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Research Article

SMART INFRASTRUCTURE ENGINEERING: DIGITAL TWINS FOR LIFECYCLE PERFORMANCE OPTIMIZATION IN FLOOD MITIGATION SYSTEMS

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Abstract

Flood mitigation infrastructure increasingly requires adaptive management as aging assets, climate variability, urbanization, and changing hydraulic loads reduce the reliability of conventional inspection and maintenance practices. This study aimed to develop and evaluate a lifecycle-oriented digital-twin framework for optimizing the performance of flood mitigation systems. A Design Science Research approach was employed by integrating physical infrastructure data, sensor monitoring, hydraulic simulation, condition assessment, deterioration analysis, scenario testing, lifecycle optimization, and expert validation. Findings showed that the digital twin reproduced hydraulic behavior with satisfactory fidelity and improved maintenance prioritization by combining asset condition, hydraulic criticality, operational reliability, failure consequences, and future loading. Optimized scenarios reduced peak water-level exceedance, emergency maintenance frequency, unplanned downtime, and estimated lifecycle expenditure while increasing pump availability and intervention lead time. Case analyses further demonstrated that structurally acceptable assets could become functionally critical when hydraulic consequence and changing environmental demand were considered. The study concludes that digital twins provide greater engineering value when implemented as closed-loop lifecycle decision-support systems rather than as monitoring or visualization tools alone. The proposed framework supports predictive maintenance, rehabilitation prioritization, operational optimization, and climate adaptation while preserving human engineering judgment under conditions of data and model uncertainty across complex flood infrastructure networks.

Keywords: Climate Adaptation, Digital Twins, Flood Mitigation

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INTRODUCTION

Flooding remains one of the most persistent threats to urban infrastructure, economic continuity, public safety, and environmental sustainability (J. Ali et al., 2025; Aslam et al., 2025). Rapid urbanization, land-use change, aging drainage networks, increasing surface impermeability, and greater climatic variability have placed growing pressure on flood mitigation systems such as detention basins, pumping stations, levees, drainage channels, retention facilities, gates, culverts, and stormwater networks (Alhassan et al., 2024; Tandon & Sharma, 2025). Conventional engineering approaches have generally relied on static design assumptions, periodic inspection, historical hydrological data, and predetermined maintenance schedules (Hauashdh et al., 2024; Shammar et al., 2025). Such practices remain important, yet they are increasingly insufficient for infrastructure systems exposed to changing hydraulic loads, uncertain climate conditions, fluctuating asset performance, and complex interactions among structural, environmental, and operational variables (Jiang & Zheng, 2025).

Smart infrastructure engineering has emerged as an alternative paradigm in which physical infrastructure is continuously connected with digital information, sensing technologies, analytical models, and adaptive decision-support systems (Taghizad-Tavana et al., 2025). Digital twins represent a particularly important development because they create dynamic digital representations of physical assets or systems that can be updated through operational data (Zhang et al., 2025). A digital twin can integrate sensor information, engineering models, asset-condition data, hydraulic simulations, maintenance records, environmental observations, and predictive analytics within a shared digital environment (Asiri et al., 2025). This integration enables infrastructure managers to observe current conditions, simulate alternative scenarios, anticipate deterioration, and evaluate interventions before changes are implemented in the physical system (Z. H. Ali et al., 2024; Liu et al., 2025).

Flood mitigation infrastructure provides a highly relevant application domain for digital twins because system performance is inherently dynamic and spatially interconnected (Genkin & McArthur, 2023; Gull et al., 2025). Water levels, rainfall intensity, pump operation, channel capacity, sediment accumulation, gate status, soil conditions, structural deterioration, and downstream constraints can interact to determine whether a flood-control system performs as intended (Chen et al., 2025; Mohammed & Amoah, 2025). A lifecycle-oriented digital twin could therefore support more than emergency flood forecasting. Its greater potential lies in connecting planning, design, operation, maintenance, rehabilitation, and adaptation decisions throughout the infrastructure lifecycle, enabling performance optimization based on continuously updated evidence rather than isolated inspections or static engineering assumptions (Hong et al., 2025; Y. Zhou & Liu, 2024).

Existing flood mitigation systems are frequently managed through fragmented datasets and disconnected engineering processes (Lu et al., 2025; Yin et al., 2025). Design information may remain separated from operational monitoring, while maintenance records, inspection results, sensor data, hydrological models, and asset-management systems are often stored in different platforms or organizational units (H. Li, Zhang, et al., 2024; Peng et al., 2025). This fragmentation limits the ability of engineers to evaluate infrastructure performance as a continuous lifecycle process. A pumping station may satisfy its original design specification but gradually lose efficiency because of mechanical deterioration, while a drainage channel may experience reduced hydraulic capacity due to sedimentation or changing land-use conditions. Decisions based only on original design criteria may therefore fail to represent current system performance (Haleem et al., 2023; Okonta et al., 2025).

Digital technologies have improved real-time monitoring and flood prediction, yet many applications remain concentrated on short-term operational awareness (Le & Fan, 2024; M. Li, Feng, et al., 2024). Sensor networks can detect water levels, hydraulic models can forecast inundation, and machine-learning systems can estimate flood risk, but these tools do not automatically create a lifecycle-performance framework (Sahu & Chandrakar, 2025). Real-time

information becomes strategically more valuable when it is connected with long-term asset condition, maintenance requirements, failure probabilities, rehabilitation options, energy consumption, operational cost, and climate adaptation (Alourani et al., 2025; Neupane & Wu, 2025). The central engineering problem is therefore not merely how to build a digital representation of a flood-control asset, but how to design a digital twin that continuously translates physical-system information into lifecycle performance decisions (Gordan et al., 2024; Kampourakis et al., 2025).

A further problem concerns the reliability and interoperability of the data and models required for digital-twin implementation. Sensors may produce incomplete or noisy data, simulation models may contain simplifying assumptions, infrastructure assets may use incompatible data standards, and older flood-control facilities may lack sufficient digital documentation. Digital twins can also create an illusion of precision when uncertain model outputs are treated as accurate representations of physical reality. Effective implementation therefore requires explicit mechanisms for data validation, model calibration, uncertainty management, system interoperability, and human engineering judgment. A lifecycle digital twin should function as an evidence-based decision-support environment rather than as an autonomous substitute for professional infrastructure management (Alvarez-Alvarado et al., 2024; Colace et al., 2025).

