Proceedings of the 57th Hawaii International Conference on System Sciences | 2024

Designing and Implementing a Robust, Modular and Interoperable Digital Twin Smart City Framework for Critical Water Spatial Infrastructure

Dr. Kostas Alexandridis
Orange County Public Works
Kostas.Alexandridis@ocpw.ocgov.com

Dr. Sonya Zhang
Cal Poly Pomona
xszhang@cpp.edu

Dr. Mehrdad Koohikamali
Cal Poly Pomona
mkoohikamali@cpp.edu

Dr. Soheil Sabri
University of Central Florida
soheil.sabri@ucf.edu

Dr. H. Erkan Ozkaya
Cal Poly Pomona
ozkaya@cpp.edu

Abstract

This paper provides a fundamental and robust understanding of digital twin technology's design, implementation, and use for managing critical water spatial infrastructure in Smart Cities. It outlines a modular and interoperable reference framework and an overview of how innovative technologies and socio-technical system considerations can form the cornerstone for smart city digital transformation efforts. We present two of our own integrative case studies as examples of such critical water infrastructure, namely in Orange County, California, US, and Victoria, Australia. We discuss key framework factors and considerations and outline a roadmap for implementing digital twin transformation for intelligent urban water management systems.

Keywords:

Digital Twin, Smart Cities, Orange County, Digital Transformation, Interoperability, Critical Infrastructure

1. Introduction

Urban infrastructure systems have recently come under tremendous stress due to the rapid rise of urbanization and increasing demands for essential resources, particularly in water management. The current rate of urban access to safe drinking water and sanitation lags behind population growth (Connor, 2015). For cities to be sustainable and resilient, necessary water spatial infrastructure must be administered and maintained effectively (Milman and Short, 2008). Emerging technologies are gaining attention as potential solutions for enhancing urban water management's monitoring, analysis, and decision-making processes to address these issues, including digital twin frameworks (Ramos et al., 2022).

Water infrastructure plays a vital role in supporting the livelihoods and economic activities of urban communities. It includes various systems, such as water supply networks, sewage treatment facilities, stormwater management systems, and flood control infrastructure. The functionality and dependability of these systems are seriously threatened by the deteriorating infrastructure and the rising frequency of extreme weather events brought on by climate change. To guarantee secure and long-lasting water services to urban populations, novel approaches that facilitate efficient planning, design, operation, and maintenance of water spatial infrastructure are urgently required.

Digital twin technology has emerged as a promising tool for urban water management. By combining real-time data acquisition, advanced analytics, and simulation capabilities, digital twins enable decision-makers to gain deeper insights into the behavior and performance of complex water systems. These virtual replicas provide a platform for testing various scenarios, optimizing resource allocation, and improving system resilience through predictive maintenance strategies. However, despite the growing interest and potential of digital twin frameworks, there is a research gap in developing robust, modular, and interoperable frameworks specifically tailored for critical water spatial infrastructure within the context of smart cities.

This study aims to review the state-of-the-art application of digital twins in smart, resilient, and sustainable water and flood management. The study will leverage two case studies in Australia and the USA to identify key components of a framework for digital twins that enhance water and flood management in the

URI: https://hdl.handle.net/10125/107284
978-0-9981331-7-1

context of smart cities. Moreover, the study argues that spatially enabled digital twins provide an opportunity for the community to participate and collaborate with decision-makers, to address the inclusiveness and collaborative challenges of digital technologies.

2. Literature Review

2.1. Diffusion of Innovation

The five main factors influencing an innovation's adoption are highly relevant to adopting Digital Twins. Specifically: (a) *Relative Advantage* - The degree to which an innovation is seen as better than the idea, program, or product it replaces; (b) *Compatibility* - How consistent the innovation is with the potential adopters' values, experiences, and needs; (c) *Complexity* - How difficult the innovation is to understand and/or use; (d) *Triability or reproducibility* - The extent to which the innovation can be tested or experimented with before a commitment to adopt is made, and; (e) *Observability* - The extent to which the innovation provides tangible results. We will examine these main factors in further detail in the following subsections.

Socio-technical systems refer to complex and interconnected systems encompassing social and technical elements, where the behavior and outcomes are influenced by the interaction between humans and technology within a specific context. These systems can exist in physical and digital realms, encompassing various domains such as organizations, communities, infrastructure, and technology-enabled platforms. These systems are characterized by the interdependence between social and technical components, as changes in one component can impact the other (Johnson and Wetmore, 2021).

Socio-technical systems theory recognizes that a system's social and technical aspects are interdependent and must be considered together to achieve optimal system performance and human well-being (Johnson and Wetmore, 2021). In the physical and digital world context, socio-technical systems can be seen as integrating technology and social structures within various domains, such as transportation, healthcare, communication, and education. The physical world represents our environment's tangible and material aspects, while the digital world pertains to the virtual and digital aspects facilitated by computer-based technologies. In many cases socio-technical system considerations can be integrated to facilitate understanding and clarifying aspects of risk, perceptions and damage assessment or the impact of extreme events in critical infrastructure (Alexandridis and Chanes, 2018).

