INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
ISSN: 2180-3242 e-ISSN: 2600-7959

IJSCET

Vol. 16 No. 2 (2025) 246-279
https://publisher.uthm.edu.my/ojs/index.php/ijscet

Managing Urban Drainage Systems with Digital Twins: Global Insights and Applications in Vietnam

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DOI: https://doi.org/10.30880/ijscet.2025.16.02.016

Article Info

Received: 21 January 2025
Accepted: 26 August 2025
Available online: 15 September 2025

Keywords

Digital twins, urban drainage systems, smart cities, Vietnam, infrastructure resilience

Abstract

This study explores the transformative role of digital twin (DT) technologies in enhancing urban drainage system (UDS) management, with a dual focus on global applications and the evolving Vietnamese context. Drawing on six international case studies—Barcelona, Graz, Houston, Odense, Xi'an, and Austin—the research synthesizes best practices in real-time monitoring, predictive analytics, and integrated infrastructure management. These benchmarks are then used to evaluate five Vietnamese cities—Hanoi, Da Nang, Hue, Son La, and Cao Bang—representing a cross-section of urban scales, geographic diversity, and digital maturity. Through a mixed-methods approach combining literature review, maturity modeling, and qualitative benchmarking, the study identifies current capabilities, challenges, and opportunities for each locality. Findings highlight the varied levels of digital readiness and underscore the need for tailored strategies addressing infrastructure gaps, data integration, and human resource capacity. The study concludes with city-specific recommendations and a proposed roadmap for advancing DT-enabled UDS management in Vietnam. These insights offer implications for public policy, smart city development, environmental resilience, and educational innovation in the context of rapid urbanization and climate change adaptation.

1. Introduction

Urban drainage systems are essential infrastructure for managing stormwater, preventing floods, and safeguarding public health and environmental quality in cities worldwide [1]. However, rapid urbanization, climate change-induced extreme weather, and aging infrastructure have intensified UDS challenges, leading to significant economic and social impacts [2]. Globally, urban flooding causes an estimated $120 billion in annual damages, disrupting livelihoods and infrastructure [3]. In Vietnam, these issues are amplified by diverse geographical and socio-economic contexts, from flash floods in mountainous regions like Son La [4] and Cao Bang [5], which threaten agricultural livelihoods, to coastal inundation in Da Nang, impacting tourism and fisheries [6], and also normal life [7], to heavy loss of life, damage to homes and production in Hue City [8], and urban runoff in Hanoi, disrupting metropolitan life [7]. Traditional UDS management, reliant on static designs and manual operations, is ill-equipped to handle these dynamic pressures, necessitating innovative digital solutions [9, 10].

Digital Twins, dynamic virtual replicas of physical systems integrated with real-time data and advanced analytics, offer a transformative approach to UDS management [9, 11]. Unlike traditional static models, DTs are dynamic virtual replicas of physical infrastructure that continuously integrate real-time data from sensors and other sources to simulate, monitor, and optimize system performance [12]. Cities such as Barcelona, Houston, and Lisbon have successfully implemented DTs for flood resilience, enabling predictive maintenance, scenario planning, and rapid response to extreme weather events [12]. These systems leverage advanced analytics and cloud computing to provide decision support, reducing flood risks and improving operational efficiency. By leveraging technologies like IoT, AI, GIS, and BIM, DTs enable real-time monitoring, predictive maintenance, and scenario planning, aligning with global smart city frameworks and emerging trends in 5G and cloud computing [9, 13]. In Vietnam, where UDS capacity meets only 20-30% of demand [14], DTs hold promise for enhancing resilience, yet their adoption remains limited due to insufficient digital infrastructure and expertise. Despite significant investments, such as the recent drainage upgrade projects in Hanoi [15] and Da Nang [16], the lack of integrated digital systems hinders proactive flood management and environmental protection, as seen in Da Nangs microplastic pollution crisis [17].

This study addresses the critical gap between Vietnams complex UDS challenges and the nascent adoption of DT technologies. The research questions are: (1) What are the key applications and components of DTs in global UDS management? (2) How are DTs or their precursors applied across Vietnams diverse urban contexts, and what are their limitations compared to global standards? The objectives are to review global DT applications, identify critical components, and evaluate their implementation in Vietnam through case studies in Son La, Cao Bang, Hue City, Da Nang, and Hanoi, capturing regional variations to inform scalable solutions. These case studies provide insights into Vietnams digital transformation journey, aligning with national smart city and Industry 4.0 policies.

The paper is structured as follows: Section 2 provides background; Section 3 outlines methodology; Section 4 presents results; Section 5 discusses findings with recommendations; and Section 6 concludes the research.

2. Background

Vietnam is undergoing a substantial digital transformation, guided by its National Digital Transformation Program under Decision No. 749/QD-TTg, issued by the Prime Minister in 2020. This initiative seeks to modernize national infrastructure and public services through the adoption of Industry 4.0 technologies. Central to this strategy is the integration of digital tools such as the Internet of Things (IoT), Artificial Intelligence (AI), Geographic Information Systems (GIS), and Building Information Modeling (BIM) across multiple sectors, including urban water management and drainage systems [18].

To implement this vision, the Ministry of Construction has mandated the phased adoption of BIM in public infrastructure projects, starting with complex class II and above projects by 2025 [19, 20]. Additionally, Decision No. 942/QD-TTg promotes smart city development by prioritizing digital technologies in urban infrastructure, including drainage and flood control [21].

More broadly, Resolution 57-NQ/TW (2024) elevates science, technology, and innovation as drivers of socio-economic development, aiming to build a high-income, digital economy by 2045. It encourages investment in digital infrastructure and supports experimental technologies for climate-resilient urban management, especially in infrastructure-intensive sectors like drainage [22].

The urgency for adopting advanced technologies in drainage system management stems from the increasing frequency and severity of urban flooding in Vietnamese cities. Rapid urbanization, aging infrastructure, and climate change have rendered conventional approaches insufficient. Major cities like Hanoi, Ho Chi Minh City, and Da Nang regularly experience inundation after heavy rain, disrupting transport, damaging property, and threatening public health. These conditions highlight the need for predictive, real-time, and integrated tools—capabilities that digital twins (DTs) are uniquely equipped to deliver.

Globally, cities such as Singapore, Rotterdam, and Helsinki [12] have deployed DTs to simulate and manage complex urban water systems, improving flood prediction and adaptive planning. Vietnam, while active in adopting BIM, GIS, and IoT in select projects, remains at an early stage in exploring DT applications in drainage. The absence of integrated DT use in this field represents a significant gap, particularly in meeting the objectives of smart city and digital transformation policies.

In summary, the increasing pressure from urban flooding and infrastructure complexity makes the application of DTs not only timely but necessary. Aligning with both global trends and Vietnam's digital development agenda, DTs offer a strategic opportunity to enhance operational efficiency, disaster preparedness, and sustainable urban infrastructure management.

3. Research Methodology

This research investigates the global application of digital twin (DT) technologies in managing UDS and evaluates their implementation within the Vietnamese context. To achieve these objectives, a mixed-methods approach was adopted, combining qualitative synthesis with case-based analysis and framework development. As illustrated in Figure 1, the study was conducted in three interrelated steps:

- Systematic literature review to explore global applications of DTs in urban drainage management;
- Case study analysis to examine current practices and readiness for digital twin adoption in selected Vietnamese cities;
- Framework development to propose a context-specific roadmap for digital twin integration in Vietnam's UDS.

Fig. 1 *The research process*

Stage 1: Systematic Literature Review

The first stage aimed to identify and analyze global trends, use cases, and technological components related to the implementation of digital twins in urban drainage systems (UDS). Additionally, it sought to establish criteria for assessing the maturity level of digital twin applications in UDS management. A systematic literature review was conducted using the Scopus database, selected due to its comprehensive coverage and recognition as "the world's largest abstract and citation database of scientific literature" [23]. The following query was used to identify relevant studies: TITLE-ABS-KEY (("digital twin" OR "digital twins") AND "urban" AND "drainage*").

This query initially yielded 21 publications. A screening process based on title and abstract relevance was conducted, resulting in the exclusion of 3 articles that did not address either urban drainage or DT applications. The remaining 18 studies were selected for in-depth analysis.

These papers were categorized along two dimensions:

- Applications of DTs: including design, monitoring, predictive analysis, and asset management;
- Technological components: such as sensors, Internet of Things (IoT), Geographic Information Systems (GIS), Building Information Modeling (BIM), and Artificial Intelligence (AI).
- The synthesis of these studies provided insight into global best practices, which later served as benchmarks for evaluating the Vietnamese context.

Stage 2: Case Study Analysis in Vietnam

The selection of Hanoi, Da Nang, Hue, Son La, and Cao Bang as representative case studies was guided by their diversity in urban scale, digital readiness, geographic location, and policy engagement in drainage infrastructure development. These five cities reflect a cross-section of Vietnam's urban landscape, ranging from major metropolitan hubs to mid-sized and mountainous provincial centers. This diversity ensures a comprehensive and balanced assessment of the challenges and opportunities for applying digital twins in different socio-technical and environmental contexts.

- Hanoi represents a large and densely populated capital city with advanced hydraulic modeling, extensive GIS databases, and early-stage IoT integration—offering a view into a high-capacity urban environment with strong policy leverage.
- Da Nang is a coastal city recognized for its proactive digital transformation efforts and international partnerships, making it a leader in smart infrastructure planning.
- Hue serves as an example of a mid-sized city with strong institutional interest in digital innovation through a recent project, but with limited system integration to date.
- Son La was selected to represent mountainous urban environments with early-stage adoption of BIM for O&M and limited real-time infrastructure, offering insights into the feasibility of DT in more constrained settings.
- Cao Bang illustrates challenges of low-resource environments, where current drainage planning is largely static and GIS-based, with minimal digital twin elements in place.

Together, these five cities provide a holistic understanding of Vietnam's urban drainage ecosystem and allow benchmarking across different levels of maturity, investment, and digital infrastructure. Table 1 shows the sources for getting information for the case studies.

Table 1 *The case studies in Vietnam*

Province	Sources
Son La	Son La Department of Construction (2021) [24], CIC. (2023, 8 April) [25]
Cao Bang	Le, T. M. P (2023) [26], Nguyen, V. T., & Ta, V. P. (2025) [27]
Da Nang	Fulbright School of Public Policy and Management. (2024) [28], Fulbright School of Public Policy and Management. (2024) [29], Dang, V. D., Dang, T. D., & Trinh, C. D. (2023) [30], Trong Hung. (2025) [31], Nguyen, L. (2025) [32]
Hue City	Nguyen, H. S. (2014) [33], Hoai Thuong. (2025) [34]
Hanoi	Vu, L. A., & Dinh, T. T. H. (2024) [35], Son Nguyen, & Van Nhi. (2023) [36], Hai Yen. (2023) [37], Cyrill, M. (2025) [38], Hoang Hanh. (2025) [39], Nguyen, K. D., & Quach, T. T. T. (2016) [40]

The case studies then are compared with global cases for benchmarking.

Selection of Global Case Studies for Benchmarking

To conduct a robust benchmarking comparison, we selected six global case studies from the systematic literature review. These cases were chosen to represent a diverse range of advanced DT applications in UDS, providing a comprehensive set of "best practices" for comparison. The selection criteria focused on the variety of DT functionalities, technological sophistication, and geographical contexts, ensuring relevance for evaluating potential UDS cases across Vietnam's diverse urban landscape (e.g., metropolitan, coastal, mountainous regions).

The selected cases offer insights into:

- Real-time control and optimization: Demonstrating how DTs enable dynamic management of water flows and infrastructure operations.
- Model simplification and computational efficiency: Highlighting methods to make complex simulations practical for large-scale urban systems.
- Visual data and resilience assessment: Showcasing innovative approaches to integrate visual information for infrastructure condition monitoring and risk analysis.
- Uncertainty diagnosis and knowledge base improvement: Illustrating how DTs can enhance the reliability of models and operational knowledge.

The six global case studies are:

- Barcelona (Spain) [41]: Noted for real-time control and urban water cycle optimization.
- Graz (Austria) [42, 43]: Focus on automated model simplification for computational speed.
- Houston (Texas, USA) [44]: Pioneering in using visual data and deep learning for infrastructure resilience assessment.
- Odense (Denmark) [45]: Known for diagnosing model uncertainties and improving knowledge bases through sensor data.
- Xi'an (China) [46]: Illustrates an efficient flood control and drainage management framework with pump optimization.
- Austin (Texas, USA) [47]: Focuses on stormwater DT with online quality control for flood hazard detection under uncertainty.