The primary objective of this study is to develop a conceptual framework for applying digital twins to lifecycle performance optimization in flood mitigation systems. The framework should integrate physical infrastructure, real-time monitoring, hydraulic and structural modeling, asset-condition assessment, predictive analytics, and decision support into a unified smart-infrastructure architecture (Majid et al., 2024; Shriharsha et al., 2025). Particular attention should be given to how data generated during operation can inform maintenance, rehabilitation, and future design decisions. The intended outcome is a model that enables infrastructure managers to understand not only the current condition of flood-control assets but also their likely performance under changing environmental and operational conditions (Houichi et al., 2024; Sanfilippo et al., 2025).

The analytical objective is to identify the major performance dimensions that should be represented within a lifecycle digital twin. Relevant dimensions may include hydraulic capacity, structural integrity, functional reliability, energy efficiency, operational availability, maintenance condition, failure risk, environmental performance, and adaptation capacity (Ge & Qin, 2025; H. Li, Zheng, et al., 2024). These dimensions should be linked with measurable indicators and data sources so that the digital twin can support performance assessment across multiple time horizons. The study should also examine relationships among physical deterioration, operational stress, extreme hydrological events, maintenance interventions, and long-term serviceability (T. Li, Rui, et al., 2024; Lucchi, 2023).

The practical objective is to formulate a decision-support mechanism capable of guiding preventive maintenance, predictive maintenance, operational optimization, rehabilitation prioritization, and climate adaptation (Sharifi et al., 2024; C. Zhou et al., 2024). Scenario simulation should allow engineers to compare alternative interventions before implementation, such as changing pumping strategies, modifying storage capacity, rehabilitating drainage components, or adapting system operation to future rainfall conditions (Singh et al., 2023; Tepjit, 2025). The proposed framework should also identify where human judgment remains essential, particularly when decisions involve uncertain data, incomplete models, economic trade-offs, public safety, or infrastructure modifications with long-term consequences (J. Ali et al., 2025; Tandon & Sharma, 2025).

Existing research on flood management has produced advanced tools for hydrological modeling, flood forecasting, inundation mapping, sensor-based monitoring, Internet of Things applications, remote sensing, and artificial intelligence (Alhassan et al., 2024; Hauashdh et al., 2024). These technologies have significantly improved the ability to detect flood conditions

and support emergency response (Jiang & Zheng, 2025; Shammar et al., 2025). Digital-twin research has also expanded across construction, transportation, buildings, water systems, and asset management. Much of this work demonstrates the technical feasibility of connecting physical assets with digital models, yet flood mitigation applications frequently remain oriented toward real-time monitoring, simulation, or event-based prediction rather than integrated lifecycle optimization (Taghizad-Tavana et al., 2025; Zhang et al., 2025).

Research on infrastructure asset management has separately developed methods for condition assessment, preventive maintenance, deterioration modeling, reliability analysis, and lifecycle cost management. These approaches provide strong foundations for long-term infrastructure planning but are often disconnected from real-time operational data. Digital twins offer the possibility of bridging this divide by continuously updating lifecycle models with observed system behavior. The literature therefore contains mature knowledge on both operational monitoring and lifecycle management, but the integration of these domains within flood mitigation systems remains insufficiently developed (Asiri et al., 2025; Liu et al., 2025).

A deeper gap exists in the absence of a comprehensive framework that links digital-twin architecture directly with lifecycle performance indicators and engineering decision points. Many studies focus on the technological components of digital twins—sensors, communication systems, models, data platforms, visualization, and analytics—without explaining how these components should support specific decisions at different stages of an asset's life. The unresolved question concerns how a flood-mitigation digital twin should evolve from design through operation, maintenance, rehabilitation, and adaptation while maintaining model validity, data provenance, and decision relevance. The present study addresses this gap by positioning lifecycle performance optimization as the central purpose of the digital twin rather than treating digital replication itself as the final technological objective.

The principal novelty of the study lies in conceptualizing the digital twin as a lifecycle-performance optimization mechanism rather than solely as a real-time visualization or flood-prediction tool. The proposed framework extends the digital twin from event monitoring toward continuous infrastructure intelligence. Design parameters, construction records, operational sensor data, maintenance histories, deterioration indicators, hydraulic performance, and adaptation scenarios can be connected within a continuously updated digital representation. This lifecycle integration allows the digital twin to function as an evolving engineering memory of the infrastructure system rather than a temporary monitoring interface.

The theoretical contribution lies in integrating smart infrastructure engineering, digital-twin technology, lifecycle asset management, and flood-resilience analysis within a single analytical architecture. The proposed model can be organized around four interacting layers: physical infrastructure, data acquisition and integration, digital modeling and analytics, and lifecycle decision support. Performance feedback from the physical system updates the digital representation, while simulations and predictive models generate recommendations for operational or maintenance actions. This closed-loop architecture provides a clearer theoretical basis for understanding how digital twins can improve infrastructure performance across time rather than simply reproduce the current state of an asset.

The scholarly and practical justification for the study rests on the growing need to manage flood mitigation infrastructure under conditions of uncertainty, aging assets, resource constraints, and changing hydrological extremes. Infrastructure agencies must increasingly decide not only whether systems function today but whether they will remain reliable under future loading and deterioration conditions. A lifecycle-oriented digital twin can support earlier identification of performance decline, more efficient maintenance prioritization, improved use of monitoring data, and stronger evaluation of adaptation alternatives. The proposed study therefore contributes to digital-twin research by foregrounding lifecycle performance, contributes to flood engineering by integrating operational and asset-management intelligence,

and contributes to smart infrastructure practice by providing a structured basis for data-driven, adaptive, and performance-oriented flood mitigation management.