Socio-technical systems play a crucial role in digital twins by incorporating the social and human aspects into the modeling, analysis, and decision-making processes. Furthermore, they play a crucial role in developing, implementing, and utilizing digital twins. In previous research, socio-technical systems' three key roles in the digital twin contexts are contextual understanding (Nochta et al., 2021), integration of social factors, and decision support. Here are some key roles that socio-technical systems have in the context of digital twins:

1. Contextual Understanding: Socio-technical systems provide a framework for understanding the social and organizational context in which digital twins operate. They help capture and model the social dynamics, relationships, and behaviors of individuals and communities that interact with the physical system being replicated by the digital twin (Tzachor et al., 2022). This understanding is essential for ensuring the digital twin accurately represents the real-world system and its socio-technical complexities.

2. Integration of Social Factors: Socio-technical systems facilitate the integration of social factors and human behavior into the digital twin, called the social factory. They consider how people interact with and are influenced by technology within the system being represented. By incorporating social aspects, such as user preferences, behavior patterns, and decision-making processes, socio-technical systems enable a more comprehensive and realistic representation of the system's behavior in the digital twin.

3. Decision Support: Socio-technical systems provide decision-makers with insights and support in utilizing digital twins for decision-making. They help analyze and interpret the data generated by the digital twin, considering social and organizational factors. This integration enables decision-makers to make informed decisions considering both technical and social aspects, leading to more effective and contextually appropriate outcomes.

In addition to the factors and dimensions outlined above, it is often important to consider social and community factors related to integrating socio-technical systems within a smart city and technology-centric design of managing critical water infrastructure. Examples of these dimensions/factors are social reciprocity, building relationships of trust among and across communities, ensuring inter-generational equity in access and use of digital assets and resources, and examining of the critical role of social, collective formal, and informal institutions. Such institutions provide the necessary background for developing capacity and capability digital twin frameworks and a critical sharing of interoperability and open standards in operational and management designs. In many smart cities and regions, the power of digital twin technologies enables us to include often and integrate massive public data, harness the power of cutting-edge technologies such as artificial intelligence and machine learning, modeling, and simulation, and increase and enhance the level of situational and operational awareness, and the level of visual intelligence in incorporating science and data-based management solutions.

2.2. Sustainability and Resilience

Recently, the resilience and sustainability concepts in smart urban and regional developments have attracted the growing attention of practitioners and researchers. Developing measurable and quantitative indicators for both resilient and sustainability concepts provided an opportunity to utilize digital technologies for measuring, monitoring, and benchmarking the communities' progress (Sabri, 2021). For example, Fu and Wang (2018) adopted a complex system thinking and introduced an integrative urban resilience capacity index (IURCI) framework to support community planning and scenario building in achieving high ecological, economic, and social resilience qualities. Furthermore, Jones and d'Errico (2019) argued that self-assessment of resilience concerning the subjectivity dimensions could be added as a complementary capability to the community. They compared the Subjective self-Evaluated Resilience Score (SERS) with the objectively evaluated approach, Resilient Index Measurement Analysis (RIMA), and suggested that both subjective and objective approaches build advantageous measurements for better community resilience. Developing scenario builders in a digital platform could achieve this hybrid method.

Spatial data infrastructure (SDI) is essential in measuring communities' resiliency and sustainability. Rahabifard et al. (2015) designed and developed an Urban Analytics Data Infrastructure (UADI) as a critical SDI to measure the quantitative urban sustainability indicators. Using the UADI platform, Rajabifard et al., 2019 demonstrated the value of SDI for measuring and monitoring the national and local progress of the UN's Sustainable Development Goals (SDGs). Furthermore, Reisi et al., 2020 used the same technology to derive transport sustainability indicators, including energy consumption by public and private vehicles. Moreover, several studies proposed the application of remote sensing data and analytics, combined with emerging technologies such as Machine Learning and Deep Learning to measure the resiliency and sustainability of communities. For example, (Assarkhaniki et al., 2021) proposed a workflow to detect the physical characteristics of urban areas using open geospatial data and Medium Resolution (MR) satellite imagery. This workflow was proposed to support measuring the resiliency and sustainability of informal settlements. While these digital platforms and methods enabled the quantitative analysis of sustainability indicators, users might not be capable of running different scenarios and adding the subjectivity dimension to the measures.

One of the major urban resilient concerns is climate adaptation, including urban policies for urban flood mitigation, preparedness, response, and recovery (Yeganeh and Sabri, 2014). Population growth and rapid urbanization led to more built-up areas over the wetlands and green spaces. To date, several studies have investigated urban flood resilient management. Previous research has established that urban flood resilient measures could be conducted through several approaches, such as flood vulnerability assessment, developing flood susceptibility maps, and flood damage assessment. These approaches support the urban and regional planners in developing flood-resilient regulations for land use zoning and urban policies. However, there is little study about real-time flood modeling and impact analysis. This limitation leaves urban planners and policymakers with less reliable data and analysis support to address the urban flood resilient and sustainable development programs.