Stage 3: Benchmarking and Recommendations

The final stage of the methodology focused on synthesizing findings from the previous two stages to propose recommendations for the adoption of DTs in Vietnam's UDS. This draws from:

- Global best practices identified in the literature review;
- Vietnamese case studies Benchmark with global best practices;
- Recommendations.

The framework outlines key components such as stakeholder coordination, technological infrastructure, policy alignment, and capacity-building needs. It aims to serve as a strategic guide for national and local governments, utility agencies, and technology providers seeking to advance digital twin applications in the urban drainage sector.

4. Results

4.1 Global Applications of Digital Twins in UDS

An analysis of 18 papers reveals a steady increase in publications related to DTs in UDS, indicating growing research interest and activity in this field. Relevant publications only began to emerge in 2020. In 2021, three papers were published, followed by two in 2022. The number peaked at five publications in 2023 before declining slightly to four in 2024. As of June 2025, three papers have been published on this topic.

In terms of geographic distribution, research on DTs in UDS spans a broad range of regions, with significant contributions from Asia, North America, and Europe. Additionally, a few studies adopt a more general or multi-contextual focus without reference to a specific region.

- Asia: 6 papers (China: 5; Indonesia: 1)
- North America: 5 papers (USA: 4; Canada: 1)
- Europe: 5 papers (Spain, Denmark, Estonia/Sweden, Austria/Germany/Canada/Colombia)
- Other/Unspecified regions: 2 papers

Table 2 summarizes the applications of Digital Twin technologies in UDS, based on information extracted from the reviewed publications. It presents key details including the focus of each study, specific applications, technologies used, and case study locations.

Table 2 *Summary of digital twin applications in urban drainage systems globally*

Authors (Year)	Focus	Application	Key Technologies	Case Study Location
Fan et al. (2025) [46]	Efficient urban flood control & drainage management	Optimize pump scheduling, balance water level & operational costs	Digital twin, optimization algorithm (NSGA-III), deep learning (LSTM), Unity3D, PLC, hydrodynamic model (GAST)	Xi'an, China
Yu et al. (2023) [48]	DT-enabled & knowledge-driven decision support for tunnel electromechanical equipment maintenance	Proactive TEE maintenance, fault detection, state prediction	Digital twin, knowledge ontology, Semantic Web, BIM, IoT, machine learning, combinatory reasoner	Wenyi Road Tunnel in Hangzhou, China
Bartos & Kerkez (2021) [49]	Interactive digital twin for natural & urban drainage	Real-time modeling, state estimation, flood detection, maintenance characterization, control	Digital twin, hydraulic solver (Saint-Venant), Kalman filtering, Python, Numba	A 5.85 km^2 urban watershed in the Midwestern United States
Kim M.-G. & Bartos (2024) [50]	Contaminant fate & transport in drainage networks	Pollutant tracking, source identification, water quality management	Digital twin, Kalman filtering, ARD equation solver, Python, Numba	A real-world stormwater network in the Midwestern United States
Sharifi et al. (2024) [51]	AI in DT models for stormwater in smart cities	Enhance stormwater efficiency/sustainability, predictive maintenance, optimize objectives	Digital twin, AI, IoT, 5G, Big Data Analytics, Visualization, Digital Platforms, GIS, Remote Sensing, SCADA	General (Smart Cities)

Authors (Year)	Focus	Application	Key Technologies	Case Study Location
Kim Y. et al. (2025) [47]	Stormwater DT with online quality control for flood hazards	Real-time monitoring, rapid flood response, predictive maintenance, sewer control	Digital twin, EKF, wireless sensor networks, hydrologic-hydraulic model (PipeDream)	Waller Creek watershed in Austin, TX
Li X. et al. (2022) [13]	Effective water-energy management in sustainable cities	Resolve waterlogging, manage water resources, improve pumping station efficiency	Digital twin, 5D DT model, MDPIS algorithm, IoT sensors, SDN	General (Sustainable Cities)
Li X. et al. (2024) [52]	Hydrodynamic model-driven optimization of drainage pumping stations	Optimize pump operations for flood management & cost control	Hydrodynamic model (GAST), evolutionary algorithms (APSO), data-driven tech, Kriging model, GPU acceleration, PLC	An experimental platform for flood management digital twin at Xi'an University of Technology
Pedersen et al. (2022) [45]	Diagnosing uncertainty in UDS models using sensor data	Identify/diagnose errors, improve network maintenance knowledge	Digital twin, water level sensors (IoT), Mike Urban software	Odense, Denmark
Li J. et al. (2023) [53]	Flood control ponding around rail transit stations	Real-time ponding calculation, backflow critical point prediction	Digital twin, 3D laser scanning, model engine, spatial computing engine, GIS	Huoying Station of Beijing Metro, Beijing, China
Savić (2025) [54]	Urban flood risk & resilience	Assess flood risk, analyze mitigation, map flood damage, green infrastructure impacts	Flood simulation, terrain mapping (SAR, LiDAR), AI, digital twins, hybrid AI models	Not specified, general discussion on urban flood risk (Montreal, Canada mentioned in context)
Schütze (2024) [43]	Automated simplification of hydrodynamic UDS models	Reduce simulation time, assess rainwater management, evaluate discharge impact	Automated model transformation, Simba# simulator, GIS, Python (swmm-api), SWMM, AI	Graz (Austria), Germany, Canada, Colombia
Tanne et al. (2023) [55]	Integrated system for urban road asset management	Real-time monitoring, condition prediction, optimize transport planning	IoT sensors, AI, BIM, Digital Twin, VR, AR, Cloud, actuators, robots	Urban areas in Indonesia, Bandung
Kim J. et al. (2023) [44]	Visual data-driven DT for UDS resilience	Identify infrastructure condition, risk analysis, proactive hazard mitigation	Digital twin, deep learning, participatory sensing, street-level visual dataset, GIS, 3D virtual city model, Yolov4, computer vision	Houston, TX, USA

Authors (Year)	Focus	Application	Key Technologies	Case Study Location
Sun et al. (2020) [41]	Real-time control of urban water cycle (UWC) under CPS	Efficient UWC management, subsystem interoperability, integrated optimization	CPS, Digital Twin, MPC, IoT, SCADA, SIMULINK/MATLAB, SWMM, MIKE Urban, EPANET, PLC	Barcelona Urban Water Cycle (UWC), Spain
Pedersen et al. (2021) [56]	Living & prototyping DTs for urban water systems	Multi-purpose value creation, operational/control, design/planning, knowledge base improvement	Digital twin, models, sensors (IoT), APIs, analytics, cloud/fog storage, user interfaces, simulation models (Mike Urban, MOPS)	Odense, Denmark
Truu et al. (2021) [57]	Integrated decision support for pluvial flood-resilient spatial planning	Reduce flood risks in urban planning, analyze climate change impact, find mitigation solutions	Planning support system (EWL), digital twin, GIS, 1D hydraulic modeling, SWMM, Python	Haapsalu (Estonia) and Söderhamn (Sweden)
Pichler et al. (2024) [42]	Fully automated simplification of urban drainage models on a city scale	Reduce computational time, assess rainwater management, evaluate discharge impact, control	Automated simplification method, SWMM, Digital Twins, Python (swmm-api, PySWMM), GIS, DEM, ML/ANN	Graz (Austria), Germany, Canada, Colombia

According to the reviewed publications, DTs in UDS are applied across various stages of the system lifecycle, enhancing capabilities in planning, monitoring, prediction, and asset management.

Applications Across the UDS Lifecycle (Figure 2)

- Design and Planning: DTs enable the simulation of hydraulic and hydrological behavior under diverse scenarios, often integrating Geographic Information Systems (GIS) and Building Information Modeling (BIM) for spatial accuracy. This supports flood-resilient urban planning by linking land use with UDS performance. Examples include modeling rainfall-runoff on urban rooftops and streamlining drainage models to accelerate design-phase processing.
- Real-Time Monitoring and Control: DTs utilize sensor data—such as from flow meters and water quality sensors—for real-time anomaly detection and dynamic control. Applications include optimizing the urban water cycle using Model Predictive Control (MPC), managing pumps and gates to reduce flood risk, estimating real-time hydraulic states, and tracking contaminant transport.
- Predictive and Scenario Analysis: DTs leverage AI and machine learning to forecast flood risks, assess green infrastructure, and simulate flood dynamics. Techniques include diagnosing model uncertainty using hydrologic signatures, simplifying models through automation, and predicting the timing of backflow events for rail transit flood control.
- Lifecycle Asset Management: DTs support infrastructure condition monitoring, enabling predictive maintenance and resilience assessments. Use cases include fault detection in electromechanical components (e.g., tunnel systems), infrastructure condition mapping, and integrated asset management for urban roads and drainage systems.

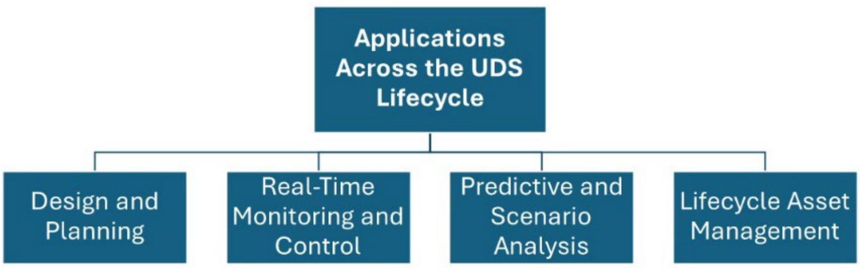

Fig. 2 *Global applications across the UDS lifecycle*

Advanced Technologies Leveraged (Figure 3):
The reviewed literature highlights a broad spectrum of advanced technologies essential for the development and effective operation of DTs in UDS:

- Sensors & IoT Devices: Critical for real-time data acquisition related to flow, water quality, water level, weather, and infrastructure status. Devices include ultrasonic level meters, electromagnetic flowmeters, voltage and current sensors, and road damage detection sensors.
- Geographic Information Systems (GIS): Used for spatial analysis, flood risk mapping, and integrating land use data to support planning and design.
- Building Information Modeling (BIM): Provides 3D digital representations of infrastructure components, supporting visualization and integration. BIM is often paired with VR/AR for enhanced user interaction and serves as a foundational layer for full DT implementation.
- Artificial Intelligence (AI) & Machine Learning (ML): Applied in predictive analytics, flood forecasting, anomaly detection, model simplification, optimization, and dynamic system analysis. Techniques include Deep Learning (e.g., LSTM), Kalman Filtering (e.g., EKF), Reinforcement Learning, and optimization algorithms such as NSGA-III and APSO.
- Real-Time Data Platforms & Cloud Computing: Provide the backbone for continuous monitoring, data storage, and dynamic control capabilities.
- Simulation & Modeling Software: Includes widely used hydrodynamic and hydrological modeling tools such as SWMM, GAST, MIKE Urban, EPANET, the Saint-Venant equations, the Green-Ampt model, and specialized engines like Pipedream and the Simba# simulator.
- Visualization & User Interfaces: Dashboards, 3D visualizations, Virtual Reality (VR), Augmented Reality (AR), and interactive tools enhance stakeholder engagement and intuitive understanding of system performance.
- Control Systems: Tools like Programmable Logic Controllers (PLCs) and Model Predictive Control (MPC) automate the operation of pumps, gates, and other infrastructure elements in response to real-time data.
- Data Management & Interoperability: Technologies such as Semantic Web standards, APIs, and Big Data Analytics facilitate data integration, knowledge extraction, and interoperability between systems.
- High-Performance Computing (HPC): GPU acceleration is used to boost the computational speed of complex numerical models and simulations.