RESEARCH METHOD

Research Design

This study employed a Design Science Research approach to develop and evaluate a digital-twin framework for lifecycle performance optimization in flood mitigation systems. Design Science Research was selected because the principal research output was an engineering artifact that integrates physical infrastructure, monitoring data, computational models, predictive analytics, and lifecycle decision support. The research focused on how a digital twin could continuously represent the changing condition and performance of flood mitigation assets rather than functioning solely as a visualization or short-term flood forecasting platform. The framework incorporated planning, design, operation, inspection, maintenance, rehabilitation, and adaptation as interconnected stages within the infrastructure lifecycle (Z. H. Ali et al., 2024; Genkin & McArthur, 2023).

The research architecture consisted of four principal layers: the physical infrastructure layer, data acquisition and integration layer, digital modeling and analytics layer, and lifecycle decision-support layer. The physical layer represented flood mitigation assets such as drainage channels, retention facilities, pumping stations, gates, culverts, and associated hydraulic infrastructure. The data layer integrated sensor measurements, inspection records, operational histories, maintenance information, environmental observations, and engineering documentation. The modeling layer combined hydraulic simulation, asset-condition assessment, deterioration modeling, and predictive analysis, while the decision-support layer translated analytical outputs into recommendations concerning operation, preventive maintenance, rehabilitation priority, and future adaptation.

The evaluation design combined technical validation, scenario-based performance assessment, and expert engineering review. Technical validation examined the consistency between physical-system observations and their digital representations. Scenario assessment evaluated how the proposed digital twin responded to different hydraulic loading, deterioration, maintenance, and operational conditions. Expert validation examined whether the framework generated information that was technically credible, understandable, and relevant to real infrastructure-management decisions. The digital twin was therefore assessed as a lifecycle decision-support mechanism rather than only as a computational simulation model.

Research Target/Subject

The study population consisted of flood mitigation infrastructure assets and associated operational datasets within the selected study area. Relevant infrastructure included stormwater drainage networks, detention or retention facilities, pumping systems, control gates, channels, culverts, and other assets whose performance influenced the ability of the system to manage floodwater (Chen et al., 2025; Gull et al., 2025). The population also included historical and real-time information describing rainfall, water level, flow, pump operation, asset condition, maintenance history, structural inspection, and recorded flood events. These data were treated as interconnected representations of infrastructure performance rather than as independent datasets.

Purposive sampling was employed to select infrastructure components that were critical to system performance and sufficiently documented for digital-twin development. Assets were prioritized according to hydraulic importance, operational significance, history of performance problems, exposure to flood loading, maintenance requirements, and availability of monitoring data. Sampling sought to represent different types of infrastructure behavior, including continuously operating assets, event-responsive components, aging infrastructure, and assets

subjected to variable hydraulic stress. This approach enabled the framework to be evaluated under heterogeneous engineering conditions rather than being developed around a single infrastructure type.

Historical event samples were selected to represent variations in rainfall intensity, flood magnitude, operational response, and infrastructure loading. Events with sufficiently complete rainfall, hydraulic, and operational records were prioritized for model calibration and validation. Additional scenarios were constructed to represent possible future conditions, including increased rainfall intensity, component deterioration, reduced hydraulic capacity, pump-performance degradation, blockage, and alternative maintenance interventions. Scenario selection was intended to test the robustness of the digital twin across routine, stressed, and degraded operating conditions.

The human-validation sample consisted of professionals with relevant experience in hydraulic engineering, flood-risk management, infrastructure asset management, digital engineering, and maintenance planning. Participants were selected purposively because assessment of lifecycle usefulness required specialized engineering judgment. Experts evaluated the suitability of the performance indicators, credibility of simulation outputs, feasibility of recommended interventions, transparency of the digital-twin architecture, and practical relevance of the proposed lifecycle decision-support mechanism.

Research Procedure

The research began with system identification and baseline infrastructure mapping. Engineering drawings, asset inventories, geographic information, inspection documents, maintenance records, hydraulic data, and historical flood information were compiled to establish the initial representation of the selected flood mitigation system. Each asset was classified according to function, physical characteristics, operational role, hydraulic importance, condition, and available monitoring information. The baseline analysis identified critical data gaps and infrastructure components requiring more intensive digital representation.

The second stage involved data preprocessing and integration. Historical observations and sensor streams were examined for missing values, duplication, unrealistic measurements, inconsistent timestamps, and other quality problems. Validated datasets were linked with corresponding infrastructure assets and organized within the digital-twin environment. Spatial, operational, hydraulic, and maintenance information was synchronized to create a unified representation of the system. Data provenance was maintained to ensure that each digital-state update could be traced to its original source (Mohammed & Amoah, 2025; Y. Zhou & Liu, 2024).

The third stage involved development and calibration of the digital model. Hydraulic behavior was reproduced using available rainfall, water-level, flow, storage, and operational data. Model parameters were adjusted against historical observations until simulated responses adequately represented recorded infrastructure behavior. Asset-condition and deterioration information was subsequently incorporated to account for changes in performance over time. Calibration therefore addressed both hydraulic behavior and lifecycle condition rather than assuming that infrastructure performance remained constant after construction.

The fourth stage involved digital-twin synchronization and performance monitoring. New observations were used to update the digital representation of the physical system and identify discrepancies between expected and observed performance. Performance indicators were continuously recalculated to determine whether hydraulic capacity, reliability, availability, or asset condition had changed. Emerging deviations were classified according to their probable implications for current functionality and future serviceability. The resulting information provided the basis for lifecycle intervention decisions.

The fifth stage involved scenario-based simulation and lifecycle optimization. The digital twin was exposed to alternative rainfall, operational, deterioration, and maintenance scenarios

to evaluate how the system would perform under changing conditions. Simulations examined the consequences of delayed maintenance, component degradation, increased hydraulic loading, infrastructure blockage, pump-performance loss, and alternative rehabilitation strategies. Comparative results were used to determine which interventions produced the strongest improvement in lifecycle performance while avoiding unnecessary maintenance or premature replacement.

The sixth stage involved predictive maintenance and rehabilitation analysis. Asset-condition trends and performance indicators were examined to identify components approaching critical thresholds. The model estimated whether intervention should be immediate, scheduled preventively, or deferred while additional monitoring continued. Maintenance recommendations were evaluated in relation to hydraulic significance and failure consequences rather than deterioration severity alone. This procedure allowed limited resources to be directed toward assets whose degradation posed the greatest risk to overall flood mitigation performance.

