

Article

A Digital Twin Dam and Watershed Management Platform

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Abstract: This paper presents an innovative digital twin dam and watershed management platform, K-Twin SJ, that utilizes real-time data and simulation models to support decision-making for flood response and water resource management. The platform includes a GIS-based geospatial digital twin of the entire Sumjin dam and river water system in Korea, with high-precision geospatial topography and facility information for dams and rivers (watershed area 4913 km², river length 173 km, and 91 water infrastructures). The platform synchronizes real-time data such as rainfall, dam and river water levels, flow rate, and closed-circuit television (CCTV), and incorporates three hydraulic and hydrological simulation models for efficient dam operation considering the river conditions. AI technology is also used to predict the river water level and suggest optimal dam discharge scenarios. Additionally, the platform includes a geotechnical safety evaluation module for river levees, advanced drone monitoring for dams and rivers, and an AI CCTV video surveillance function. The digital-twin-based platform supports efficient decision-making for smart flood responses and contributes to reducing flooding damage and optimal operation through better smart water management.

Keywords: digital twin; dam; river management; watershed; cyber physical system; water resource; levee; geospatial; digitalisation



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1. Introduction

Climate change and torrential rains are adding to the difficulties in dam operation and downstream river management. Flood-related disasters have increased by 134% since 2000, with the majority of flood-related deaths and economic losses recorded in Asia, according to the World Meteorological Organization [1]. According to the World Bank, water-related disasters have been the most common type of disaster over the past 50 years, accounting for 70% of all deaths resulting from natural disasters [2]. Recent research [3,4] shows that the risk of floods would be increased by a warmer climate, and extreme flooding caused by global warming is becoming increasingly common worldwide and poses a significant threat to both human life and economic stability. There has been a significant increase in climate change impact assessment studies due to the recognition that changes in climate can have a profound effect on water availability and intensify the occurrence of floods [5]. With the progression of global warming, it is anticipated that the hydrological cycle will undergo intensification, resulting in heightened levels of extreme precipitation events and an augmented risk of flooding [6]. According to the Intergovernmental Panel on Climate Change (IPCC), extreme weather events such as floods have become more frequent and severe due to climate change [7]. The rise in global temperatures has resulted in an increase in atmospheric moisture, leading to more storms and heavy rainfall [2]. Consequently, flood risks, along with associated societal damages, are expected to continue to increase with each degree of global warming [7]. Moreover, the IPCC projects that heavy precipitation events are very likely to increase in frequency over most regions during the 21st century, leading to more rain-induced floods [7]. One note is that it is important to analyze the complex relationships among various variables, including extreme precipitation events, that contribute to flood extremes [8]. Observational

evidence [9] suggests that hydrometeorological extremes, including droughts and floods, are increasing globally.

South Korea suffered severe water disasters in August 2020 and 2022 due to the longest rainy season ever and unexpected torrential rain [10–14]. Precipitation shifts have historically led to some of the largest and most damaging floods and the Oroville dam incident in the western United States [15], and river floods have caused significant damage in Europe [16] and the Lower Mississippi River region [17]. The Yangtze River in Asia, affected by the East Asian monsoon, experiences frequent flooding in summer [18]. These extreme events are occurring more frequently due to climate change, which poses a greater risk than normal runoff events.

Since we have to prepare dams and river basins for extreme rainfall conditions, the demand for more scientific and intelligent data-driven watershed management is rapidly increasing [19–21]. As a conventional approach, the utilization of numerical simulations for large-scale dams and river basins has gained significant popularity. It is still valid and useful; however, traditional approaches to numerical modeling often encounter challenges when it comes to effectively modeling and managing dams and reservoirs. Avesani et al. [22] highlighted that large-scale hydrological models pose considerable demands in terms of memory allocation and CPU time, especially when the assessment of modeling uncertainty is necessary. Moreover, Nazemi and Wheeler [23] demonstrated that the current capacity of large-scale models to accurately represent human water demands is relatively limited, particularly in the context of future projections and coupled land–atmospheric simulations.

As a multidisciplinary approach, another trend of this era is digital transformation. In other words, active discussions are being held on whether efficiency and productivity can be increased by digitalizing traditional knowledge-based watershed and water infrastructure management. We are now in an era of radical “new destructive creation” by digital transformation for the first time in human history. The digital transformation triggered by the fourth industrial revolution is creating an even greater digital divide due to COVID-19 in 2020. In his book “The Fourth Industrial Revolution The Next”, Klaus Schwab, founder of the World Economic Forum, introduces various interesting developments in fourth-industrial technology [24]. These technologies are ushering in a new era of building and expanding the impact of digitalization in new ways we never expected.