2.3. Technology in Industry and Business

Even though the digital twin is a relatively new technology, it has experienced tremendous adoption by businesses in several industries, such as manufacturing, energy and utilities, healthcare, transportation and logistics, construction and infrastructure, and aerospace and defense. Digital twins offer several benefits and challenges from a diffusion of innovation standpoint. The benefits of adopting a digital twin technology include improved operational efficiency (Feng et al., 2023), optimized asset management, real-time decision-making, training, and simulation, to name a few. However, the adoption of digital twin technology comes with several challenges, including data quality, integration, security, and privacy, scalability, interoperability, and standards (Lei et al., 2023), model complexity, accuracy and validation, cost and return on investment, organizational and cultural change, and legal and regulatory challenges (Lei et al., 2023).

Apart from Municipalities and government agencies, several types of businesses and organizations could benefit from a digital twin smart city framework for critical water spatial infrastructure. The first ones that come to mind are (1) water utility companies, (2) engineering and consulting firms that help design, plan, and manage the infrastructure, (3) technology providers that include hardware providers such as sensors, and services providers including data analytics companies, (4) water management, maintenance, and service providers, (5) environmental monitoring and conservation organizations, as well as (6) research institutions and academia. Digital twins framework and the integrated data generated can benefit other businesses or help build businesses that don't currently exist. The current businesses that would benefit significantly from a digital twin smart city framework for critical water spatial infrastructure would be (1) Insurance Companies, (2) Real Estate Firms and Real Estate Market Place Companies (e.g., Zillow), and (3) Agriculture firms. Agriculture firms heavily depend on flooding or water shortages for making informed decisions regarding risk management, crop selection, livestock management, infrastructure investment decisions, and disaster preparedness. Many other new business areas can emerge, such as digital twin service providers that can communicate the benefits of the digital twin smart city framework for critical water spatial infrastructure and make it accessible to other businesses.

The success of adopting the digital twin framework depends on capitalizing on its benefits while addressing its challenges. Table 1 summarizes the benefits and challenges of the digital twin smart city framework for critical water spatial infrastructure based on the five diffusion factors of the Diffusion of Innovation Theory.

Relative Advantage: Accurate risk assessment and management, which would lead to improved decision-making and operational efficiency, are some of the main advantages of the digital twin framework compared to traditional systems.

Compatibility: The Digital twin framework provides real-time data on asset performance, maintenance needs, and operational optimization.

Complexity: Visualization of a problem enhances communication and discussion of its solutions and chances of being included in the overall decision-making process.

Reproducibility/Triability: Digital twin technology allows users to run simulations and experiments. This significantly increases the trialability of the digital twin framework.

Observability: To enhance the adoption rate, the digital twin framework should demonstrate the extent to which it would bring tangible results to firms.

Table 1. Diffusion of Innovation Factors for Digital Twin Smart City

Diffusion of Innovation Factors	Benefits	Challenges
Relative Advantage	Accurate Risk Assessment and Management, Improved Decision Making, Operational Efficiency, Ability to handle Complexity	Data Integration and Quality
Compatibility	Enhanced Asset Management	Interoperability and Modularity, Organizational and Cultural Change
Complexity	Data Visualization and Accessibility	Model Accuracy, Validation and Complexity
Reproducibility	Simulations and Experimentation	Scalability and Complexity
Observability	Effective Planning and Design	Data Security and Privacy

2.4. Digital Twin and Smart Cities

Digital Twins are becoming increasingly effective as a tool to support the development and management of smart cities and continue to grow due to rapid advancements in the Internet of Things (IoT). Digital twins contribute to various domains of smart cities, including urban planning (Schrotter and Hürzeler, 2020), construction and resource optimization (Sabri et al., 2022), transportation and traffic, disaster management, and energy management.

Urban Planning: Digital twins allow urban planners to visualize and simulate various scenarios before implementing changes and evaluate the potential impact of proposed changes, leading to more informed decision-making processes and more efficient and sustainable urban development. Furthermore, through integrating and comprehensively analyzing data from diverse sources such as satellite imagery, sensor networks, and demographic information, digital twins empower urban planners to analyze the effects of proposed developments, evaluate land use patterns, assess infrastructure and population density, and optimize resource allocation. The digital twin of Zurich improves urban planning and decision-making by providing accessible 3D spatial data and promoting application development and collaboration by releasing this data as Open Government Data (Schrotter and Hürzeler, 2020). Similarly, the digital twin of New York

City enhances the CityGML Transportation Model by incorporating 3D spatial-semantic representation of the street space, allowing for improved vehicle navigation, detailed traffic simulations, and speed limit analysis.