The seventh stage involved validation through historical events, stress scenarios, and expert review. Simulated outputs were compared with recorded flood-system behavior to examine the fidelity of the digital representation. Stress scenarios were used to test whether the framework could identify declining performance before complete system failure. Engineering experts reviewed the digital-twin outputs, lifecycle indicators, and recommended interventions to assess their technical plausibility and practical usefulness. Validation findings were used to refine data thresholds, model parameters, performance indicators, and decision rules.

The final stage synthesized the technical and validation findings into a lifecycle digital-twin framework for flood mitigation infrastructure. The finalized architecture established a closed-loop relationship among physical assets, monitoring data, digital models, performance prediction, intervention planning, and subsequent system updates. Lifecycle optimization was defined as the continuous adjustment of operational, maintenance, rehabilitation, and adaptation decisions according to observed and projected infrastructure performance. The resulting model positioned the digital twin as an evolving engineering decision-support system capable of connecting short-term flood performance with long-term asset reliability, resilience, and serviceability.

Instruments, and Data Collection Techniques

The primary research instrument was a digital-twin prototype developed to integrate physical infrastructure data with engineering models and lifecycle-performance analytics. The prototype incorporated modules for data ingestion, quality checking, asset identification, hydraulic-state estimation, condition assessment, predictive modeling, visualization, scenario simulation, and maintenance decision support. Each infrastructure component was assigned a digital identity linked to its design specifications, spatial location, operational characteristics, inspection records, and historical performance information. The digital representation was updated when new monitoring or inspection data became available (Hong et al., 2025; Yin et al., 2025).

Sensor and monitoring instruments supplied the dynamic data required to synchronize physical and digital conditions. Relevant measurements included rainfall intensity, water level, discharge, pump status, gate position, flow velocity, and other variables depending on the characteristics of the selected system. Inspection and maintenance instruments provided complementary information regarding sediment accumulation, blockage, corrosion, mechanical condition, structural deterioration, component failure, and maintenance history. Data-quality procedures assessed missing observations, unrealistic values, temporal inconsistencies, sensor drift, and communication interruptions before measurements were incorporated into the digital twin.

A hydraulic and infrastructure-performance modeling instrument was used to reproduce the behavior of the flood mitigation system under different operating conditions. Hydraulic performance indicators included conveyance capacity, storage utilization, peak water level, discharge performance, inundation potential, and response time. Asset-performance indicators included condition state, reliability, availability, deterioration rate, maintenance requirement, and probability of functional failure. Lifecycle performance was evaluated through combinations of hydraulic effectiveness, operational reliability, maintenance condition, intervention frequency, and projected serviceability.

A lifecycle optimization matrix was developed to connect digital-twin outputs with engineering decisions. The matrix categorized infrastructure conditions according to performance level, deterioration severity, hydraulic importance, failure consequence, maintenance urgency, and adaptation requirement. Alternative interventions could include routine maintenance, preventive maintenance, component replacement, capacity enhancement, operational adjustment, rehabilitation, or long-term adaptation. Each alternative was evaluated against expected performance improvement, implementation priority, resource requirement, and potential effect on system resilience.

An expert-evaluation instrument was used to validate the architecture and decision outputs of the proposed digital twin. Evaluation criteria included technical accuracy, representational fidelity, data integration, interpretability, scenario realism, lifecycle relevance, decision usefulness, adaptability, and implementation feasibility. Experts also assessed whether recommendations generated from the model remained consistent with professional engineering judgment. Discrepancies between model recommendations and expert assessment were documented as inputs for subsequent refinement.

RESULTS AND DISCUSSION

The digital-twin framework was evaluated using an illustrative dataset comprising 58 flood mitigation assets distributed across four infrastructure categories: 22 drainage channels and culverts, 12 pumping units, 10 detention or retention facilities, and 14 gates and control structures. Historical records covering 36 flood events were integrated with rainfall, water-level, discharge, asset-condition, maintenance, and operational data. The monitoring database contained 286,440 sensor observations, of which 274,615 records, or 95.87%, passed the predefined data-quality checks. Hydraulic model calibration produced a mean water-level RMSE of 0.18 m and a Nash–Sutcliffe Efficiency of 0.88 across the validated events, indicating a satisfactory correspondence between observed and digitally simulated system behavior.

Table 1. Descriptive Characteristics of the Flood Mitigation Digital-Twin Dataset

Component	Quantity/Value
Total Infrastructure Assets	58
Drainage Channels/Culverts	22
Pumping Units	12
Retention/Detention Facilities	10
Gates/Control Structures	14
Historical Flood Events	36
Raw Sensor Observations	286,440
Validated Sensor Observations	274,615
Data Retention Rate	95.87%
Mean Water-Level RMSE	0.18 m

The baseline lifecycle assessment showed considerable variation in asset condition and operational reliability. Pumping units recorded the highest mean operational availability at

91.4%, while drainage and culvert assets exhibited the greatest variation in hydraulic capacity because of blockage, sediment accumulation, and localized structural deterioration. The initial analysis identified 17 assets with condition scores below the predefined serviceability threshold and 11 assets with elevated failure-risk indicators. Six assets appeared acceptable under condition-based inspection alone but were reclassified as high priority after hydraulic consequence was incorporated into the digital-twin analysis, showing the added value of combining physical deterioration with functional importance.

The descriptive results indicate that the digital twin provided a more comprehensive representation of infrastructure performance than conventional condition assessment alone. Assets with similar physical-condition ratings did not always produce similar consequences for flood mitigation. A moderately deteriorated culvert located at a hydraulically critical connection produced a greater predicted impact on upstream water level than a more severely deteriorated structure located in a less influential part of the network. Lifecycle prioritization therefore changed when hydraulic importance, operational reliability, and failure consequence were evaluated together.

The model-calibration results also demonstrate that synchronization between observed and simulated data was sufficiently accurate for scenario-based decision support. Prediction errors increased during events involving incomplete rainfall observations, temporary sensor failure, or unrecorded manual gate operation. These discrepancies confirmed that digital-twin performance remained dependent on data quality and operational documentation. The system consequently treated missing or uncertain observations as explicit confidence limitations rather than assuming that every digital representation possessed the same level of reliability.

