta, S. (2023) Flooding in the Digital Twin Earth: the case study of the Enza river levee breach in December 2017, *Water*, **15** (9), 1644.
- Teo, T.-A. & Wu, H.-M. (2017) Analysis of land cover classification using multi-wavelength LiDAR system, *Applied Sciences*, **7** (7), 663.
- Torfs, E., Nicolai, N., Daneshgar, S., Copp, J. B., Haimi, H., Ikumi, D., Johnson, B., Plosz, B. B., Snowling, S., Townley, L. R., Valverde-Pérez, B., Vanrolleghem, P. A., Vezzaro, L. & Nopens, I. (2022) The transition of WRRF models to digital twin applications, *Water Science and Technology*, **85** (10), 2840–2853.
- Valverde-Pérez, B., Johnson, B., Wärf, C., Lumley, D., Torfs, E., Nopens, I. & Townley, L. (2021) *Digital Water-Operational Digital Twins in the Urban Water Sector: Case Studies*. London, UK: International Water Association. White paper.

- Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M. T. H., Yillia, P., Ringler, C., Burek, P. & Wiberg, D. (2016) [Modeling global water use for the 21st century: the Water Futures and Solutions \(WFaS\) initiative and its approaches](#), *Geoscientific Model Development*, **9** (1), 175–222.
- Wenzheng, L. (2022) 'Digital Twin Riverbasin and Digital Riverbasin Engineering', *s.l., IEEE 12th International Conference on Electronics Information and Emergency Communication (ICEIEC)*, pp. 107–110.
- Xue, Y., Houser, P. R., Maggioni, V., Mei, Y., Kumar, S. V. & Yoon, Y. (2019) [Assimilation of satellite-based snow cover and freeze/thaw observations over high mountain Asia](#), *Frontiers in Earth Science*, **7**, 115.
- Zhang, D., Heery, B., O'Neil, M., Little, S., O'Connor, N. E. & Regan, F. (2019) [A low-cost smart sensor network for catchment monitoring](#), *Sensors*, **19** (10), 2278.

First received 31 July 2024; accepted in revised form 27 January 2025. Available online 13 February 2025