Disaster Management: Digital twins can be used in crisis informatics and cyber-infrastructure to help disaster management teams to gain a better understanding of the disaster, make more accurate predictions of future disasters, and develop more effective strategies in all phases of disaster management, including mitigation, preparation, response, and recovery. Creating a digital twin for disaster management involves modeling techniques and integration with real-time data and interdependent infrastructure networks. Cities like Lisbon and Helsinki strive to improve their flood resilience by utilizing digital twins, including 3D mapping and flood resilience modeling and simulation. These flood models can accurately calculate water flow's direction, depth, and velocity by integrating hydro-meteorological data, GIS, BIM, and more. Leveraging real-time smart city data collected from information and communications technology (ICT) sensors, the Flood Alert System (FAS) in Houston's Texas Medical Center (TMC) offers comprehensive digital twin solutions. These solutions encompass community simulation models and digital image tools, empowering stakeholders to make well-informed decisions and develop efficient strategies for managing rainfall and flood events (Ford and Wolf, 2020). Integrated with the river, water, power, and transportation networks, a digital twin of the City of Calgary is built, calibrated, and validated using open street map data, Digital Elevation Model (DEM), and satellite images to replicate the impacts of the 2013 flood event, providing a platform for devising risk mitigation strategies under future hazards.

Smart Communities: Smart City Digital Twins (SCDTs) are virtual replicas of cities that integrate real-time data from human and infrastructure systems to facilitate effective city management and improve the quality of life in urban environments. SCDTs help citizens and stakeholders in a city become more informed, empowered, and involved, promoting community engagement and social innovations through awareness initiatives and digital inclusion, leading to substantial and continuous improvements that positively impact the city's infrastructure, public services, and the overall well-being and prosperity of the community. A Smart Uptown Digital Twin of the City of Columbus, Georgia, exemplifies the importance of integrating community dynamics into monitoring and forecasting urban hazard exposure, showcasing how SCDT can enhance accessibility and responsiveness for city managers in engaging with community dynamics. On the other hand, incorporating crowd-sourced, geospatial-temporal human behavior data from the community can significantly enhance the development of more dynamic, sophisticated, effective, and scalable SCDTs (Miotti and Jain, 2021).

3. Methodology and Research Questions

The key research question that we aim to address is: *How the Digital Twins Complex Spatial Framework can facilitate the integration and interoperability of diverse urban data sources (such as geospatial data, IoT sensor data, and infrastructure data) to support comprehensive analysis and decision-making in smart cities?*. Figure 1 below illustrates a conceptual framework used in our case study implementation by listing specific applications, models, and infrastructure layers and principles in the digital twin design.

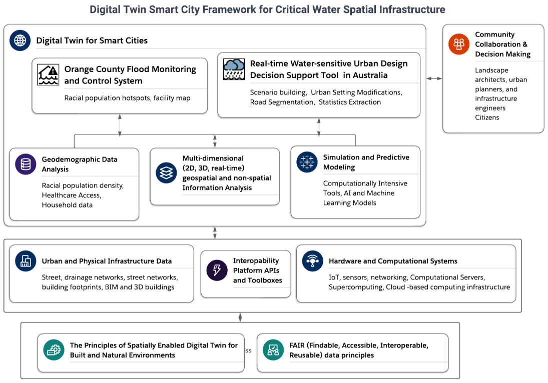

Figure 1. Digital Twin Smart City Framework for Critical Water Spatial Infrastructure

Generally speaking, the framework includes the development and implementation of:

1. A robust and adaptive digital twin framework that enables a distributed computing infrastructure, including edge-computing, real- and near-real-time sensor integration, and AI and Machine Learning-ready operational interoperability.
2. A set of proposed and required data and community-driven standards, objects, classifications, and computational architectures that facilitate and enable integration of various and diverse types of datasets (e.g., real-time data, spatial and GIS data, temporal and time-series data, simulation modeling prediction data and metadata, AI and machine-learning model classifications and prediction data, along with structural-semantic digital twin graph models that encodes the entity and object relationships in capturing real-world and metaverse relationships).

3. A suite of tools that facilitate, enable, and empower scientific discovery, science-based inferential statistics, and decision-theoretic investigations on digital twin computational infrastructure, including on-premise servers, cloud computational infrastructure, edge computing clusters, and supercomputing operational data and model layers.

4. A digital transformational governance framework that aims to support management, decision-making, and operational control of the digital twin framework, especially targeting critical public infrastructure and digital infrastructure with emergency response implications for climate change, natural disasters, and natural security. Such framework is aimed at advancing and serving national goals of improving our digital literacy, reducing or mitigating digital gaps (social, racial, economic and inter-generational), and empowering visual intelligence (VQ) for decision-makers and end-users at both the institutional governance and the broader community level.