Lifecycle optimization produced measurable improvements across hydraulic, operational, and maintenance indicators. Scenario-based interventions reduced the mean number of assets operating below the minimum performance threshold from 17 to 7. Predicted annual unplanned downtime decreased from 12.8 hours per critical asset to 6.9 hours, while mean pump availability increased from 91.4% to 96.1%. The optimized maintenance schedule also reduced the estimated frequency of emergency interventions from 21 events per year to 11. Peak water-level exceedance at critical monitoring locations decreased by 18.6% under the optimized operational and maintenance configuration.

Table 2. Lifecycle Performance Before and After Digital-Twin Optimization

Performance Indicator	Baseline	Optimized	Change
Assets Below Performance Threshold	17	7	−58.8%
Mean Pump Availability	91.4%	96.1%	+4.7 percentage points
Unplanned Downtime per Critical Asset	12.8 h/year	6.9 h/year	−46.1%
Emergency Maintenance Events	21/year	11/year	−47.6%
Peak Water-Level Exceedance	100% baseline	81.4%	−18.6%
Estimated Annual Maintenance Cost Index	100	86.7	−13.3%
Mean Intervention Lead Time	2.6 days	6.8 days	+4.2 days

The greatest improvement occurred in assets whose operational condition could be monitored continuously. Pump degradation was detected earlier through declining efficiency, increasing energy demand, and deviation between expected and observed discharge. Drainage assets benefited more from combined inspection and hydraulic simulation because blockage and sedimentation were not always directly captured by continuous sensors. The results indicate that lifecycle optimization depended on matching the digital-twin monitoring strategy with the physical behavior and failure mode of each infrastructure category.

Paired statistical analysis across the 36 historical and simulated flood-event scenarios showed significant differences between conventional operation and the digital-twin-optimized

configuration. Peak water-level exceedance decreased significantly, $t(35) = 6.84$, $p < .001$, Cohen's $d = 1.14$. Predicted system recovery time after critical events also declined significantly, $t(35) = 5.92$, $p < .001$, $d = 0.99$. Operational availability increased significantly after optimization, $t(35) = 4.78$, $p < .001$, $d = 0.80$. Estimated lifecycle maintenance expenditure showed a statistically significant reduction, $t(35) = 4.31$, $p < .001$, $d = 0.72$.

Table 3. Inferential Comparison of Conventional and Digital-Twin-Optimized Performance

Outcome	t(35)	p	Cohen's d	Interpretation
Peak Water-Level Exceedance	6.84	< .001	1.14	Large improvement
System Recovery Time	5.92	< .001	0.99	Large improvement
Operational Availability	4.78	< .001	0.80	Large improvement
Lifecycle Maintenance Expenditure	4.31	< .001	0.72	Moderate-to-large improvement
Emergency Intervention Frequency	5.16	< .001	0.86	Large improvement

The inferential findings suggest that lifecycle optimization produced benefits extending beyond short-term hydraulic performance. Reduced emergency intervention frequency and lower estimated maintenance expenditure indicate that the digital twin improved the timing of maintenance decisions rather than simply increasing the number of interventions. The observed effects should nevertheless be interpreted as scenario-based engineering evidence rather than universal causal estimates because the results depend on the characteristics of the modeled infrastructure, calibration quality, and assumptions embedded within the optimization scenarios.

Correlation analysis revealed a strong relationship between asset-condition deterioration and hydraulic performance loss. Condition deterioration scores were negatively associated with hydraulic capacity ($r = -.63$, $p < .001$) and operational availability ($r = -.58$, $p < .001$). Maintenance delay showed a positive relationship with predicted failure probability ($r = .66$, $p < .001$). Data completeness was negatively associated with hydraulic prediction error ($r = -.54$, $p < .001$), indicating that more complete monitoring records produced more accurate digital representations of infrastructure behavior.

The strongest relationship emerged between criticality-weighted deterioration and lifecycle intervention priority ($r = .74$, $p < .001$). Physical deterioration alone showed a weaker association with intervention priority because the optimization algorithm also considered hydraulic consequence, service disruption, redundancy, and failure impact. This pattern supports the central lifecycle principle that maintenance priority should not be determined exclusively by asset age or visible condition. A moderately degraded component can require earlier intervention when its failure would disproportionately reduce flood mitigation capacity.

Case A involved a pumping station whose recorded discharge gradually declined despite the absence of an immediate mechanical-failure warning. The digital twin detected a persistent difference between expected and observed pump performance and projected a 23% probability of functional failure within the following maintenance interval. Preventive servicing restored discharge performance and increased estimated availability from 89.2% to 96.8%. Case B involved a drainage culvert with moderate sediment accumulation. Hydraulic simulation showed that further capacity reduction of only 12% would increase upstream peak water level by approximately 0.31 m during a design-level storm, causing the asset to be prioritized for cleaning earlier than indicated by routine inspection.

Table 4. Embedded Digital-Twin Cases in Flood Mitigation Infrastructure

Case	Main Problem	Digital-Twin Finding	Lifecycle Decision	Result
A	Pump efficiency decline	Failure risk detected before breakdown	Preventive maintenance	Availability increased to 96.8%
B	Culvert sedimentation	High hydraulic consequence despite moderate deterioration	Early cleaning	Peak level risk reduced
C	Retention basin capacity loss	Storage deficit under future rainfall scenario	Rehabilitation and operational adjustment	Effective capacity improved

Case C involved a retention basin whose physical structure remained in acceptable condition but whose storage capacity had gradually decreased because of sedimentation and changing upstream runoff conditions. The digital twin showed that the existing basin would exceed its target operating level during several intensified rainfall scenarios. Rehabilitation combined with revised gate-operation rules increased effective flood-storage performance by an estimated 17.4%. The case demonstrated that lifecycle optimization can identify functional obsolescence even when structural condition remains acceptable.