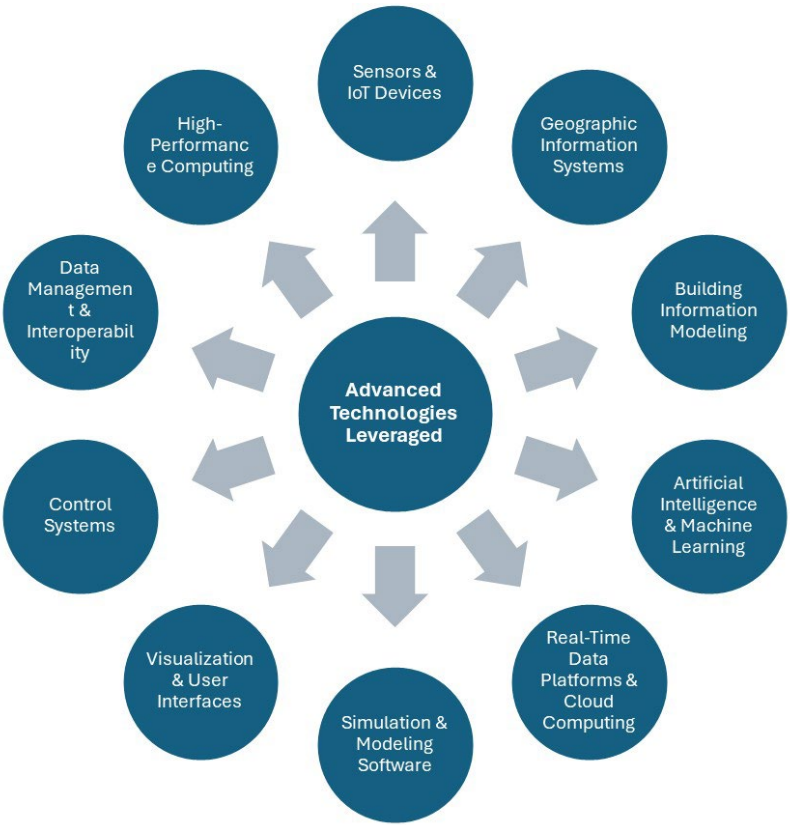

Fig. 3 *Advanced technologies leveraged in the applications of digital twins in UDS*

Figure 4 illustrates a conceptual framework of DTs for UDS, emphasizing the integration between physical infrastructure and digital components.

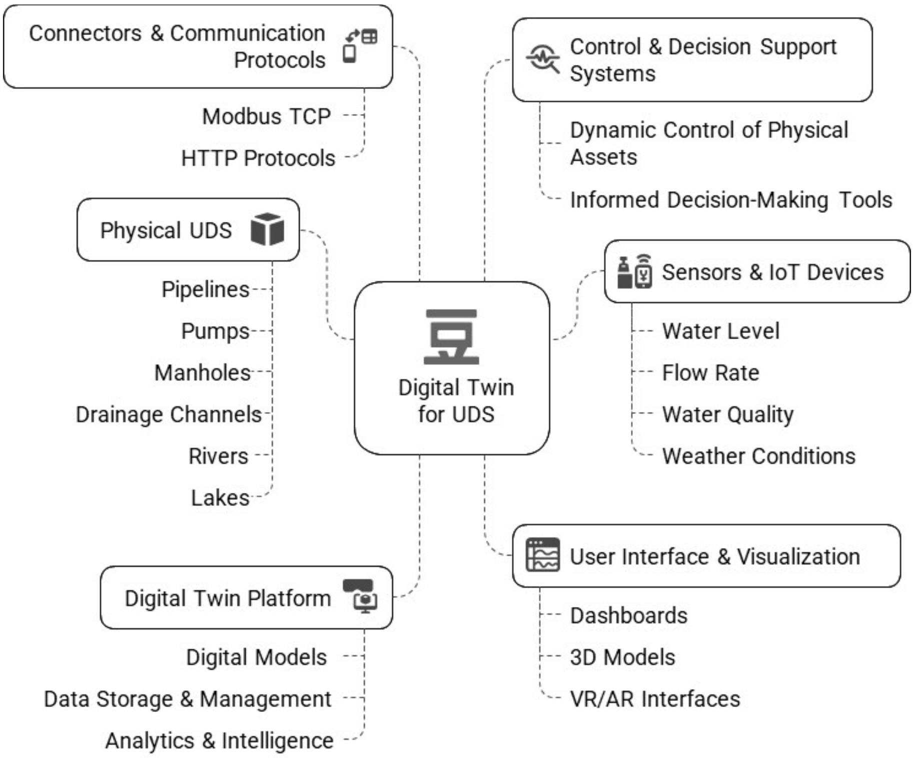

Fig. 4 *Conceptual framework of digital twin for urban drainage systems*

The framework can evolve through different maturity levels:

1. Basic (Static Models): Characterized by 2D AutoCAD drawings and manual data management.
2. Prototyping DT: Incorporates BIM and limited IoT integration (e.g., the Son La pilot project).
3. Advanced DT: Features AI-driven analytics and real-time capabilities (e.g., Barcelona's CPS framework).
4. Living DT: Utilizes deep learning and cloud computing for comprehensive, dynamic, and autonomous management (e.g., Houston's visual data-driven DT).

This conceptual framework highlights the complexity and interdisciplinary nature of implementing DTs in UDS, emphasizing the integration of various technologies and data flows to achieve proactive and resilient urban water management.

4.2 DT Applications in Son La Province, Vietnam

Son La Province, located in the mountainous northwest of Vietnam, experiences heavy seasonal rainfall and is particularly vulnerable to flash flooding. The UDS in Son La City, comprising drainage channels along the Nam La River and a wastewater treatment plant, plays a crucial role in mitigating flood risks and ensuring environmental sustainability.

In response to the increasing frequency of extreme weather events and the need for improved flood resilience, the Son La Department of Construction initiated a pilot project in 2022 to modernize UDS management [24]. The initiative seeks to adopt a Building Information Modeling (BIM)-based framework as a foundational step toward implementing a comprehensive Digital Twin (DT) system. This approach aims to enable real-time data integration, dynamic system modeling, and data-driven decision-making. The perceived existing challenges include:

- Legacy Systems: Current UDS management practices rely heavily on 2D AutoCAD drawings, paper-based documentation, and conventional software. These methods are static, non-interactive, and labor-intensive, complicating real-time data access and situational awareness during flood events.
- Data Fragmentation: Lack of centralized data storage and integration hinders cross-department collaboration and efficient analysis.
- Limited Monitoring: Minimal sensor deployment limits the ability to detect, predict, and respond proactively to flood conditions or wastewater management failures.

The key components of the BIM-based digital twin pilot recognised include:

- Digital Modeling: Replaces 2D drawings with a 3D BIM model, improving visualization and the understanding of system interconnectivity.

To improve UDS management, a pilot project was launched in 2022 following the Son La Department of Construction's proposal, with a total budget of VND 450 million (USD 18,750) [24]. The project aims to adopt a BIM framework as a precursor to full DTs, integrating real-time data and 3D visualization to enhance decision-making and operational efficiency.

- IoT and Sensor Integration: Deployment of 10 IoT sensors along the Nam La River and drainage channels for real-time monitoring of water levels and flow rates.
- GIS Mapping: Utilized for terrain analysis and infrastructure mapping to support flood risk assessment.
- User Dashboard: A centralized platform for visualizing flood-prone areas and optimizing pump operations.
- Software Tools: Implementation supported by Autodesk AEC software.
- Common Data Environment (CDE): Established on the BIM platform to enable collaborative work and centralized document management.
- SCADA System: Monitors environmental indicators including COD, TSS, pH, DO, and NH_4 levels, along with water inflow and outflow.
- Cloud-Based Database: Developed using HTML, CSS, JavaScript, PHP, and SQL for seamless data access and scalability.

Funding is sourced from the 2021 UDS operational budget and aligns with national digital transformation policies (Decree 15/2021/ND-CP and Decision 749/QD-TTg), which advocate the use of BIM and digital technologies in smart city development. Table 3 summarizes the BIM-based DT Implementation in Son La UDS.

Table 3 *Summary of BIM-based DT implementation in Son La UDS*

Aspect	Details	Challenges	Solutions
Objective	Enhance UDS management with BIM for monitoring and flood mapping	Limited scope	Expand to full DT with AI
Components	10 IoT sensors, BIM 3D model, GIS, Autodesk AEC	Limited sensor coverage	Deploy more sensors
Budget	VND 450M (consultation, training, software)	High initial costs	Justify via long-term savings
Outcomes	30% less maintenance time, 10% cost savings	Lack of analytics	Integrate machine learning
Policy Alignment	Decree 15/2021, Decision 749/QD-TTg	Interoperability issues	Align with smart city frameworks

Rationale for Proposed Solutions

The transition from a basic BIM model to a full Digital Twin system is driven by the need for a more adaptive and intelligent urban drainage infrastructure in the face of increasingly erratic rainfall patterns. While the current pilot lays the groundwork, its limited scope restricts the full potential of DTs in disaster prevention and infrastructure optimization. Expanding the system to incorporate Artificial Intelligence (AI) will facilitate predictive analytics, enabling authorities to forecast flood risks and simulate different drainage scenarios under climate stress conditions.

The initial deployment of 10 sensors has helped build momentum for real-time monitoring; however, sensor coverage remains sparse, limiting the system's resolution and responsiveness. Additional sensors will improve data granularity and enable a more accurate spatial understanding of flood-prone areas, essential for localized interventions.

Although the project required a significant upfront investment, the long-term cost-effectiveness justifies the initial expenditure. The implementation has already demonstrated operational benefits, including a 30% reduction in maintenance time and a 10% cost saving. These results strengthen the economic rationale for continued investment in expanding and scaling the system.

The absence of advanced data analytics was identified as a bottleneck. Integrating machine learning models will allow the system to learn from historical patterns, enhancing its capacity to generate alerts and support strategic planning. These capabilities are crucial for developing an adaptive, self-learning system in the future.

Finally, while the project aligns with Vietnam's digital transformation policies, interoperability with national and municipal platforms remains a challenge. Standardizing the DT framework with existing smart city architectures will ensure long-term scalability and foster collaboration across sectors. This alignment is not only a technical requirement but also a strategic one to ensure the project receives institutional support and regulatory coherence.

4.3 Cao Bang Province, Vietnam

Cao Bang, located in the mountainous northeast of Vietnam, is highly prone to flash floods due to its steep topography and intense seasonal rainfall. The province's Urban Drainage System (UDS), composed of basic drainage channels and limited-capacity treatment facilities, struggles to mitigate these risks effectively. Traditional methods such as manual field surveys and static topographic maps are still widely used, severely limiting the responsiveness and accuracy of flood management efforts.

In response to these challenges, a study launched in 2023 introduced the use of Geographic Information System (GIS) technologies and MIKE FLOOD hydrodynamic modeling as foundational tools for an eventual Digital Twin (DT) system. With a modest budget of VND 200 million funded by local authorities, the project set out to identify flood-prone zones and enhance planning and decision-making capabilities for disaster preparedness and infrastructure development.

The existing UDS relies on manual surveys and basic topographic maps, which significantly limit the ability to respond quickly and accurately during flood events. This is the limitation of the current system.

Components of the GIS/MIKE FLOOD-Based DT Initiative

- GIS Technology (ArcGIS): Used to construct an urban drainage database, supporting the storage, transformation, and visualization of spatial data. It integrates various layers, including canals, drainage systems, land use, and groundwater levels.
- National Geographic Database Alignment: The GIS model adheres to the standards of Vietnam's National Geographic Database (VN-2000, WGS-84, National Elevation System), ensuring compatibility with broader regional datasets.
- Data Collection Methods: Information is sourced from the national geographic database, existing drainage system drawings (.dwg format), and official reports. Field surveys and GPS technology are also employed to gather detailed spatial and attribute data.
- Database Management System (DBMS): Tools are used to develop and manage the database, which is categorized into current and planned drainage system data sets.

The project is aligned with Vietnam's national smart city development policies. Early outcomes show a 15% reduction in flood impacts in targeted areas and enhanced urban planning efficiency. Despite these gains, the absence of real-time data and limited funding restrict the full potential of the digital transformation. Table 4 summarizes the project's key aspects and associated challenges.

Table 4 *Summary of GIS/MIKE FLOOD implementation in Cao Bang UDS*

Aspects	Details	Challenges	Solutions
Objective	Map flood zones for better UDS planning	No real-time data	Add IoT sensors
Components	GIS, MIKE FLOOD, open-source tools	Limited coverage	Expand mapping
Budget	VND 200M (data, software, support)	Funding constraints	Seek grants
Outcomes	15% reduced flood impact	Static model	Integrate dynamic data
Policy Alignment	Smart city policies	Scalability issues;	Enhance infrastructure

Rationale for Proposed Solutions

The current project provides a significant first step in digitally transforming flood risk management in Cao Bang. However, its reliance on static models and offline data limits its effectiveness, particularly in responding to flash floods that require real-time monitoring and adaptive responses. Therefore, the integration of IoT sensors is a logical next phase. These devices would enable continuous monitoring of rainfall, water levels, and flow velocities, feeding real-time data into MIKE FLOOD and GIS models for dynamic simulations and predictive alerts.