The water management sector, like many others, is experiencing a wave of significant digital innovations. Various endeavors have been undertaken to explore more efficient and intelligent platforms for water resource management, utilizing cutting-edge digital technologies. For instance, Zeng et al. [25] demonstrated the potential of integrating the Internet of Things (IoT) with Blockchain technology for smart water resource management and effective monitoring of agricultural fields. Tomaszewski and Kołakowski [26] discussed the challenges faced by 5G/6G mobile networks in sectors crucial for sustainable natural resource utilization, including water management. Huang et al. [27] investigated changes in surface water area using the Google Earth Engine cloud platform. Hasan and Abed [28] examined the characteristics and design of a Web GIS Platform for monitoring water resources, enabling information dissemination, exchange, and management through the Internet. Stein et al. [29] provided valuable insights from case studies conducted in Paris and Berlin, exploring the potential of digital solutions to enhance public awareness of urban water management issues.

Despite these commendable efforts, to the best of our knowledge, there have been few attempts to apply digital twin technology across an entire dam and river basin for comprehensive digitalized smart water resource management and data-driven decision-making. Here, ‘digital twin’ is defined as a virtual digital model of an asset, process, or service in the real world. It is an interaction between the physical and digital worlds. This connection and communication between reality and digitalized features allows for real-time monitoring, intuitive understanding of situations, the possibility to identify any issue before it occurs, and various simulations and prediction modeling, and facilitates optimal decision-making.

Digital twin technology has gained significant attention in recent years as a promising approach for improving the efficiency, reliability, and sustainability of various industries. A digital twin is a virtual replica of a physical system, process, or product that enables real-time monitoring, analysis, and optimization of its performance. The use of digital twins has become increasingly popular in fields such as manufacturing, energy, healthcare, transportation, and construction, among others. The technology enables companies to simulate and test different scenarios in a virtual environment, reducing the need for costly physical testing and experimentation.

In the manufacturing industry, Grieves [30] provided an early overview of digital twin technology, while Lattanzi et al. [31] reviewed its practical implementation issues. In predictive maintenance, van Dinter et al. [32] identified data quality and modeling techniques as key challenges, while Somers et al. [33] emphasized the importance of effective testing for reliability and safety. O'Sullivan et al. [34] presented a case study of implementing a digital twin in a large-scale smart manufacturing facility, highlighting the challenges of collaboration and selecting appropriate modeling techniques. In the energy sector, Clausen et al. [35] presented a digital twin framework to improve energy efficiency and occupant comfort in public and commercial buildings, while Fu et al. [36] provided a brief review of digital twin technology in the electric power industry. Bortolini et al. [37] reviewed digital twin applications for building energy efficiency. Yu et al. [38] conducted a review of energy digital twin technology for industrial energy management. In transportation, papers by Yin and Cai [39], Rudskoy et al. [40], Kušić et al. [41], Dasgupta et al. [42], and Gao et al. [43] have discussed the recent advancements and applications of digital twins in urban road landscape design analysis, intelligent transport systems, real-time synergy of traffic data streams, adaptive traffic control systems, and transportation infrastructure, respectively. These papers highlight the potential benefits of digital twins for improving system efficiency, optimizing operations, and reducing congestion. However, they also underline the need to address challenges related to data acquisition, modeling, simulation, and integration to facilitate the wider adoption of digital twin technology in these sectors.

The literature reviews presented in this text demonstrate the potential benefits of digital twin technology in various industries, including manufacturing, energy, and transportation. However, the implementation of digital twin technology also has challenges. The literature reviews identify several key challenges, including data acquisition, modeling, simulation, integration, and validation. For example, data integration is critical for creating an accurate digital twin, and modeling techniques must be carefully selected to ensure the virtual system accurately represents the physical system. Additionally, there is a need for standardization, privacy concerns, and complexity in implementing digital twin technology in real-world scenarios, which require further research.

Despite these challenges, the potential benefits of digital twin technology are significant, and the literature suggests that addressing these challenges would facilitate the wider adoption of digital twin technology in various industries. Overall, digital twin technology holds great promise for improving efficiency, reducing costs, and enhancing system reliability and safety in many different fields.

Despite the numerous examples of papers discussing digital twins in various fields, it is worth noting that there is a notable absence of digital twin application cases or reviews in the specific domain of water resource management. This suggests a potential gap in the literature that could benefit from further exploration and research in the future.