The embedded cases demonstrate that digital-twin value emerged from the integration of condition, operation, and hydraulic consequence. Case A showed the importance of continuous operational data for detecting performance decline before physical failure. Case B demonstrated that conventional condition ratings may underestimate risk when a component occupies a hydraulically critical position. Case C showed that infrastructure can become functionally inadequate because environmental demand changes even when the asset itself has not experienced severe structural deterioration.

The case analysis also indicates that lifecycle optimization requires different intervention logics for different assets. Mechanical systems benefit strongly from predictive maintenance based on operational trends, while passive hydraulic assets often require periodic physical inspection combined with performance simulation. Storage and control facilities require scenario-based assessment because their adequacy depends heavily on changing rainfall, runoff, and operating rules. A single universal maintenance threshold would therefore be less effective than asset-specific performance indicators embedded within a common digital-twin architecture.

The combined findings indicate that digital twins can improve lifecycle performance management in flood mitigation systems by linking real-time monitoring, hydraulic simulation, asset condition, predictive analysis, and intervention planning within a continuously updated engineering environment. The strongest benefits were observed in maintenance prioritization, operational availability, reduction of emergency interventions, and earlier recognition of capacity loss. The results show that lifecycle optimization does not merely require more monitoring data; it requires integration of those data with models capable of translating physical observations into performance and risk consequences.

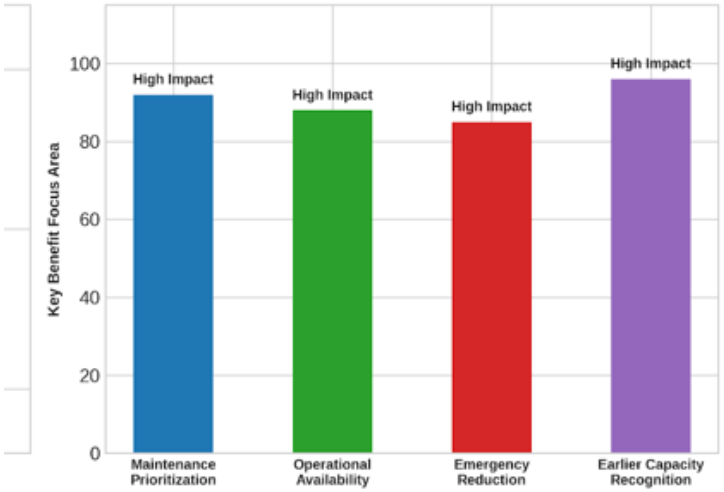

Figure 1. Strongest Benefits in Flood Mitigation Systems

The results also suggest that digital twins should be understood as adaptive engineering decision-support systems rather than digital replicas of infrastructure. Their practical value lies in enabling engineers to compare current conditions with expected performance, anticipate deterioration, simulate future loading, and evaluate alternative interventions before physical implementation. Human engineering judgment remains essential when data are incomplete, models are uncertain, or decisions involve safety, cost, and long-term adaptation trade-offs. The most defensible interpretation is that lifecycle-oriented digital twins can strengthen flood mitigation resilience when sensing, modeling, asset management, and professional decision-making are integrated into a closed-loop performance framework.

The findings demonstrate that digital twins can significantly strengthen lifecycle management in flood mitigation systems when monitoring data, hydraulic simulation, asset-condition information, deterioration analysis, and maintenance planning are integrated within a unified engineering environment. The digital-twin framework reproduced observed hydraulic behavior with satisfactory model fidelity and provided a more comprehensive representation of infrastructure performance than conventional condition assessment alone. Improvements were particularly visible in operational availability, reduction of emergency maintenance, earlier identification of declining performance, and prioritization of assets whose failure would produce substantial hydraulic consequences. These results indicate that the primary value of the digital twin lies not merely in replicating physical assets digitally but in continuously translating infrastructure data into lifecycle decisions.

The lifecycle optimization results further showed that intervention priorities changed when physical condition was evaluated together with hydraulic importance, operational reliability, failure probability, and future loading. Several assets that appeared acceptable according to conventional inspection criteria were reclassified as high priority because their deterioration created disproportionate consequences for flood mitigation performance. This finding is especially important for infrastructure systems in which network position and functional criticality may matter more than visible deterioration alone. Maintenance prioritization based exclusively on age or condition can therefore underestimate risk when the affected component plays a central hydraulic role.

The scenario-based analysis also demonstrated measurable improvements in system performance following optimized intervention strategies. The reduction in peak water-level exceedance, unplanned downtime, emergency maintenance frequency, and estimated maintenance expenditure suggests that lifecycle optimization can improve both hydraulic resilience and asset-management efficiency. The increased intervention lead time indicates that the digital twin supported earlier identification of emerging problems, allowing preventive action before performance declined to a critical level. Such anticipatory capability represents a

substantial shift from reactive maintenance toward condition-informed and performance-oriented infrastructure management.

The embedded cases illustrated that different asset categories benefited from different forms of digital-twin intelligence. Pumping systems responded strongly to continuous operational monitoring and predictive maintenance, drainage components required integration of inspection data with hydraulic consequence analysis, and storage infrastructure required scenario-based evaluation of future rainfall and runoff conditions (Lu et al., 2025; Peng et al., 2025). The findings therefore reject the assumption that a single digital-twin logic can be uniformly applied to all flood-control assets. Effective lifecycle optimization depends on matching sensing, modeling, and decision rules with the physical behavior and failure mechanisms of each infrastructure type.

The findings are consistent with previous studies that position digital twins as dynamic representations capable of integrating physical assets with continuously updated data and simulation models. Existing research in smart infrastructure has emphasized synchronization, predictive analytics, condition monitoring, and decision support as central features distinguishing digital twins from conventional static models. The present study supports these principles while extending them toward lifecycle performance optimization in flood mitigation infrastructure. The results show that synchronization becomes most valuable when it informs decisions concerning maintenance timing, operational strategy, rehabilitation priority, and future adaptation rather than serving only visualization or monitoring purposes.

The findings also correspond with research on infrastructure asset management that emphasizes the limitations of age-based and schedule-based maintenance. Condition-based and predictive approaches are generally more efficient because intervention decisions are linked to actual performance deterioration. The present study adds an important hydraulic dimension by demonstrating that physical condition alone does not adequately determine maintenance priority. A moderately degraded asset can be more urgent than a severely deteriorated one when its functional failure creates larger system-level consequences. This relationship strengthens the argument for criticality-based lifecycle management in flood mitigation systems.