The existing GIS and MIKE FLOOD system covers only high-priority urban areas. Yet flash floods in Cao Bang often originate in upstream or peri-urban zones that are currently unmapped. Expanding the mapping scope will enhance the province's ability to plan and intervene across the full watershed, not just localized hotspots. This step is essential to transition from reactive management to proactive, system-wide flood resilience.

The project's limited funding has constrained the scope of modeling, training, and infrastructure acquisition. To overcome this, securing external grants or partnerships—especially through Vietnam's national digital transformation fund or international donors—could ensure the continuity and scalability of the project. Targeted funding could support hardware investments, platform upgrades, and integration with national digital infrastructure.

Finally, the project currently lacks the technical capacity to support scalable, interoperable digital systems. Investing in digital infrastructure (e.g., scalable cloud platforms and open data standards) will allow the province to scale the system as more data and stakeholders become involved. It will also facilitate integration into broader smart city platforms, ensuring the longevity and institutional relevance of the initiative.

4.4 Hue City, Vietnam

Hue City, located in central Vietnam, is internationally recognized for its rich cultural heritage, historical monuments, and ancient infrastructure. However, the city is also highly susceptible to seasonal flooding, which threatens both its historic assets and its urban population. The city's aging UDS, combined with increasing rainfall variability due to climate change, has made flood risk management a pressing urban challenge. From 2020 to 2023, a digital transformation project supported by international academic and technical partners—particularly from Germany—was implemented to address these vulnerabilities. With a total investment of VND 300 million, the initiative focused on modernizing flood management strategies by introducing Digital Twin (DT)-oriented technologies. The project marked a strategic shift from traditional paper-based systems to digital infrastructure capable of simulation, visualization, and future real-time integration.

Historically, UDS management in Hue relied on manual records and outdated maps, leading to slow response times during flood events. The initiative introduced key digital tools as precursors to DTs system.

Core components of the DT-Oriented Initiative

- Digital Twin Modeling: The project initiated the development of a dynamic digital replica of the city's UDS. This foundational model was intended to simulate drainage behavior under different flood scenarios and support urban planning.
- Sensor Infrastructure (Planned): Though not fully installed during the pilot, sensor-based systems were included in the design to eventually enable real-time monitoring of rainfall intensity, water levels, and flow velocity.
- Hydraulic and Hydrological Modeling: Advanced commercial or academic tools were employed (likely developed in collaboration with German partners) to model stormwater flows, capacity bottlenecks, and overflow risks.
- Data Integration Platform: Designed as the digital backbone of the system, this platform aggregates model data, historical records, and real-time sensor inputs (once deployed) to support informed decision-making.
- Visualization Tools: User-friendly dashboards and geospatial visualizations were created to communicate simulation results and real-time conditions to planners, engineers, and stakeholders.
- Artificial Intelligence / Machine Learning (Planned): Although not implemented during the project period, AI/ML modules were proposed to enhance predictive analytics and long-term optimization of the UDS.
- GIS Mapping: A key success of the initiative was the mapping of over 200 kilometers of drainage pipelines and 500 manholes, creating a comprehensive spatial database for infrastructure management and flood risk zoning.

The initiative was funded through international development assistance, demonstrating growing global interest in supporting heritage-rich cities to become more climate resilient. Notable outcomes include a 20% increase in planning efficiency and the creation of a digital GIS inventory of Hue's UDS. However, the system remains static, and without real-time feedback mechanisms or analytics capabilities, it cannot yet fulfill the potential of a fully functioning Digital Twin (Table 5).

Table 5 *Summary of project implementation in Hue UDS*

Aspect	Details	Challenges	Solutions
Objective	Enhance planning with GIS database	No real-time data	Add sensors
Components	GIS mapping, 200 km pipelines	Static data	Incorporate IoT
Budget	VND 300M (mapping, software)	High costs;	Secure more funding
Outcomes	20% better planning efficiency	No analytics	Develop AI tools
Policy Alignment	Smart city initiatives	Interoperability	standardize systems

Rationale for Proposed Solutions

While the Hue City project made significant strides in digitizing the city's UDS, its most notable limitation is its reliance on static, historical data. The GIS maps and models provide valuable insights for planners, but without real-time data, the system cannot predict or respond dynamically to emerging flood conditions. To overcome this, the deployment of IoT sensors is an essential next step. These devices will enable continuous data flows from the field, including rainfall intensity, water levels in critical drains, and flow velocities in major pipelines. Such integration would empower the digital twin model to operate dynamically, with simulation and alert functions based on real-world conditions.

Moreover, while the hydrological models used in the project simulate different flooding scenarios, their predictive power is limited without AI or machine learning modules. By incorporating AI, the system could identify patterns in historical data, learn from past flooding events, and generate near-real-time predictions of drainage system performance under different weather conditions. These tools can also help in optimizing maintenance schedules, pump operations, and emergency response plans.

The high costs associated with developing and maintaining a DT system—especially those involving commercial software, hardware procurement, and technical capacity—remain a key barrier. However, mobilizing additional international funding or national-level smart city grants can help scale the project and transition from a static system to a full DT. Showcasing Hue's status as a UNESCO heritage city also offers an angle for international collaboration under climate adaptation or cultural resilience programs.

Finally, interoperability challenges persist, as Hue's digital systems must be compatible with national smart city platforms and databases to support long-term integration. By adhering to common data standards and ensuring system scalability, Hue can establish a model of digitally enhanced flood management that other heritage or medium-sized cities in Vietnam could replicate.

4.5 Da Nang City, Vietnam

Da Nang, a coastal city in central Vietnam, faces persistent challenges from tidal flooding and microplastic pollution, with concentrations measured at 1,482.0 ± 1,060.4 items/m^3. These hazards not only affect urban infrastructure and daily life but also pose long-term risks to public health and marine ecosystems. To enhance the city's resilience, a World Bank-funded digital transformation initiative was launched in 2021 with a total investment of VND 500 million. The project focused on developing a digital Urban Drainage System (UDS) database using the Storm Water Management Model (SWMM) to strengthen flood planning and improve environmental monitoring capabilities.

Prior to this initiative, UDS management in Da Nang was constrained by manual data collection methods and outdated mapping tools—approaches that failed to keep pace with the city's fast-changing hydrological and environmental conditions.

Key Components of the Digital Transformation Initiative (Table 6):

- Digital Modeling (SWMM): The SWMM platform enabled detailed simulation of stormwater flows, drainage network behavior, and pollution transport under various rainfall and tidal scenarios.
- GIS Integration: ArcGIS was used to digitally map and analyze 10 critical drainage points, creating a foundational layer of spatial data for decision-making.
- Open-Source Technologies: The use of free and extensible software solutions (e.g., EPA SWMM) allowed for future upgrades, cost savings, and potential integration with IoT systems.
- IoT Sensor Framework (Planned): Although not fully deployed at the time, the system was designed to integrate sensors capable of capturing real-time data on water level, flow rate, and rainfall.
- SCADA System: Centralized monitoring of drainage infrastructure and wastewater facilities, aggregating data from future IoT devices for city-wide operational visibility.
- Central Control Software: Interfaces with SCADA and sensors to provide alerts, operational insights, and remote control capabilities for drainage infrastructure.

- Cloud Storage: A cloud-based system facilitates scalable storage of sensor data and model outputs, ensuring high accessibility and disaster resilience.
- Mobile Applications: Field engineers and staff use mobile tools to update the system on-the-go, streamlining data entry and emergency responsiveness.
- Wireless Data Transmission: GPRS/3G/4G connectivity ensures smooth data flow from remote field devices to control centers in near real-time..

The project improved urban flood planning by 25% and helped identify major flood-prone areas. However, the absence of real-time data acquisition technologies remains a barrier to achieving a fully functional DT system.

The initiative has led to a 25% improvement in flood planning efficiency, enabling better identification of high-risk areas and more accurate prediction of urban drainage performance under extreme weather conditions. However, the lack of real-time data acquisition and pollution analytics tools remains a critical gap preventing the system from evolving into a fully functional DT.

Table 6 *Summary of SWMM implementation in Da Nang UDS*

Aspect	Details	Challenges	Solutions
Objective	Manage floods with SWMM database	No real-time data	Add IoT
Components	SWMM, GIS, 10 drainage points	Limited scope	Expand monitoring
Budget	VND 500M (data, software)	Funding needs	Seek partnerships
Outcomes	25% improved planning	Pollution monitoring	Enhance tools
Policy Alignment	World Bank initiatives	Scalability	Integrate sensors

Rationale for Proposed Solutions

The SWMM-based modeling in Da Nang represents a substantial leap forward from manual drainage management, offering planners a dynamic tool for simulating rainfall-runoff patterns, pipe capacity limits, and tide-induced backflows. Yet the true power of such models lies in dynamic, real-time calibration, which currently remains unfulfilled. To unlock the full potential of the system, the incorporation of Internet of Things (IoT) sensors is essential. These devices will provide continuous, automated input on key parameters—rainfall, water level, flow velocity—which can be used to update the SWMM model in real time, increasing accuracy and responsiveness.

The project's current focus on 10 critical drainage points, while a prudent starting point, captures only a portion of the city's drainage complexity. Expanding the spatial coverage of data collection—both in terms of geographic scope and monitored parameters—will allow the model to better reflect on-the-ground realities, including informal settlements, industrial runoff zones, and coastal tide influence.

Given the scale of Da Nang's infrastructure and the advanced technology required, sustainable financing remains a barrier. One strategic solution is to establish multi-stakeholder partnerships, drawing on public-private investment models, development aid, and municipal co-funding. These partnerships can support not only technical expansion but also the maintenance and scaling of real-time systems.

In addition to hydrological management, the growing problem of microplastic pollution in Da Nang's urban waterways highlights the need for enhanced environmental monitoring tools. By integrating smart sensors capable of detecting water quality parameters (e.g., turbidity, suspended solids, conductivity), the system could serve dual roles: flood prevention and pollution mitigation. This aligns with both urban sustainability goals and the World Bank's climate-smart city frameworks.

Lastly, for the system to evolve into a fully interoperable Digital Twin platform, Da Nang must ensure that its SCADA, GIS, IoT, and modeling tools adhere to common data standards and communication protocols. Doing so will not only improve internal integration but also allow seamless connectivity with regional or national platforms in the future.

4.6 Hanoi City, Vietnam

Hanoi, the capital of Vietnam and one of the country's fastest-growing metropolitan areas, has been increasingly vulnerable to urban flooding due to rapid urban expansion, outdated drainage systems, and insufficient planning tools. As new developments strain the city's legacy infrastructure, the frequency and intensity of localized floods have increased, posing serious risks to property, traffic, and public health.

In 2024, a targeted project was launched to evaluate and enhance the city's Urban Drainage System (UDS) performance using MIKE URBAN, a specialized hydraulic modeling platform. With a budget of VND 400 million, the project focused on the Yen Hoa–Hoa Bang urban area—an area experiencing recurring inundation due to overburdened conduits and poor runoff management.

Prior to the initiative, Hanoi's drainage planning relied on outdated hydraulic models, which lacked the capacity to simulate current urban hydrodynamics. This shortcoming severely limited the city's ability to deliver timely flood warnings or optimize drainage system upgrades.

Components of the DT Precursor (Table 7):

- Digital Modeling (MIKE URBAN): Enabled accurate simulation of stormwater behavior, pipe capacity, and overflow conditions within the Yen Hoa–Hoa Bang catchment. The model was essential in identifying flood-prone nodes and bottlenecks within the conduit network.
- Conduit Analysis: Approximately 60% of issues identified in the pilot area were attributed to blocked, undersized, or deteriorated pipelines, providing direct evidence for targeted rehabilitation.
- Open-Source Tools: Complemented MIKE URBAN with cost-effective geospatial and data analysis tools. These were proposed to be integrated with real-time data sources in future expansions.
- Sensor Infrastructure (Planned): While not implemented during the initial phase, the study acknowledged the necessity of integrating real-time monitoring devices (e.g., water level, flow velocity sensors) to support dynamic decision-making in future stages.

The project, funded through local government budgets, led to measurable outcomes: flood duration in pilot zones was reduced by 20%, and the modeling process helped identify infrastructure inefficiencies—particularly those related to aging conduits.