5. A research and scientific understanding of the variables, dimensions, forces, actors, and processes driving institutional change from the ground up. Drawing from the relevant literature on institutional governance and the management of the Commons, this partnership aims to investigate the relationship between the computational and relational engineering of digital twin frameworks and the necessary socio-technical framework required to (a) address, manage, and tame the necessary complexity of interactions; (b) provide and foster a highly competent and technical digital transformation workforce for the future, and; (c) facilitate the emergence of a new paradigm of P partnerships (government, academia, industry) in promoting innovational and technological diffusion and proliferation within the broader social and public domain.

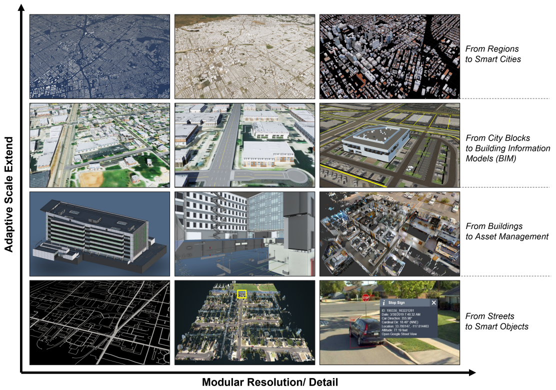

Figure 2. OCDT Scalability and Modularity Framework

The scalability and modularity aspects of the framework are outlined in Figure 2, and provide an example and overview of a two-dimensional matrix representation of the scalability vs. modularity components in the OCDT framework in Orange County, California. From top to bottom (vertical y-axis) and from left to right (horizontal x-axis), the adaptive level of scale and resolution increases.

4. Case Study Applications

This section provides an analytical overview of two integrated case studies designed, conducted, and implemented by the research team in this paper. These case studies are used for the digital transformation/digital twin framework as pilot implementations. Specifically, (a) Orange County Flood Monitoring System, see also section 4.1 in Southern California, USA, and (b) Disaster planning water management in Victoria, Australia, see also section 4.2.

4.1. Orange County Flood Monitoring and Control System

The Orange County real-time flood monitoring and control system (often called the *OC Hydstra* network) consists of approximately 85 flood monitoring stations located throughout the County (see right subgraph on 4. Of these, 62 provide ALERT system inputs, reporting on regular real-time intervals ranging from 1 - 5 minutes on average. ALERT stands for ”Automated Local Evaluation in Real Time,” using real-time remote IoT sensors sending environmental water and flood data to base servers via radio transmission. The National Weather Service of California developed the standard in the 1970’s and Orange County has participated since 1983 with its own network of Hydstra stations contributing to the Southern California ALERT System. The Orange County ALERT System consists of three computer/server base stations and three radio repeaters. In response to extreme weather conditions, we coordinate monitoring and response to threats of flooding, mudslides, and debris flows. During these periods, the ALERT System provides crucial continuous information to the Operation Center.

4.1.1. Geodemographic Data Analysis Figure 3 provides a geostatistical spatial overview of the demographic characteristics of key racial population groups in Orange County, California. The top row showcases the related hot spot analyses of the geodemographic densities for Hispanic and Asian population groups. Specifically, each of the subgraphs shows (a) Hot-Spot Clusters for the Hispanic population in Census tracts; (b) Hot-Spot Clusters for the Asian population in Census tracts, and (c) Watershed boundaries and the extent of flood zone predictions (100-year and 500-year storms) for Orange County. As can be seen from the graph, racial and demographic diversity in the county roughly corresponds and aligns with extreme event vulnerability and risk exposure spatially, especially in the north, northeast (for Hispanic), and northwest (for Asian) parts of the County.

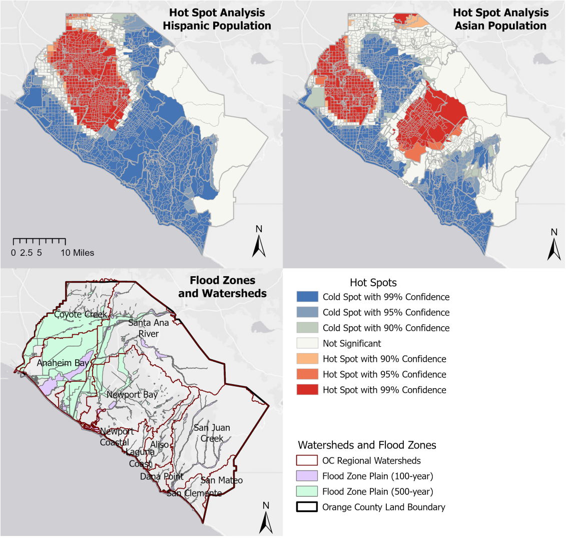

Figure 3. Geostatistical and geodemographic overview of Orange County

4.1.2. Real-time Water Monitoring Network

The critical water and flood control infrastructure for Orange County is shown in the following Figure 4. The left subgraph presents the availability and density of the county's critical water and flood management infrastructure, including major flood and flood control channels, drain lines and water bodies around the county. The density of such managed infrastructure corresponds and aligns with the county's major watersheds and the landscape's terrestrial and surface topographic arrangements. The right subfigure provides an overview of both the critical water management structures (dams and reservoirs), as well as the real-time water and flood monitoring Hydstra stations (n=85) spatially distributed around Orange County. The purpose and scope of such a real-time water monitoring network is twofold: (a) to provide accurate, real-time, and content-rich data for the condition of the water availability and weather conditions throughout the County, and (b) provide early-working and emergency services in case on large storm events, catastrophic water crises, and other water-based natural resource emergency management situations. An example of real-time dynamics for the Hydstra monitoring network can be found in the OCPW Hydstra Website or the live data Hydstra Dashboard.