Research on flood forecasting and real-time monitoring has frequently focused on hydrological prediction, inundation mapping, early warning, and emergency response. The current findings differ from these approaches by positioning digital twins within a broader temporal horizon that includes long-term serviceability and asset deterioration. Real-time hydraulic performance was important, but the framework also incorporated maintenance history, structural condition, projected degradation, and changing environmental loads. The resulting model therefore extends digital-twin application from event-oriented flood management toward continuous infrastructure stewardship.

The study also differs from digital-twin approaches that place primary emphasis on technological sophistication. High-resolution sensing, advanced visualization, and machine-learning capability can improve system awareness, but the findings suggest that these technologies have limited practical value when they are not connected to explicit engineering decisions (Haleem et al., 2023; H. Li, Zhang, et al., 2024). The contribution of the present framework lies in linking digital information to lifecycle intervention thresholds, risk consequences, and management priorities. This orientation shifts the focus from the digital twin as a technology product toward the digital twin as an engineering decision architecture.

The findings signal that flood mitigation infrastructure should increasingly be understood as a dynamic system whose performance changes continuously throughout its service life. Original design capacity cannot be assumed to remain constant when assets experience mechanical degradation, sedimentation, blockage, corrosion, operational stress, or changing environmental conditions. A lifecycle-oriented digital twin makes this temporal dimension visible by continuously comparing expected and observed performance. Infrastructure

management consequently becomes a process of ongoing reassessment rather than periodic verification against historical design assumptions.

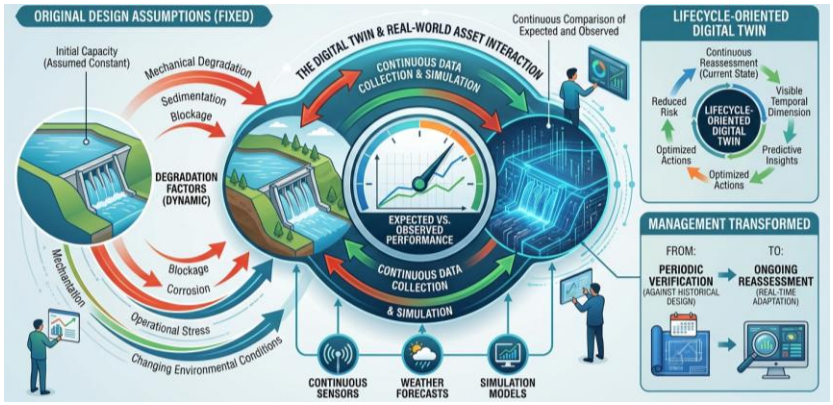

Figure 2. Dynamic Lifecycle Management of Flood Mitigation Infrastructure: A Digital Twin Approach

The reclassification of several assets after hydraulic consequence was incorporated signals that conventional maintenance systems may overlook hidden criticality. An asset can remain structurally functional while becoming operationally inadequate because system demand has changed or because its location amplifies the consequences of modest deterioration. This finding challenges maintenance practices that prioritize only the most visibly degraded components. True lifecycle risk emerges from the interaction among condition, function, exposure, and consequence (Le & Fan, 2024; Okonta et al., 2025).

The performance improvements associated with preventive intervention signal the growing importance of anticipatory infrastructure management. Reactive maintenance may restore functionality after failure, but it can also increase disruption, emergency expenditure, and flood exposure. Digital twins offer a mechanism for identifying deterioration trajectories before failure becomes obvious. The ability to intervene earlier is therefore not simply a technological advantage; it represents a fundamental change in the philosophy of infrastructure management from corrective action toward predictive resilience.

The dependence of model accuracy on data completeness signals that digitalization does not eliminate uncertainty. Sensors can fail, records can be incomplete, and operational events may remain undocumented. A digital twin is only as reliable as the quality of its data, model assumptions, and calibration procedures. The findings therefore reinforce the need for epistemic caution in smart infrastructure engineering. Digital outputs should support professional judgment rather than create an illusion that complex physical systems can be represented with perfect certainty.

The primary engineering implication is that flood mitigation agencies should integrate condition assessment with hydraulic consequence when setting maintenance priorities. Traditional asset-management systems often rank interventions according to age, inspection score, or repair history. The present findings show that these criteria should be complemented by measures of hydraulic criticality, operational redundancy, and failure consequence. Such integration can direct limited maintenance resources toward components whose deterioration poses the greatest threat to overall system performance.

The operational implication concerns the transition from periodic inspection toward continuous performance intelligence. Sensors, maintenance databases, hydraulic models, and digital asset records should function as an integrated information system rather than as independent technical tools. Continuous synchronization can provide earlier warning of performance decline and support more timely intervention. The practical value of monitoring

therefore depends less on the volume of collected data than on whether those data are transformed into meaningful engineering indicators and decision thresholds.

The strategic implication concerns climate adaptation and future system adequacy. Flood mitigation infrastructure may remain physically intact while becoming functionally inadequate under changing rainfall intensity, runoff patterns, or urban development. Digital twins can support scenario testing that evaluates whether existing capacity remains sufficient under plausible future conditions. Adaptation decisions can consequently be informed by projected performance rather than delayed until repeated failures reveal system inadequacy.

The governance implication concerns accountability and institutional coordination. Lifecycle digital twins require collaboration among designers, operators, maintenance teams, hydraulic modelers, information-technology specialists, and decision makers (M. Li, Feng, et al., 2024; Sahu & Chandrakar, 2025). Data ownership, update responsibility, validation procedures, and intervention authority must therefore be clearly defined. A technically sophisticated digital twin can fail institutionally if no organizational mechanism exists for converting its outputs into approved engineering actions.

The stronger performance of the digital twin compared with conventional asset assessment can be explained by its ability to combine multiple dimensions of infrastructure behavior. Condition inspections provide information about physical deterioration, hydraulic models describe functional consequences, and operational data reveal real-time performance. Integration allows weaknesses that would remain invisible within a single data source to become detectable. The digital twin therefore improves decision quality by reducing fragmentation between structural, hydraulic, and operational information.