Table 7 *Summary of MIKE URBAN implementation in Hanoi UDS*

Aspect	Details	Challenges &	Solutions
Objective	Assess floods with MIKE URBAN	No real-time data	Add sensors
Components	MIKE URBAN, conduit analysis	Limited coverage	Expand scope
Budget	VND 400M (data, software)	Costly upgrades	Seek funding
Outcomes	20% reduced flood durations	No analytics	Integrate AI
Policy Alignment	Smart city policies	Urban sprawl	Improve infrastructure

Rationale for Proposed Solutions

The 2024 MIKE URBAN initiative represents a foundational step in modernizing Hanoi's flood management systems. However, its most significant limitation lies in the absence of real-time data inputs, which undermines the ability of the model to provide predictive alerts or simulate conditions dynamically. To address this, the integration of IoT sensors is an immediate priority. These sensors would continuously feed field-level data (e.g., water levels, flow velocities, rainfall intensity) into the MIKE URBAN model, allowing it to reflect current conditions and provide live feedback to decision-makers.

While the initial study was limited to the Yen Hoa–Hoa Bang catchment, scaling the modeling framework city-wide is critical given Hanoi's sprawling urban landscape and diversity of drainage challenges. Expanding the model's scope would support a system-wide diagnostic capability and allow for more strategic investment in flood prevention and UDS upgrades.

Given the high costs associated with hydraulic modeling tools, system retrofitting, and smart sensor integration, Hanoi must explore additional funding avenues, including public-private partnerships, climate adaptation funds, and international development grants. This will help sustain and scale the initiative beyond its pilot phase.

The project also currently lacks the use of advanced analytics or artificial intelligence, which could play a transformative role in forecasting flood events, optimizing maintenance, and simulating future urban expansion scenarios. Integrating AI-driven predictive tools into the MIKE URBAN platform would allow city planners to move from reactive to proactive flood management.

Lastly, the challenge of urban sprawl in Hanoi is not purely a technical issue—it is also institutional and policy-driven. To ensure that future drainage infrastructure keeps pace with development, the city must incorporate model-driven planning protocols into its urban growth management strategy. This would align with national smart city policies and help ensure that infrastructure planning, permitting, and investment decisions are all informed by data from the digital system.

5. Discussion

5.1 Son La Case

Son La has initiated its transition toward digital management of UDS through the adoption of Building Information Modeling (BIM). The primary objective of this initiative is to improve the efficiency and transparency of infrastructure operation and maintenance (O&M). A pilot proposal has been launched to implement BIM in managing the city's drainage and wastewater treatment system, serving as a foundational step toward broader digital transformation across the province's urban technical infrastructure.

This early-stage effort centers on developing a centralized platform that integrates drainage asset data with operational workflows. By enabling improved coordination across departments and enhancing maintenance planning, the project aligns with international best practices in digital asset management and process optimization. Although still in the prototyping phase, this effort lays the groundwork for a more sophisticated DT system.

Initial Outcomes and Benefits

- The pilot project has already demonstrated tangible improvements:
- Maintenance inspection times have been reduced by 30%, and operational costs lowered by 10%.
- Installed sensors now provide early flood warning capabilities along the Nam La River.
- The platform allows for holistic visualization of design documentation, aiding in error detection and environmental incident response.
- Document management has been enhanced through a Common Data Environment (CDE) with a user-friendly interface and high security.
- The system currently meets operational needs for the city's wastewater treatment facilities.
- It establishes a foundation for scaling BIM applications across other infrastructure sectors in the province, contributing to Son La's digital transformation roadmap.

Challenges

Despite these initial achievements, the Son La project faces multiple challenges:

- Limited Sensor Coverage: With only 10 sensors deployed across a 12-kilometer drainage network, the current coverage falls short of global standards.
- Lack of AI-Driven Analytics: The platform lacks predictive analytics and decision support powered by artificial intelligence.
- Human Resource Constraints: There is a shortage of IT-skilled personnel, and significant time is needed to train the existing workforce.
- Interoperability Barriers: Integrating BIM with other information systems remains technically complex.
- Investment Costs: High upfront costs for software, sensors, and platform upgrades present financial challenges.

Digital Twin Maturity Assessment

Son La's current system can be classified as a "prototyping digital twin," characterized by its foundational use of BIM without AI integration or extensive sensor feedback. This positions the city in the early stages of digital maturity, significantly trailing "living digital twin" systems such as those in Barcelona or Odense, which feature real-time monitoring, AI-powered analytics, and high sensor density.

Strengths and Comparative Insights

The Son La project (Table 8) benefits from strong alignment with national digital transformation policies and has demonstrated early operational gains. The establishment of a CDE and a 3D BIM model provides a platform for scaling toward more complex DT applications. However, when benchmarked against international cases:

- Sensor and Analytics Capabilities are minimal relative to Odense, which uses hundreds of sensors for feedback calibration.
- System Scalability is limited, in contrast to city-wide deployments like in Barcelona and Graz.
- Institutional Capacity remains a bottleneck, highlighting the need for workforce development and technical support.

In summary, Son La's pilot represents a promising entry point into the digital transformation of urban infrastructure. With continued investment, capacity building, and gradual integration of AI and IoT, the city has the potential to evolve from a prototype BIM system into a scalable, intelligent digital twin platform.

Table 8 *Summary of the case of Son La*

Category	Details
Objective	Improve efficiency and transparency in UDS operation and maintenance via BIM adoption.
Scope	Pilot project focusing on drainage and wastewater treatment systems; serves as a foundational digital transformation initiative.
Key Components	BIM 3D modeling, Common Data Environment (CDE), IoT sensors (10 units), centralized platform for asset and workflow integration.
Initial Outcomes	30% reduction in maintenance inspection time- 10% operational cost savings- Early flood warnings via sensors- Enhanced documentation and visualization
Digital Twin Maturity Level	Prototyping DT – BIM-based system without AI or high-density sensor integration.
Challenges	Limited sensor coverage- Absence of AI-based analytics- Shortage of skilled personnel- Integration complexity- High initial investment
Comparative Gaps	Fewer sensors than Odense- Lower scalability than Barcelona or Graz- Weak institutional capacity
Policy Alignment	Strong alignment with national digital transformation initiatives; early-stage compliance with smart city frameworks.
Potential for Advancement	High, with pathways for scaling through IoT expansion, AI integration, and institutional capacity development.

5.2 Cao Bang Case

Cao Bang has initiated a digital transformation focused on developing a Geographic Information System (GIS)-based database to manage its urban drainage infrastructure. This effort marks a foundational step toward modernizing the city's planning, monitoring, and operational capabilities. The database includes spatial data on drainage assets, pipe networks, and urban land use, enabling stakeholders to visualize and analyze the system comprehensively.

While the system does not yet support real-time data acquisition or advanced analytics, it effectively organizes historical and static data, identifies infrastructure bottlenecks, and supports future expansion planning. This initiative represents a substantial improvement over traditional approaches that relied on fragmented documentation and manual record-keeping.

Initial Outcomes and Benefits

- Centralized Spatial Database: Supports planning and maintenance activities with improved data organization.
- Interdepartmental Collaboration: Facilitates cooperation through shared digital maps across departments.
- Enhanced Transparency and Accessibility: Technical staff and decision-makers can access infrastructure records more efficiently.
- Improved Data Management: Enables quick data updates and supports queries, streamlining urban drainage management.
- Enhanced Spatial Awareness: Officials can locate drainage structures and view attributes (e.g., flood frequency, severity) from their offices—especially valuable during adverse weather events.
- Analytical Foundation: Lays the groundwork for integrating Digital Elevation Models (DEMs) to support flood forecasting and damage prevention.
- Model for Replication: Serves as a reference for other Vietnamese cities exploring GIS technology for urban infrastructure.

Key Challenges

- Lack of Real-Time Monitoring: No sensor or telemetry systems are currently integrated, limiting the system's ability to detect changes or respond to flooding dynamically.
- Limited Predictive Capabilities: The absence of modeling tools or data analytics hinders risk forecasting and scenario analysis.
- Data Standardization Issues: Disparate data formats across departments create interoperability obstacles.
- Institutional Capacity Gaps: Staff require further training in GIS, digital tools, and data management to fully leverage the system.

- Resource-Intensive Setup: Developing and maintaining the GIS database is laborious and expensive, which may limit scalability.
- Lack of Advanced Analytics: The system currently lacks AI or machine learning tools that would enable predictive modeling or automated insights.

Digital Twin Maturity Assessment

Cao Bang's system operates at a "Basic – Static GIS Database" level. It offers foundational spatial documentation but lacks dynamic feedback, simulation, or real-time data integration. Compared with global examples such as Odense or Houston—which utilize live sensor data and AI-driven modeling—Cao Bang's infrastructure reflects the earliest stage of digital twin (DT) development (Table 9).

Comparative Strengths and Global Insights

- Strategic GIS Development: Cao Bang's approach mirrors the early steps taken by cities like Graz, which evolved from simplified GIS models to automated systems.
- Scalability Potential: With adequate investment and technical support, the system could integrate telemetry, hydrological modeling, and decision support functions to evolve into a more advanced smart drainage platform.

Strengths of Cao Bang's Approach

- Established GIS Database: A structured and centralized system for spatial and attribute data is now in place.
- Policy Alignment: The project aligns with national mandates promoting GIS adoption in urban planning and infrastructure management.
- Improved Operational Awareness: Allows municipal staff to track and analyze infrastructure without relying on manual site visits.
- Forward-Thinking Vision: Recognition of integrating GIS with DEM data for flood modeling highlights a proactive approach to future development.

Gaps Compared to Global Digital Twin Benchmarks

- Low Maturity Level: Cao Bang's system remains several steps behind cities like Son La (in the prototyping phase) and far from the advanced DT systems in Barcelona, Houston, or Odense.
- No Real-Time Data Integration: The absence of sensor networks and IoT platforms is a major limitation. Global DTs depend on continuous data streams for monitoring and response.
- Lack of Predictive and Automated Intelligence: Advanced DTs leverage AI/ML for simulation, optimization, and decision-making—capabilities not present in Cao Bang.
- No Active System Control: There is no use of automated mechanisms (e.g., programmable logic controllers or model predictive control) to adjust physical infrastructure in response to real-time conditions.
- High Implementation Barriers: Significant investment in skilled personnel, technology, and infrastructure will be necessary to progress toward a full DT.

Table 9 *Summary of the case of Cao Bang*

Category	Details
Objective	Establish a GIS-based drainage infrastructure database to modernize planning, monitoring, and asset management.
Scope	Static GIS platform covering drainage networks, urban land use, and infrastructure attributes; no real-time or dynamic modeling capability.
Key Components	GIS mapping, centralized spatial database, interdepartmental data sharing, manual data collection, potential for DEM integration.
Initial Outcomes	Centralized spatial database- Improved interdepartmental collaboration- Enhanced accessibility and data update efficiency- Foundations for flood modeling
Digital Twin Maturity	Basic – Static GIS Database – No sensors, analytics, or simulation; foundational stage of digital twin development.
Key Challenges	No real-time monitoring- No AI/predictive analytics- Interoperability issues- Limited GIS skills- High setup/maintenance cost
Comparative Strengths	Policy-aligned GIS adoption- Operational improvements in data access and visualization- Early parallels with cities like Graz
Global Gaps	No live data feeds (vs. Odense/Houston)- No AI/ML-driven simulation (vs. Barcelona)- No automated system control- Low maturity

Category	Details
Scalability Potential	High—future integration of telemetry, hydrological models, and decision support tools can evolve system toward a smart drainage platform.
Policy Alignment	Supports national strategies promoting GIS for urban infrastructure management and climate resilience.

5.3 Hue City Case

Hue City faces significant challenges in managing its UDS, compounded by frequent flooding, aging infrastructure, and rapid urban development. While the city has begun exploring digital tools for drainage planning, current implementation remains basic and predominantly manual.

At present, data is primarily gathered through surveys and community-based monitoring, with limited use of GIS or modeling software. Planning efforts still rely heavily on historical flood records and expert judgment, rather than predictive analytics or simulation tools (Table 10).

Initial Outcomes and Emerging Benefits

- Community Engagement: Local involvement in monitoring has increased public awareness and responsiveness.
- Pilot GIS Applications: GIS-based maps are being piloted in select infrastructure projects, enhancing spatial planning and visualization.