Therefore, this paper provides an overview of realistic digital twins in the field of water resource management, their applications, as well as their potential future developments. The advantage of digital twins in large-scale water management lies in innovations in productivity and efficiency in the way we work. They can also reduce time and labor, and improve reliability in the decision-making process. In the field of water management of dams and rivers, the benefit of digitalization is the 'data-based smart water management.' The goal is to solve many tasks that have been routinely carried out in the past more intuitively, reliably, and quickly with the help of the digital world. The advantages of

digital twins and the direction we wish to pursue in smart water resource management can be summarized by the following five categories.

- Visualization: Visualize the three-dimensional representation of geospatial information and data analysis results for easy understanding.
- Intuition: Intuitively acquire information or knowledge with the help of digitization without a complex reasoning process.
- Data synchronization: Increase productivity by providing real-time synchronization of related data.
- Extract value and knowledge from information: Provide information with engineering value to users and contribute to rapid and reliable decision-making.
- Sustainable use and practice: A usability-based platform that practitioners can continuously and conveniently use in their actual work.

Based on this background, efforts to implement a digital twin platform have begun in the field of water management for better scientific flood control. Recently, the Ministry of Science and ICT and the National Intelligence Agency (NIA) in South Korea have launched the National Infrastructure Digitalization Project. As a part of this project, the K-water consortium developed a digital twin watershed platform for the Sumjin River basin [44,45]. The ‘National Infrastructure Digitalization Project’ is being carried out to strengthen national competitiveness and foster the Going Digital industry by leading its application to the nation’s major infrastructure.

2. Digital Twin Watershed Platform

We introduce a pilot project that builds a water management platform of dams and rivers as a digital twin. In other words, we realize data-based smart water management by replicating water management in the real world with the digital world. This digital twin platform can be an effective alternative to respond to recent climate change and unexpected flooding. The project is being built for the water system of the Sumjin dam and river basin in Korea, and is named ‘K-Twin SJ’ (Figure 1). The K-water consortium developed a digital twin platform and services for the first time in Korea for water management [46]. In this project, a digital-twin-based smart platform links dams with rivers for water management and flood analysis. The visualized 3D platform is built for the Sumjin River basin. The main contents are high-precision 3D geospatial informatization, water infrastructure 3D twin modeling, location-based POI (point of interest) visualization, dam/river real-time data visualization, an advanced drone monitoring system, AI (artificial intelligence) CCTV (closed-circuit television) image analysis, AI dam operation optimization, and levee safety analysis.

2.1. Platform Architecture

The digital twin platform for watershed water management is developed with a focus on intuitiveness and user satisfaction with sustainable services. Based on 3D geospatial information, a digital twin for the dam and river system is implemented. The platform combines real-time water management data with geospatial information. The platform integrates flood analysis and dam operation scenarios. It is designed to provide a variety of services by building a platform capable of visualization, data synchronization, monitoring, simulation, and prediction (Figure 2).

The platform integrates 2D/3D geospatial information of various shapes and structures to realize visualization with an appropriate LOD (level of detail). LOD is a standard that defines the precision of data modeled in 3D. Flood analysis model (K-Drum, K-River, K-Flood) prediction and dam/river operation information are converted into geospatial information, and visualization is performed on a 3D twin. The engine used for visualization is XDWorld, an open-source geospatial information engine. Water level changes due to floods and dam operations are also implemented.



Figure 1. Sumjin digital twin watershed platform, K-Twin SJ 2.0.