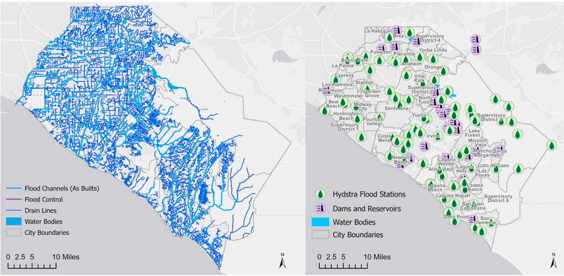

Figure 4. Critical Water Management and Flood Control Infrastructure in Orange County, California

4.2. Urban Flood Management and Planning System in Australia

Between 1967 and 2013, floods cost the Australian government AUD47.9 billion, or 28 percent of all losses, due to natural disasters, and caused more loss of lives in urban areas than any other disaster in Australia (Ladds et al., 2017). Urban flooding has become increasingly prevalent, destructive, and challenging to predict. Changes in rainfall patterns brought about by climate change coupled with unprecedented urbanization in floodplain areas can be considered drivers of increased risk in urban flooding. These more extreme and frequent flood events mean experts such as first responders, policymakers, and urban planning and design practitioners face increasingly urgent, challenging, and expensive decisions on how, where, and what flood response, recovery, and infrastructure they must implement.

4.2.1. Multi-dimensional Geospatial and Non-geospatial information

The current urban flood management and planning schemes rely on static flood models and historical flood events (e.g. 50 and 100 years). To address current limitations, (Langenheim et al., 2022) proposed a decision support tool called: *real-time water-sensitive urban design decision making* implemented on a spatially enabled digital twin platform. The digital twin was initially built for the Victorian state government as a proof of concept to demonstrate the value of digital technologies to address the sustainability and resilient challenges in an urban redevelopment project called Fishermans Bend (Tzachor et al., 2022). The platform was developed for users with no specialist knowledge to engage with practitioners in decision-making (Sabri et al., 2023). This platform incorporated the principles of spatially enabled digital twin for built and natural environments (ANZLIC, 2019). As such, the platform made multi-dimensional (2D, 3D, real-time) spatial and non-spatial information inclusive and accessible (Figure 5), using cloud-based geospatial technology and adopting FAIR (Findable, Accessible, Interoperable, Reusable) data principles.

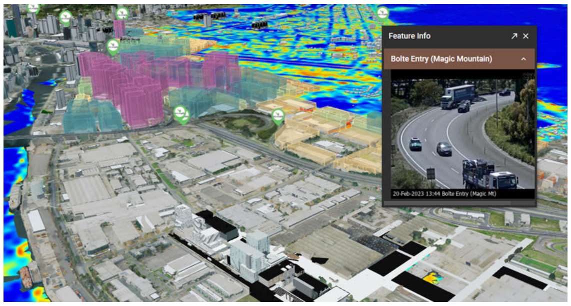

Figure 5. Integrating multi-dimensional data (2D, 3D, and Real-time) in a spatially enabled Digital Twin. Source: Sabri et al., 2023

The real-time water-sensitive tool allows landscape architects, urban planners, and infrastructure engineers to collaborate in developing and testing flood-responsive urban development scenarios. This tool can answer a fundamental question: What are effective near- mid- and long-term incremental design scenarios for the Fishermans Bend precinct development and landscape that can be planned and built to make the site resilient to urban floods? Using digital twin capabilities, the tool leverages different integrated and harmonized urban data, including existing street and drainage networks, proposed precinct structure planning framework, and future street networks. In addition, the digital twin enables integrating the geospatial data such as digital elevation models (DEM), building footprints, and 3D buildings in different formats (e.g. Object Models, 3D GeoTiles, Extruded 2D).

4.2.2. Simulation and Predictive Modeling As illustrated in Figure 1, the real-time water-sensitive urban design is necessary to support decision-making for critical water infrastructure. Thus, its user interface is designed to provide several capabilities (Figure 6):

- A scenario builder allows users to experiment with various scenarios and observe the outcomes in real-time.
- Urban setting modification (e.g., building height and footprint change, urban road network change). The user can propose new roads in water sub-catchments, and immediately, the water storage capacity of the proposed road will be calculated.
- Segmentation of roads, allowing users to make changes in road width and investigate each segment of the road network separately.
- Extract the statistics of different scenarios, including total storm water capacity by road types and sub-catchments(Kiloliter).