Key Challenges

- Limited Data Infrastructure: The lack of sensor networks and access to up-to-date digital base maps hampers progress.
- Fragmented Governance: Multiple agencies are responsible for drainage and flood management, leading to disjointed data sharing and decision-making.
- Resource Constraints: Budget limitations restrict investment in digital technologies and workforce capacity-building.
- Reactive Management: Interventions are largely driven by emergency response, rather than long-term system optimization.

Digital Twin Maturity Assessment

- Hue City is currently in the “analog-to-digital transition” stage—featuring basic mapping and documentation but lacking an integrated platform for real-time monitoring, analysis, and operations. This level of maturity is significantly below the "living digital twin" status seen in leading cities like Barcelona or Xi’an.

Comparative Strengths and Insights

- Learning from Odense: The Danish city’s approach—starting with water-level sensors and uncertainty diagnostics—could serve as a practical model for Hue’s gradual digital evolution.
- Priority Actions: Focus should be placed on establishing a shared data infrastructure and initiating pilot sensor deployments in high-risk flood zones.

The recent internationally supported project is expected to significantly modernize UDS management in Hue by enabling:

- Improved Flood Prediction: Enhanced accuracy and timeliness in forecasting.
- Real-Time Monitoring: Continuous system oversight for proactive interventions.
- Operational Optimization: Smart management of pumps, gates, and other infrastructure.
- Enhanced Decision Support: Data-driven insights for urban planners and climate adaptation.
- Capacity Building: Knowledge transfer and technical training for local personnel.

Ongoing Project Challenges

As a complex, international initiative, THE PROJECT faces several critical challenges:

- Data Availability and Quality: Ensuring reliable and comprehensive data from existing and new sensor networks.
- System Interoperability: Harmonizing diverse data sources and software platforms.
- Local Capacity: Effectively transferring technical expertise and ensuring local operational ownership.
- Sustainability: Maintaining system performance and evolution beyond initial funding.
- High Initial Investment: Advanced technologies and infrastructure require substantial upfront costs.

Digital Twin Maturity: An Evolving Landscape

Hue’s UDS management, is classified as “Advanced – In Development”. The project signifies a major leap toward a fully functional Digital Twin, marked by international collaboration and a focus on predictive and real-time capabilities. In contrast to other Vietnamese initiatives—such as Son La’s BIM-based pilot—Hue’s effort is more comprehensive, positioning it closer to global leaders in urban drainage digitalization.

Strengths of Hue City’s Approach

- Clear Digital Twin Vision: Unlike many cities that begin with general digitalization, Hue's THE PROJECT project directly targets the development of a complete Digital Twin, setting a high strategic benchmark.
- Robust International Collaboration: Partnerships with German academic and industrial institutions (University of Stuttgart, THE PROJECT GmbH) bring cutting-edge technologies and best practices.
- Focus on Real-Time and Predictive Capabilities: The integration of sensor data and flood forecasting represents best-in-class DT features for proactive system management.
- Comprehensive Scope: The project addresses flood prediction, operations, and strategic planning—signaling a holistic approach to UDS modernization.

Remaining Gaps Compared to Global Benchmarks

- Development Stage: While forward-thinking, the project is still in early development. Cities like Barcelona and Odense already operate living DTs with extensive data histories and refined analytics.
- Sensor Infrastructure: Success depends heavily on robust sensor networks and integrated data platforms. Incomplete or unreliable data would undermine model accuracy.
- Sustainability and Local Ownership: International support must be coupled with strong local commitment (e.g., from HEPCO) to ensure long-term continuity and evolution.
- System Integration: Future efforts should ensure interoperability with broader smart city systems (e.g., traffic, energy, waste) to prevent data silos.
- Funding Continuity: Advanced DT systems require ongoing investment. Securing stable, long-term funding is essential for full operationalization.

Table 10 *Summary of the case of Hue City*

Category	Details
Objective	Modernize UDS management with predictive modeling, real-time monitoring, and integrated decision support through an internationally supported DT project.
Scope	Transition from manual systems to a full Digital Twin platform integrating GIS, sensors, modeling tools, and stakeholder collaboration.
Key Components	Community monitoring, pilot GIS mapping, real-time sensor integration (planned), flood forecasting, smart infrastructure operations.
Initial Outcomes	Community engagement and awareness- GIS-based visualization piloted- Strategic planning and training under international guidance
Digital Twin Maturity	Advanced – In Development – Project targets full DT capability with predictive analytics and real-time monitoring but remains in early implementation.
Key Challenges	Data gaps and fragmented governance- Limited local technical capacity- Interoperability and sustainability concerns- High initial investment
Comparative Strengths	Vision-driven DT development- International partnerships (e.g., University of Stuttgart, THE PROJECT GmbH)- Focus on proactive system management
Global Gaps	Early-stage implementation vs. mature DTs like Barcelona- Dependence on future sensor deployment- Needs strong local ownership and funding
Scalability Potential	High—if sensor networks, data platforms, and institutional commitment are sustained, Hue could become a national DT model for heritage cities.
Policy Alignment	Supports Vietnam's smart city and climate adaptation agendas; aligns with national and international digital resilience goals.

5.4 Da Nang Case

The digital transformation of Da Nang's urban drainage system has already delivered several notable benefits, reinforcing the city's commitment to building a smarter, more resilient urban infrastructure (Table 11).

Initial Outcomes and Benefits

Digital technology implementation in Da Nang's UDS has yielded several tangible benefits:

- Improved Data Management: A centralized, unified GIS-based database enables easier retrieval, updating, and analysis of drainage infrastructure data.
- Enhanced Operational Efficiency: Real-time monitoring allows for early flood warnings, optimized pump station operations, and reduced manual labor—leading to more efficient maintenance and system performance.

- Better Flood Prevention: Access to real-time data supports proactive flood mitigation strategies and faster response during heavy rainfall events.
- Foundation for Smart City Development: These initiatives align with Da Nang's broader smart city vision, leveraging technology to improve urban management.

Challenges

Despite these advances, several key challenges hinder Da Nang's full transition to a mature digital twin system:

- High Investment Costs: Deploying sensor networks, advanced software platforms, and robust data infrastructure requires substantial financial resources.
- Technical Expertise: There is a need for skilled personnel to operate and maintain complex digital systems, including expertise in data analytics and cybersecurity.
- Data Security and Interoperability: Protecting sensitive data and ensuring seamless integration across different platforms remain critical concerns.
- Continuous Data Updates: Maintaining up-to-date, accurate data is essential to ensure the effectiveness of digital systems.
- Microplastic Pollution: Although not yet addressed directly by digital twin technologies, microplastic contamination in drainage channels presents an emerging issue, underscoring the future need for integrated water quality monitoring.

Digital Twin Maturity Level

Da Nang's UDS management system is currently classified as "Prototyping Digital Twin." With a comprehensive GIS database and ongoing integration of IoT sensors and SCADA systems, the city is progressing toward dynamic capabilities. However, it has yet to fully incorporate AI-driven predictive analytics or develop a complete virtual model characteristic of advanced digital twin environments.

Strengths of Da Nang's Approach

- Robust Digital Foundation: The city has successfully established a GIS-based infrastructure, serving as a vital backbone for further digital twin development.
- Commitment to Real-Time Monitoring: The integration of IoT and SCADA systems demonstrates a strong commitment to responsive, real-time data acquisition and centralized system control.
- Policy and Financial Backing: Support from international partners such as the World Bank, coupled with ongoing infrastructure investment, reflects a favorable policy environment.
- Early Positive Results: Initial improvements in operational efficiency, data handling, and flood prevention validate the city's digital investments.

Gaps and Challenges Compared to Global Benchmarks

- Digital Twin Maturity: While Da Nang is in the prototyping phase, cities like Barcelona, Houston, and Odense have achieved "Living Digital Twin" status, characterized by AI integration, real-time simulation, and full predictive modeling.
- Limited Predictive Intelligence: Da Nang's system focuses on real-time data and control but lacks advanced machine learning capabilities for accurate forecasting, anomaly detection, and automated decision support.
- Sensor Network Density and Data Quality: Although IoT sensors are in place, the current network may lack the coverage, density, and quality control needed to match leading international examples.
- System Interoperability and Data Silos: As digital systems expand, ensuring interoperability between GIS, SCADA, IoT, and future AI platforms—and avoiding isolated data silos—will be a persistent challenge.
- Workforce Development: The transition to a fully integrated digital twin demands expertise in data science, AI, simulation modeling, and IT system integration, which may be in short supply.
- Emerging Environmental Pressures: The rising concern of microplastic pollution highlights a need for expanding the scope of digital twin systems to include advanced water quality monitoring, extending beyond flood control to broader environmental management.

Table 11 *Summary of the case of Da Nang*

Category	Details
Objective	Enhance UDS efficiency and resilience through GIS, IoT, and SCADA integration, contributing to the city's smart city and flood prevention goals.
Scope	Comprehensive GIS-based UDS database, real-time monitoring with IoT sensors and SCADA systems; limited use of AI or predictive analytics.
Key Components	GIS database, SWMM modeling, SCADA system, IoT sensors, centralized control software, cloud storage, mobile apps.
Initial Outcomes	25% improvement in flood planning- Real-time monitoring and pump optimization- Improved system performance and data accessibility
Digital Twin Maturity	Prototyping Digital Twin – Real-time data capabilities emerging; predictive AI and full system simulation yet to be implemented.
Key Challenges	High investment cost- Technical expertise shortages- Interoperability issues- Data security concerns- Need for continuous updates
Comparative Strengths	Strong digital foundation- Real-time system integration (IoT + SCADA)- International support (e.g., World Bank)- Policy-aligned smart city vision
Global Gaps	Lacks AI/predictive intelligence (vs. Barcelona, Houston)- Limited sensor density- Emerging microplastic pollution not yet integrated in monitoring
Scalability Potential	High—platform can be scaled with more sensors, predictive analytics, and broader environmental monitoring (e.g., water quality).
Policy Alignment	Fully aligned with national smart city objectives and

5.5 Hanoi Case

Hanoi, the capital of Vietnam, is a rapidly urbanizing metropolis increasingly vulnerable to flooding. Its complex river network, low-lying topography, and intensifying rainfall—exacerbated by climate change—place immense pressure on an aging and insufficient UDS. Historically managed through conventional methods, Hanoi now recognizes the urgent need to embrace advanced digital technologies for improved flood control and operational efficiency (Table 12).

Objectives and Strategic Initiatives

Hanoi has initiated several modernization efforts for UDS management, often in partnership with international collaborators such as JICA. The city's digital transformation aims to:

- Develop flood risk maps and early warning systems to provide accurate and timely forecasts for vulnerable urban areas.
- Implement real-time monitoring and control systems to enable dynamic operational management of drainage infrastructure.
- Establish comprehensive digital databases for efficient storage and analysis of spatial and infrastructure data.
- Promote smart drainage solutions to enhance system responsiveness and resilience.

From Traditional to Evolving UDS Management

Historically, Hanoi's UDS relied on paper documentation and AutoCAD drawings—prone to fragmentation and reactive response strategies. However, the city is progressively shifting toward proactive, data-driven management, integrating digital technologies and establishing smart operation centers.

Core Technologies and Digital Tools

Hanoi's digital transition incorporates both foundational systems and emerging technologies:

- Hydraulic/Hydrological Modeling (MIKE FLOOD, MIKE URBAN): Used for flood risk mapping, flood inundation simulation, and early warning system development, integrating rainfall-runoff processes with 1D/2D modeling and GIS.
- Geographic Information System (GIS): Essential for managing spatial and attribute data on infrastructure (e.g., pipes, manholes, pump stations), supporting database development and flood mapping.
- Internet of Things (IoT) Sensors: Deployed for real-time tracking of water levels, rainfall, and flow rates; broader deployment in water resource management indicates expansion potential.
- Real-time Data Platforms: Support data collection and transmission from field sensors to centralized servers, enabling timely operational insights.

- SCADA Systems: Facilitate centralized monitoring and control of critical infrastructure such as pump stations and sluice gates.
- Smart Operation Centers: Function as integrated control hubs, centralizing data, enabling real-time monitoring, and supporting decision-making.
- Digital Elevation Models (DEM): Used for topographic analysis and model development.
- AI and Machine Learning (AI/ML): Not yet fully integrated but recognized as essential for future predictive analytics and decision optimization.
- Cloud Storage: Used to manage large datasets generated by sensors and modeling platforms.