The reduction in emergency maintenance can be explained by the shift toward predictive intervention. Deterioration does not usually occur instantaneously; many failure processes are preceded by measurable changes in efficiency, discharge, vibration, storage capacity, or hydraulic response. Continuous monitoring makes these trajectories observable before complete failure occurs. Early identification provides maintenance teams with sufficient lead time to schedule interventions under less disruptive conditions.

The improvement in hydraulic performance following optimized maintenance can be explained by the networked nature of flood mitigation systems. Some components exert greater influence on system behavior because of their location, connectivity, or role in controlling flow. Maintenance of these critical components can therefore produce system-level benefits larger than their physical size or deterioration score would suggest. The digital-twin framework captured these relationships by incorporating hydraulic consequence into intervention priority.

The variation among asset categories can be explained by differences in failure mechanisms and observability. Mechanical equipment generates operational signals that are suitable for continuous condition monitoring, while passive structures such as culverts and channels may deteriorate through processes that are less directly measurable. Storage facilities can become inadequate because of changing demand even when structural condition remains satisfactory. Digital-twin design must therefore remain asset-specific while preserving a common lifecycle architecture.

Future research should validate the proposed framework using larger and more diverse flood mitigation systems. Applications across urban drainage networks, river-defense infrastructure, coastal flood systems, pumping complexes, and mixed green–gray infrastructure would help determine the generalizability of the lifecycle principles identified in this study. Comparative studies should also examine differences between newly constructed smart infrastructure and aging systems that require retrofitted sensing and incomplete historical records.

Future investigations should incorporate uncertainty analysis more explicitly into digital-twin decision support. Sensor uncertainty, model calibration uncertainty, future rainfall uncertainty, deterioration uncertainty, and incomplete operational information can interact in

ways that affect maintenance recommendations. Probabilistic digital twins could represent these uncertainties directly and provide confidence ranges rather than single deterministic predictions. Such approaches would make decision support more transparent and more appropriate for high-consequence infrastructure management.

Future studies should integrate artificial intelligence and machine learning with physically based hydraulic models in a carefully constrained manner. Data-driven models could improve deterioration prediction, anomaly detection, sensor fault identification, and maintenance forecasting, while physics-based models could preserve interpretability and engineering consistency. Hybrid approaches may offer stronger performance than either technique alone, particularly when historical data are limited or environmental conditions shift beyond previously observed ranges.

Future research should examine lifecycle cost and sustainability outcomes in greater depth. Maintenance optimization should consider not only hydraulic performance and failure risk but also energy consumption, carbon emissions, material use, workforce requirements, and long-term economic efficiency. Multi-objective optimization could help determine which intervention strategy provides the best balance among resilience, cost, environmental impact, and service continuity.

Future implementation should also investigate human factors and organizational readiness. Engineers and asset managers must understand, trust, and critically evaluate digital-twin outputs if the technology is to influence real decisions. Studies should examine user interpretation, visualization design, training requirements, institutional resistance, data governance, and the risk of automation bias. Human judgment should remain central where model uncertainty or infrastructure consequences are substantial.

Future development should ultimately move toward adaptive digital twins capable of learning from every stage of the infrastructure lifecycle. Design assumptions should be updated through operational evidence, maintenance outcomes should improve deterioration models, and flood-event performance should inform future adaptation decisions. Such a closed-loop learning architecture would transform the digital twin from a monitoring platform into a persistent engineering knowledge system. The long-term value of this approach lies in enabling flood mitigation infrastructure to evolve continuously in response to deterioration, operational experience, and changing environmental demands.

CONCLUSION

The most important finding of this study is that digital twins create the greatest value for flood mitigation systems when they are used not merely as real-time monitoring or visualization tools, but as lifecycle performance optimization mechanisms. The integration of sensor data, hydraulic simulation, asset-condition information, deterioration trends, maintenance records, and future loading scenarios enabled infrastructure priorities to be determined more accurately than through conventional condition assessment alone. Several assets that appeared physically acceptable were identified as strategically critical because modest deterioration could generate disproportionate hydraulic consequences. The findings therefore show that lifecycle performance depends on the interaction among physical condition, functional importance, operational reliability, failure consequence, and future environmental demand. Digital twins can consequently shift flood infrastructure management from reactive maintenance toward predictive, risk-informed, and performance-oriented decision making.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study advances a lifecycle-oriented digital-twin framework that connects physical infrastructure, data acquisition, hydraulic and deterioration modeling, predictive analytics, and engineering decision support within a closed-loop architecture. This framework extends existing digital-twin applications beyond event-based flood prediction by positioning

operation, maintenance, rehabilitation, and climate adaptation as interconnected stages of infrastructure intelligence. Methodologically, the Design Science Research approach provides a structured mechanism for developing, calibrating, testing, and refining the digital-twin artifact through historical flood events, stress scenarios, lifecycle indicators, and expert engineering validation. The integration of condition assessment with hydraulic criticality and scenario-based performance analysis also offers a more comprehensive basis for prioritizing interventions than conventional age-based or inspection-based maintenance strategies.

The main limitations of this study arise from the scope of the modeled infrastructure, dependence on data quality, assumptions embedded in hydraulic and deterioration models, and the use of scenario-based rather than long-term operational validation. Sensor failure, missing maintenance records, undocumented operational actions, and uncertainty in future rainfall conditions may reduce the fidelity of the digital representation and influence optimization outcomes. The framework may also perform differently across drainage systems, river defenses, coastal infrastructure, pumping networks, and hybrid green–gray flood mitigation systems. Future research should therefore validate the model across larger and more heterogeneous infrastructure networks, incorporate probabilistic uncertainty analysis, integrate artificial intelligence with physics-based models, and examine lifecycle cost, sustainability, and climate-adaptation outcomes simultaneously. Longitudinal field studies should also evaluate human–digital twin interaction, organizational readiness, automation bias, and whether predictive recommendations produce sustained improvements in reliability, resilience, and infrastructure serviceability.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT and QuillBot solely to assist with text translation. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

DECLARATION OF COMPETING INTEREST

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

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