Figure 6. Real-time Water-sensitive Urban Design Decision Support Tool developed on a spatially enabled Digital Twin. Source: Rahmani, 2023

This tool will simultaneously support multiple simulation and prediction models, utilizing weather data, IoT sensor data, and machine learning techniques. This capability can integrate the forecast water usage to improve the operational and design phases of water infrastructure development. In addition, the Digital Twin technology will facilitate real-time impact analysis using weather forecasts and data alongside real-time flood modeling that can be calibrated with customized flood-responsive sensor data.

5. Discussion and Conclusions

This study aimed to develop a robust framework for spatially enabled digital twins to enhance water and flood management in the context of smart cities. Very little was found in the literature that provided such a framework for a smart and inclusive community. The study explored two cases in the USA and Australia to identify different approaches to provide a multi-scale, modular, and collaborative digital solution.

This study confirmed that the digital twin provides a profound opportunity for governments, businesses, and communities to work collaboratively and address the unexpected climate change challenges. The case of OCDT demonstrated how urban and regional data in different scales can be integrated into a geospatial platform to support decision-making from a building level to a regional level. This case has also highlighted the significance of data interoperability, a challenge communicated in the previous research.

Another important attribute of digital twins is their capability to facilitate real-time or near-real-time analytics. For instance, the role of geospatial technologies and cloud computing in the development of a real-time scenario builder for water-sensitive urban design development and analysis in Australia demonstrated the value of digital twins in smart urban planning and disaster management processes. Furthermore, both OCDT and Australian cases indicated the value of 3D geospatial data integration; this was also reported in European cities.

These findings suggest the proposed integrated digital twin with a complex spatial framework is crucial to addressing smart, sustainable, and resilient urban and regional water and flood management. However, further investigation is still needed to validate and ensure the reliability of open data, visualization, prediction/machine learning models, applications, measurements, and benchmarks. Additionally, there is a need to develop standards, methodologies, and hardware specifications for robust and scalable systems.

References

Alexandridis, K., & Chanes, C. (2018). Water Quality and Health Impacts of Hurricanes Irma and Maria in the US Virgin Islands on September 2017. *Paper at the ASTHO Insular Area Climate and Health Summit, Association of State and Territory Health Officials, Ala Moana, Honolulu, Hawaii, May 29-31, 2018.*

ANZLIC. (2019). *Principles for Spatially Enabled Digital Twins of the Built and Natural Environment in Australia* (tech. rep.). The Australia and New Zealand Land Information Council (ANZLIC). https://www.anzlic.gov.au/resources/principles-spatially-enabled-digital-twins-built-and-natural-environment-australia

Assarkhaniki, Z., Sabri, S., & Rajabifard, A. (2021). Using open data to detect the structure and pattern of informal settlements: An outset to support inclusive SDGs' achievement [4 citations (Crossref) [2023-08-16] Publisher: Taylor & Francis]. *https://doi.org/10.1080/20964471.2021.1948178*, 1–30. https://doi.org/10.1080/20964471.2021.1948178

Connor, R. (2015). *The United Nations world water development report 2015: Water for a sustainable world* (Vol. 1). UNESCO publishing.

Feng, H., Lv, H., & Lv, Z. (2023). Resilience towarded Digital Twins to improve the adaptability of transportation systems [0 citations (Crossref) [2023-08-16]]. *Transportation Research Part A: Policy and Practice*, *173*, 103686. https://doi.org/10.1016/j.tra.2023.103686

Ford, D. N., & Wolf, C. M. (2020). Smart Cities with Digital Twin Systems for Disaster Management [48 citations (Crossref) [2023-03-10]]. *Journal of Management in Engineering*, *36*(4), 04020027. https://doi.org/10.1061/(asce)me.1943-5479.0000779

Fu, X., & Wang, X. (2018). Developing an integrative urban resilience capacity index for plan making [15 citations (Crossref) [2023-08-16]]. *Environment Systems and Decisions*, *38*(3), 367–378. https://doi.org/10.1007/s10669-018-9693-6

Johnson, D. G., & Wetmore, J. M. (Eds.). (2021). *Technology and society: Building our sociotechnical future* (Second edition). The MIT Press.