Initial Outcomes and Benefits

The integration of digital technologies has led to several key improvements:

- Enhanced Flood Forecasting: MIKE models have enabled more accurate risk mapping and early warning systems.
- Improved Data Management: GIS systems facilitate efficient storage, analysis, and sharing of UDS data.
- Operational Efficiency: SCADA and real-time sensors optimize drainage operations and reduce response times.
- Support for Smart City Development: These efforts align with Hanoi's broader digital transformation and smart urban management agenda.

Persistent Challenges

Despite meaningful progress, several challenges remain:

- Rapid Urbanization and Climate Impact: Ongoing growth and unpredictable weather patterns place continuous strain on existing systems.
- Aging Infrastructure: Much of the UDS is outdated, complicating the integration of new technologies.
- Data Standardization and Integration: Combining legacy and real-time data across platforms and agencies remains complex.
- High Investment Requirements: Scaling digital infrastructure citywide requires substantial capital.
- Technical Capacity: A skilled workforce is needed to support advanced modeling, analytics, cybersecurity, and system maintenance.
- Comprehensive Monitoring: Achieving full-scale, real-time UDS coverage remains a long-term goal.

Digital Twin Maturity Assessment

Hanoi's UDS system is currently at the "Prototyping Digital Twin" stage, characterized by:

- Established GIS systems.
- Advanced hydraulic modeling.
- Ongoing integration of real-time monitoring tools.
- Development of smart operation centers.

While promising, a fully integrated Digital Twin—featuring AI-driven predictive control and seamless physical-virtual feedback loops across the entire UDS—remains in development.

Strengths of Hanoi's Approach

- Strong Modeling Foundation: Long-standing use of MIKE models positions Hanoi ahead in simulation and early warning capabilities.
- Real-Time Monitoring Commitment: Active deployment of IoT and SCADA systems shows strategic commitment to data-driven management.
- Comprehensive Digital Scope: Projects span modeling, mapping, forecasting, and control—across large areas of the city.
- Policy Alignment: The city's initiatives support national smart city and digital transformation goals.
- Global Collaboration: International partnerships (e.g., JICA) provide access to cutting-edge knowledge and best practices.

Remaining Gaps Compared to Global Benchmarks

- Full Digital Twin Integration: Hanoi's efforts are progressing, but lag behind global "Living DT" leaders like Barcelona, Xi'an, or Austin, which feature AI-based learning systems and citywide feedback integration.
- Predictive Intelligence: AI/ML tools are not yet fully leveraged for advanced forecasting, anomaly detection, or automated control.
- Sensor Network Coverage: For a city of Hanoi's scale, achieving high-density sensor deployment and ensuring reliable data quality remain critical hurdles.
- Legacy System Interoperability: Integrating modern platforms with older infrastructure and formats requires complex solutions.
- Capacity Building and Investment: A robust transformation demands sustained investment in both technology and human capital.

- Environmental Monitoring Expansion: Future digital systems must also address urban water quality concerns, including microplastic monitoring, for a more holistic UDS approach.

Table 12 *Summary of the case of Hanoi*

Category	Details
Objective	Modernize UDS through digital technologies to improve flood forecasting, operational efficiency, and smart urban management.
Scope	Integration of GIS, hydraulic modeling, SCADA, IoT sensors, and smart operation centers across Hanoi’s flood-prone urban zones.
Key Components	MIKE FLOOD/URBAN models, GIS mapping, SCADA systems, IoT sensor networks, smart control centers, DEMs, cloud platforms; AI/ML integration planned.
Initial Outcomes	Enhanced flood risk forecasting- Real-time operational control- Efficient data management- Alignment with Hanoi’s smart city agenda
Digital Twin Maturity	Prototyping Digital Twin – Advanced modeling and sensor systems in place; working toward full AI integration and citywide real-time feedback loop.
Key Challenges	Rapid urbanization & climate stress- Aging infrastructure- Data standardization- Capital & technical capacity gaps- Limited full-scale monitoring
Comparative Strengths	Strong modeling legacy with MIKE suite- Expanding real-time systems (IoT, SCADA)- Strategic alignment with national policies- Global collaboration (JICA)
Global Gaps	No AI-driven predictive control yet (vs. Xi’an, Barcelona)- Sensor network coverage incomplete- Legacy integration challenges- No environmental quality integration
Scalability Potential	High—project

6. Benchmarking with Global Cases

As Vietnam charts its course toward smarter, more resilient cities, a crucial battleground lies underground—beneath the streets, where stormwater flows, sensors flicker to life, and data pulses through evolving networks. Across the country, from Hanoi to Cao Bang, cities are grappling with the twin forces of rapid urbanization and climate volatility, seeking answers in digital technology.

To illuminate Vietnam’s path, we look outward—benchmarking against six leading international cases: Barcelona (Spain), Graz (Austria), Houston (USA), Odense (Denmark), Xi’an (China), and Austin (USA). These cities represent a spectrum of innovation in urban drainage management, offering valuable lessons in maturity, technology, outcomes, and challenges. Table 13, Table 14 summarize the findings.

Table 13 *Summary of the benchmarking six global case studies*

Case	Overall Maturity Level	Primary Application Focus	Key Digital Technologies	Sensor Coverage/Data Sources	Analytics & Intelligence	Outcomes/Benefits	Challenges	Scalability
Barcelona (Spain)	High	Real-time urban water cycle optimization	Cyber-physical systems, SCADA, IoT	City-wide sensor network	Advanced simulation & real-time control	Efficiency, flood prevention, resource optimization	System complexity, integration costs	High
Graz (Austria)	Medium-High	Model simplification for drainage simulation	Model transformation algorithms	Existing model data	Automated model abstraction	Computational efficiency, faster analysis	Loss of detail, initial data calibration	Medium
Houston (Texas, USA)	High	Infrastructure resilience assessment	Visual data processing, deep learning, AI	Visual sensor networks, urban databases	AI prediction, infrastructure stress mapping	Predictive resilience, damage prevention	Data integration, AI training needs	Medium-High
Odense (Denmark)	High	Model uncertainty diagnosis	Sensor integration, uncertainty analysis tools	Water level sensors	Hydrologic and hydraulic signature analysis	Improved model calibration, accuracy	Sensor maintenance, data interpretation	Medium
Xiân (China)	High	Flood control & drainage optimization	Digital Twin, Unity3D, LSTM, NSGA-III	PLC, flow meters, ultrasonic sensors	Deep learning, real-time control, simulation	Cost savings, risk reduction, water level control	Model integration, initial setup	High
Austin (Texas, USA)	Medium-High	Flood hazard detection	Stormwater DT, online quality control	Urban flood sensors	Hazard prediction under uncertainty	Early warning, proactive flood management	Model uncertainty, real-time data handling	Medium

Table 14 *Vietnam localities - digital drainage benchmarking*

Locality	Overall Maturity Level	Primary Application Focus	Key Digital Technologies	Sensor Coverage/Data Sources	Analytics & Intelligence	Outcomes/Benefits	Challenges	Scalability
Hanoi	Medium	Flood risk mapping, early warning, smart drainage	MIKE FLOOD, GIS, IoT, AI	Real-time sensors, GIS layers, remote sensing	Hydraulic modeling, real-time warning systems	Better flood response, improved drainage maps	Fragmented systems, scaling to entire city	Medium
Da Nang	Medium-High	Infrastructure management, public asset inventory	GIS, IoT, digital database platforms	Public infrastructure and asset data	Database analytics, infrastructure condition tracking	Efficient asset use, improved planning	Data integration, resource constraints	High
Hue	Low-Medium	Urban drainage upgrades, community-based monitoring	Manual planning support, early GIS	Limited; mainly survey data	Planning tools, limited forecasting	Awareness raising, planning inputs	Lack of real-time data, funding gaps	Low
Son La	Low-Medium	Digital transition via BIM for O&M	BIM, GIS (planned), IoT (planned)	Not yet fully implemented	Digital modeling under development	Improved O&M potential	Early-stage implementation, funding	Medium
Cao Bang	Low-Medium	Urban drainage GIS database	ArcGIS	None; static spatial data	Manual mapping, no real-time analytics	Foundational dataset for planning	Lack of automation and dynamic modeling	Medium

Let's look at the global leaders first. In Barcelona, a high-functioning digital twin orchestrates an entire urban water cycle. Its integrated cyber-physical system—melding SCADA, IoT, and real-time simulation—allows operators to manage floods before they form, optimize resources, and respond with pinpoint precision. The system is complex and costly but sets the gold standard.

Xi'an, on the other side of the globe, demonstrates how cutting-edge technology—DTs, Unity3D simulations, LSTM neural networks, and multi-objective optimization—can turn predictive control into a daily operational reality. It's not just managing floods; it's staying steps ahead of them.

Meanwhile, in Houston, deep learning and visual sensors scan the infrastructure for stress and failure points, feeding AI models that forecast resilience risks. Odense fine-tunes its hydrologic models using sensor-driven uncertainty analysis, while Graz achieves computational agility through automated model simplification. Austin, balancing innovation and practicality, harnesses DTs for stormwater hazard detection—predicting floods with uncertainty modeling and real-time feedback.

Each of these cities tells a different story of how urban drainage can evolve—from reactive to predictive, from fragmented to fully integrated.

The cases in Vietnam show that the cities are on the move (Table 15). In Hanoi, Vietnam's capital, the ambition is clear. Hanoi stands at a medium maturity level, relying on a suite of tools—MIKE FLOOD, GIS, IoT, and emerging AI applications—to simulate flood scenarios and issue early warnings. The city's smart operation centers are taking form, but Hanoi still lacks the real-time integration, predictive intelligence, and sensor saturation seen in cities like Barcelona or Xi'an. Hanoi could benefit from Xi'an's deep-learning models and Barcelona's citywide cyber-physical systems. Compared to Houston's proactive AI-driven resilience assessments, Hanoi remains largely reactive. Yet, its established modeling foundation, combined with ongoing digital integration, signals a city well-positioned for leapfrogging if the right investments are made.

Da Nang is considered a digital foundation ready to scale. Da Nang emerges as one of Vietnam's frontrunners. With a medium-high maturity level, it has built a robust GIS database and actively incorporates IoT sensors into its asset management systems. The city is efficient, organized, and data-rich—but it's not yet predictive. Da Nang could follow Odense's path by layering real-time diagnostics onto its existing database or borrow from Graz's model simplification to speed up simulations. It has the infrastructure; what it needs now is intelligence—AI, machine learning, and scenario modeling—to convert insight into foresight.

Hue is a city at the starting line. In contrast, Hue still relies heavily on manual data collection and early-stage GIS mapping. Its low-to-medium maturity places it in the foundational phase of digital transformation. Compared to global peers, Hue lacks real-time data, dynamic modeling, and predictive tools. But there's a clear path forward. Cities like Odense, which began with modest sensor deployments and evolved toward advanced model calibration, provide a practical roadmap for Hue: start small, integrate gradually, and build the data trust needed for deeper modeling.

Regarding Son La, the city's digital journey began with Building Information Modeling (BIM) for operations and maintenance—a forward-thinking move in a region still developing its infrastructure. The city's digital twin is still in its infancy, but the foundation is promising. Benchmarking against Xi'an, Son La could eventually scale its BIM systems into fully functional DTs by integrating real-time data, IoT, and predictive modeling. This would move it from static asset modeling to active flood management.

Cao Bang, with its low-to-medium maturity, has focused on building a GIS-based map of its drainage infrastructure—a crucial first step. But without sensors, automation, or dynamic modeling, it remains far from real-time responsiveness. Here, Graz offers an ideal benchmark. Cao Bang could implement simplified modeling algorithms, automate updates, and start experimenting with sensor data to unlock the next stage of digital capability. From static maps to intelligent systems—it's a journey that begins with one sensor.

Table 15 *Summary of key opportunities*

Province	Best Benchmark Pair	Why It Fits
Hanoi	Xi'an & Barcelona	Solid modeling base; ready for real-time optimization and predictive AI
Da Nang	Odense & Graz	Strong data foundation; scalable with advanced analytics
Hue	Odense	Needs gradual sensor integration and basic model feedback loops
Son La	Xi'an	Promising BIM groundwork; potential for full digital twin lifecycle
Cao Bang	Graz	Simplified modeling and GIS offer a practical pathway to scale

Vietnam's cities are at different points on the digital twin spectrum—from Hanoi's emerging modeling centers to Cao Bang's foundational maps. Yet they all share a common destination: smarter, more resilient, and more responsive UDS. The path forward isn't about catching up to Barcelona or Xi'an overnight. It's about taking measured, informed steps—drawing from global insights and tailoring them to local realities. Whether through AI-driven forecasting, model simplification, or smart asset management, Vietnam's provinces have the tools—and now the benchmarks—to evolve. With continued investment, cross-sector collaboration, and a focus on phased development, Vietnam's digital water infrastructure can transform from passive to predictive, from fragmented to fully integrated. The future flows here—not just in pipes and drains, but in data, decisions, and the cities that rise above the flood.

7. Recommendations

Drawing from the benchmarking analysis and lessons from global practices, this section outlines a strategic roadmap to guide Vietnamese cities in adopting digital twin (DT) technologies for urban drainage management. The recommendations are presented across short-, medium-, and long-term horizons, with each phase addressing specific gaps in technical capacity, institutional coordination, and infrastructure readiness (Figure 5).

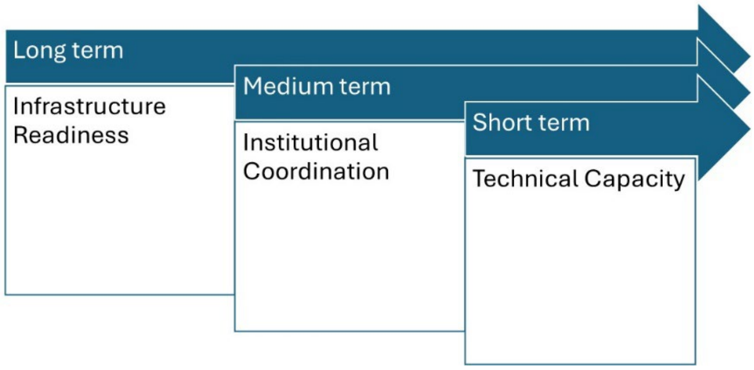

Fig. 5 *Strategic roadmap to guide Vietnamese cities in adopting DT for UDS management*

The following subsections discuss each of the horizons.

7.1 Short-Term Recommendations

The short-term recommendations are illustrated in Figure 6.

Fig. 6 *Short-term strategies*

(1) Enhance Digital Asset Inventories and GIS Systems

The initial phase of digital twin maturity, as demonstrated in Graz and Cao Bang, begins with building structured spatial databases. Provinces should digitize drainage networks using GIS platforms to enable better planning, documentation, and coordination. Municipalities can adopt open-source GIS tools (e.g., QGIS) to reduce costs while laying the groundwork for data sharing and integration.

(2) Pilot Sensor Deployment in High-Risk Areas

Installing a small number of flow or rainfall sensors in flood-prone districts can provide immediate benefits. For example, Odense achieved notable improvements in uncertainty reduction by deploying low-cost water level sensors to inform drainage model calibration. In Vietnam, cities like Hue or Son La can use such pilots to develop local expertise in real-time monitoring and improve responsiveness to flood events.

(3) Develop Unified Data Standards

Fragmented systems remain a major barrier to scale. Vietnam should develop a standardized data schema for drainage infrastructure, compatible across GIS, BIM, and modeling platforms. This approach mirrors practices in Barcelona, where integrated data standards allow seamless communication across SCADA, IoT, and modeling tools.

(4) Launch Capacity-Building Programs

Many cities cite a lack of trained personnel as a limiting factor. Training programs—delivered through universities, online platforms, and international partnerships—should target engineers, planners, and technicians. Topics should include digital modeling (MIKE URBAN, SWMM), GIS and BIM use, sensor integration, and basic AI concepts. Initiatives like the ASEAN Smart Cities Network could provide regional support for these efforts.

7.2 Medium-Term Recommendations

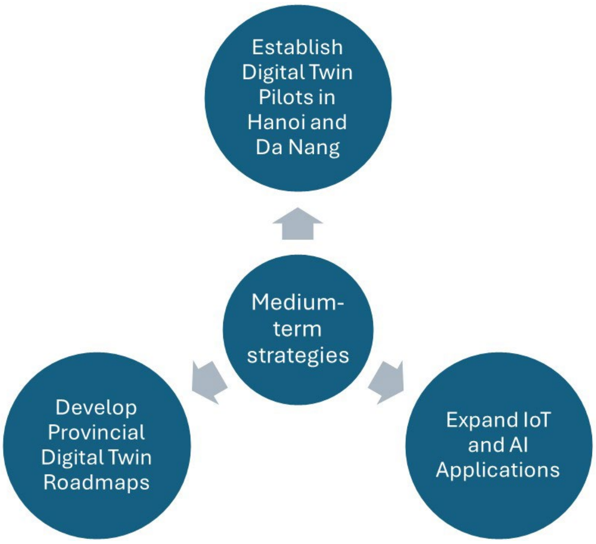

Fig. 7 *Medium-term strategies*

(1) Establish Digital Twin Pilots in Hanoi and Da Nang

Given their current infrastructure and institutional readiness, these two cities are ideal candidates for deploying full-scale pilot DT platforms. This includes integration of live sensor feeds, AI-supported flood forecasting, and real-time visualization. Lessons from Xi'an and Houston suggest that even partial AI integration (e.g., LSTM models for rainfall forecasting) can drastically improve system responsiveness and cost-efficiency.

(2) Expand IoT and AI Applications

Cities should invest in expanding IoT networks to cover critical drainage nodes and integrate cloud-based AI for early-warning systems. For example, Austin's stormwater DT uses AI for anomaly detection and alert generation under uncertainty. In Vietnam, a phased AI rollout can begin with pattern recognition for drainage flow anomalies and evolve toward full scenario simulations.

(3) Develop Provincial Digital Twin Roadmaps

Each city should create its own DT roadmap, outlining targets, investments, and technical milestones. These documents can ensure consistency with national digital strategies while accounting for local constraints and ambitions. Provincial roadmaps will also support the case for funding through climate adaptation or smart city initiatives.

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7.3 Long-Term Recommendations

Fig. 8 *Long-term strategies*

(1) Institutionalize Digital Twins in National Urban Policy

Digital twins should be formally embedded in Vietnam's urban infrastructure and smart city policies. They should be referenced in key national frameworks such as the "National Digital Transformation Program to 2025" and the "Urban Development Strategy to 2030." As seen in the European Union's Digital Europe program, top-down mandates can accelerate local innovation through clarity, coordination, and funding.

(2) Establish a National Urban Digital Infrastructure Platform

Vietnam should develop a centralized platform or digital twin observatory that aggregates tools, datasets, and case studies. This would function as both a knowledge hub and a technical support system for provincial DT efforts. Cities could upload models, access national datasets (e.g., rainfall, soil permeability), and benchmark their progress through shared dashboards.

(3) Enable Sustainable Financing Mechanisms

Long-term digital transformation requires stable financing. Mechanisms such as green bonds, digital infrastructure grants, and outcome-based financing (e.g., flood reduction metrics) can support deployment. International development banks and climate funds (e.g., Green Climate Fund, ADB Urban Resilience programs) should be engaged to co-finance DT projects aligned with SDGs and Paris Agreement commitments.

(4) Promote Cross-Sectoral Integration

As cities evolve, DT applications must extend beyond drainage to incorporate transportation, energy, and land-use systems. Integrated DTs will allow cities to simulate interdependencies (e.g., storm impacts on traffic or energy systems) and design holistic solutions. This system-of-systems approach, seen in Barcelona and Xi'an, will be essential for building climate-resilient, livable urban environments.

8. Conclusion

This study investigates the current state of digital twin (DT) applications for managing urban drainage systems (UDS) in selected Vietnamese provinces and benchmarks them against six international case studies. The findings reflect Vietnam's growing commitment to digital transformation, as evidenced by early-stage initiatives in cities such as Da Nang, Hanoi, Son La, Cao Bang, and Hue. However, a comparative analysis reveals a significant gap in digital maturity between these Vietnamese cities and global leaders like Barcelona, Xi'an, and Houston.

Whereas global cities are leveraging cyber-physical systems, artificial intelligence, and real-time sensor networks to enable predictive and adaptive drainage system management, most Vietnamese cities remain in foundational or pilot phases. For example, Da Nang's urban infrastructure database and IoT integration point toward a more advanced DT system but still lack AI-supported decision-making capabilities. Hanoi demonstrates promise with flood modeling and GIS tools, though it faces challenges in cross-departmental integration. Provinces like Son La and Cao Bang have made important strides with BIM- and GIS-based documentation but still require major investments to evolve from static data management to dynamic, intelligent systems.

Key findings include:

- Early digital efforts are already yielding tangible benefits. In Son La, BIM-based maintenance planning has improved operational efficiency, while Cao Bang's GIS system has enhanced transparency in urban planning.
- Institutional and technical constraints remain major barriers. These include limited sensor networks, inadequate technical capacity, fragmented governance, and inconsistent data standards.
- Global best practices provide scalable models for progress. Cities like Odense and Graz show that full-scale DT implementation is not a prerequisite for meaningful improvement—phased integration and model simplification can still yield results.

To bridge the digital maturity gap, Vietnam must adopt a phased, context-sensitive approach supported by national coordination and sustained investment. The policy recommendations outlined—ranging from sensor deployment and data standardization to AI pilot projects and institutional reforms—can help cities develop smart, adaptive, and resilient urban drainage infrastructure.

Ultimately, scaling digital twin technologies in Vietnam's urban drainage sector offers more than operational efficiency—it represents a strategic investment in climate resilience, sustainable urban development, and digital innovation. As urbanization and extreme weather events strain existing infrastructure, digital twins can provide the predictive insights and operational flexibility needed to protect both communities and ecosystems.

Broader Implications

Educational Implications

This research serves as a foundational resource for academic institutions in Vietnam and Southeast Asia aiming to incorporate digital twin concepts into curricula for civil engineering, urban planning, and environmental management. The differentiated case studies provide rich teaching materials to illustrate real-world challenges and progress in infrastructure digitization. The benchmarking methodology also offers a practical framework for student projects in systems engineering, data science, and smart urban governance.

Public Policy Implications

The findings support evidence-based policymaking by highlighting priority areas for regulatory support, funding mechanisms, and institutional reform. Key recommendations include:

- Establishing national mandates for data standardization and interoperability
- Incentivizing public-private partnerships to accelerate digital infrastructure investment
- Embedding DT requirements in urban drainage and climate adaptation plans
- Strengthening local government capacity for implementation, monitoring, and evaluation

These insights can inform updates to the National Digital Transformation Program (Decision 749/QD-TTg) and the Smart City Development Framework (Resolution 52-NQ/TW), aligning urban drainage modernization with broader sustainability and innovation goals.

Smart City Program Development

For smart city planners and technology integrators, the study provides actionable guidance on how cities at different stages of digital maturity can adopt tailored digital twin pathways. The city-specific recommendations act as roadmaps for integrating UDS management into broader smart city ecosystems. In addition, by identifying scalable pilot projects and opportunities for intercity knowledge transfer, this research supports the development of regional innovation clusters and DT incubators.

Societal Impact

At the societal level, improved UDS management through digital twins contributes directly to flood resilience, environmental protection, and public health. As cities like Da Nang and Hanoi modernize their infrastructure, predictive analytics and real-time monitoring can reduce economic losses, protect lives, and promote more equitable service delivery. In the long run, well-integrated DT systems can also enhance citizen engagement through open data platforms and early warning systems, fostering participatory and accountable urban governance.

In short, the implications of this research extend far beyond technological innovation. They offer a blueprint for embedding data-driven infrastructure into national development strategies, strengthening institutional capabilities, and advancing more climate-resilient, inclusive, and future-ready cities in Vietnam and similar contexts.

However, this research study has several limitations. First, it relies solely on a literature review to draw insights from global case studies, meaning that only cases documented in existing publications could be analyzed, which constrains the scope and depth of discussion. Second, the study lacks validation through expert consultation or field verification, which could have strengthened the findings. These limitations restrict the generalizability of the results, and future research incorporating empirical data and expert input is recommended to provide more comprehensive and validated outcomes.

Acknowledgement

The authors would like to express their sincere gratitude to Hanoi Architectural University and Hanoi University of Civil Engineering, for their support of this research. Special thanks are also extended to the Editor and Reviewers, for their valuable advice and guidance throughout the study.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *VM, VYN, QTP;* ***data collection:*** *VM, VYN, QTP;* ***analysis and interpretation of results:*** *VM;* ***draft manuscript preparation:*** *VM, VYN, QTP. All authors reviewed the results and approved the final version of the manuscript.*

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