Jones, L., & d'Errico, M. (2019). Whose resilience matters? Like-for-like comparison of objective and subjective evaluations of resilience [33 citations (Crossref) [2023-08-16]]. *World Development*, *124*, 104632. https://doi.org/10.1016/j.worlddev.2019.104632

Ladds, M., Keating, A., Handmer, J., & Magee, L. (2017). How much do disasters cost? A comparison of disaster cost estimates in Australia [38 citations (Crossref) [2023-08-16] Publisher: Elsevier Ltd]. *International Journal of Disaster Risk Reduction*, *21*, 419–429. https://doi.org/10.1016/j.ijdrr.2017.01.004

Langenheim, N., Sabri, S., Chen, Y., Kesmanis, A., Felson, A., Mueller, A., Rajabifard, A., & Zhang, Y. (2022). Adapting a Digital Twin to Enable Real-Time Water Sensitive Urban Design Decision-Making [0 citations (Crossref) [2023-03-17] ADS Bibcode: 2022ISPAr48W4...95L]. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *48W4*, 95–100. https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-95-2022

Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey [6 citations (Crossref) [2023-08-16]]. *Automation in Construction*, *147*, 104716. https://doi.org/10.1016/j.autcon.2022.104716

Milman, A., & Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector [164 citations (Crossref) [2023-08-16] Publisher: Elsevier]. *Global Environmental Change*, *18*(4), 758–767. https://doi.org/10.1016/j.gloenvcha.2008.08.002

Miotti, M., & Jain, R. (2021). Modeling aggregate human mobility patterns in cities based on the spatial distribution of local infrastructure. *Hawaii International Conference on System Sciences 2021 (HICSS-54)*. https://aisel.aisnet.org/hicss-54/da/digital_twins/3

Nochta, T., Wan, L., Schooling, J. M., & Parlikad, A. K. (2021). A socio-technical perspective on urban analytics: The case of city-scale digital twins [49 citations (Crossref) [2023-08-16] Publisher: Taylor & Francis]. *Journal of Urban Technology*, *28*(1-2), 263–287. https://doi.org/10.1080/10630732.2020.1798177

Rahmani, N. (2023). Digital Twin for Real -Time sensitive urban design decision making. Retrieved June 9, 2023, from https://eng.unimelb.edu.au/csdila/research/digital-twin/digital-twin-for-real-time-sensetive-urban-design-decision-making

Rajabifard, A., Sabri, S., Chen, Y., Agunbiade, M., & Kalantari, M. (2019). Urban Analytics Data Infrastructure: Critical SDI for Measuring and Monitoring The National and Local Progress of SDGs [Publisher: CRC Press]. *Sustainable Development Goals Connectivity Dilemma: Land and Geospatial Information for Urban and Rural Resilience*, 243.

Rajabifard, A., Thompson, R. G., & Chen, Y. (2015). An intelligent disaster decision support system for increasing the sustainability of transport networks [Issue: 2]. *Natural resources forum*, *39*, 83–96.

Ramos, H. M., Morani, M. C., Carravetta, A., Fecarrotta, O., Adeyeye, K., López-Jiménez, P. A., & Pérez-Sánchez, M. (2022). New challenges towards smart systems' efficiency by digital twin in water distribution networks [15 citations (Crossref) [2023-08-16] Publisher: MDPI]. *Water*, *14*(8), 1304. https://doi.org/10.3390/w14081304

Reisi, M., Sabri, S., Agunbiade, M., Rajabifard, A., Chen, Y., Kalantari, M., Keshtiarast, A., & Li, Y. (2020). Transport sustainability indicators for an enhanced urban analytics data infrastructure [12 citations (Crossref) [2023-08-16] Publisher: Elsevier Ltd]. *Sustainable Cities and Society*, *59*, 102095. https://doi.org/10.1016/j.scs.2020.102095

Sabri, S., Chen, Y., Lim, D., Rajabifard, A., & Zhang, Y. (2022). An Innovative Tool for Optimised Development Envelope Control (dec) Analysis and Scenario Building in Digital Twin [0 citations (Crossref) [2023-03-17] ADS Bibcode: 2022ISPAr48W4..117S]. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *48W4*, 117–123. https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-117-2022

Sabri, S. (2021). Chapter 1 - Introduction: Being smarter for productivity, livability, and sustainability. In H. M. Kim, S. Sabri, & A. Kent (Eds.), *Smart Cities for Technological and Social Innovation* (pp. 1–8). Academic Press. https://doi.org/10.1016/B978-0-12-818886-6.00001-0

Sabri, S., Winter, S., & Rajabifard, A. (2023). Creating digital twins to save our cities. Retrieved May 23, 2023, from https://pursuit.unimelb.edu.au/articles/creating-digital-twins-to-save-our-cities

Schrotter, G., & Hürzeler, C. (2020). The Digital Twin of the City of Zurich for Urban Planning [68 citations (Crossref) [2023-03-17] Publisher: Springer]. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science 2020 88:1*, *88*(1), 99–112. https://doi.org/10.1007/S41064-020-00092-2

Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals [5 citations (Crossref) [2023-03-17] Number: 10 Publisher: Nature Publishing Group]. *Nature Sustainability*, *5*(10), 822–829. https://doi.org/10.1038/s41893-022-00923-7

Yeganeh, N., & Sabri, S. (2014). Flood vulnerability assessment in Iskandar Malaysia using multi-criteria evaluation and fuzzy logic [15 citations (Crossref) [2023-08-16]]. *Research Journal of Applied Sciences, Engineering and Technology*, *8*(16), 1794–1806. https://doi.org/10.19026/rjaset.8.1167