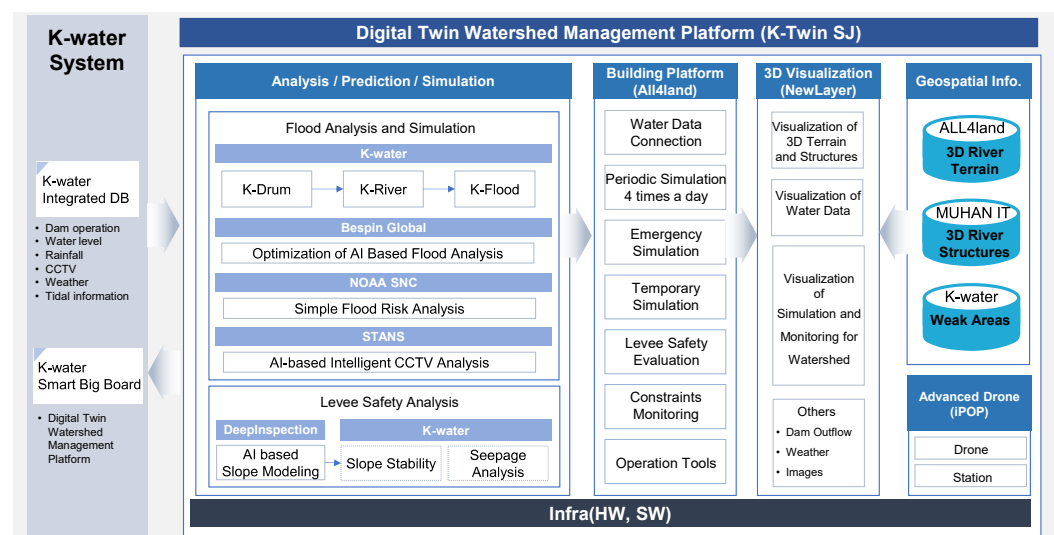


Figure 2. Architecture of the digital twin platform for Sumjin dam and river basin (K-Twin SJ).

The main contents of the project, K-Twin SJ, are summarized as follows [30,31,47].

- Construction of a digital-twin-based Sumjin dam and river water management platform.
- Creation of high-precision 3D geospatial information of the entire water system of the 173 km long dams and river basins.
- Three-dimensional object modeling for twins of dams and river infrastructure (bridges and weirs).
- Linking and monitoring of real-time water management data of dams and watersheds.
- Flood analysis model construction and simulation operation linking dams and rivers.
- Prediction of a river's water level based on an AI learning model and presenting an optimal dam discharge scenario.
- Loading a safety evaluation module for levees (for seepage and slope stability).
- Digital reality modeling and geometry creation for levees with no as-built drawings.
- Introduction of a high-performance drone system for monitoring dams and rivers.
- Developing AI CCTV video analysis.

The K-Twin SJ digital twin platform has been developed to support simultaneous access by 500 users. The platform comprises five distinct servers, namely the web server, web application server, database server, flood simulation server, and additional analysis server. The hardware specifications for each server are outlined in Table 1. It is worth noting that all server networks are equipped with dual ports and connected at a speed of 10 Gb/s.

Table 1. Hardware specification of digital twin platform, K-Twin SJ.

Server	OS	CPU	RAM	Storage (SSD)	Storage (HDD)	GPU
Web	Linux	2.1 GHz, 8 Core	64 GB	2 × 480 GB		
Web Application	Linux	2.1 GHz, 16 Core	128 GB	2 × 480 GB	2 × 2 TB	
Database	Linux	2.1 GHz, 16 Core	128 GB	2 × 480 GB	2 × 3.84 TB	
Flood Simulation	Windows	2 × 2.4 GHz, 12 Core	256 GB	2 × 480 GB	2 × 3.84 TB	
Other Analysis	Windows	2 × 2.4 GHz, 12 Core	256 GB	2 × 480 GB	2 × 3.84 TB	2 × RTX 6000

2.2. 3D Geospatial Reality Modeling

It is essential to visualize 3D geospatial information including topographic features and water infrastructure to build a digital twin platform for the entire Sumjin dam and river system. To visualize the real-world environment and assets in the digital world, it is necessary to acquire 3D geographic information and 3D models of structures. The Sumjin dam and river basin covers a vast area of about 4913 km² with a 173 km long river (Figure 3). The geospatial information data for the fundamental river basin were obtained from authoritative sources, specifically the certified digital elevation model (DEM) with a grid resolution of 5 m × 5 m and the orthoimage with a resolution of 25 cm. These data were acquired from the National Geographic Information Institute (NGII), South Korea, a government agency responsible for providing geospatial information. However, since more high-precision data were required for river topography information to respond to floods, a separate aerial survey was conducted. In this project, an aerial LiDAR (light detection and ranging) survey and drone photogrammetry were applied [48].

2.2.1. Aerial LiDAR Survey

Aerial LiDAR surveying was performed to build a digital elevation model (DEM) linking the dam and river into a digital twin 3D virtual environment (Figure 4). In general, information on the elevation of levees, the cross-sectional geometry of the river, and the topography of the river bank is very important for flood prediction. Therefore, high-precision reality modeling is required. In the Sumjin River basin, the orthographic image and DEM provided by the government were used fundamentally. However, the river area was surveyed with a LiDAR sensor mounted on a helicopter to obtain more precise topographic data. Compared to general aircraft, helicopters can fly at relatively low altitudes. Therefore, they are suitable for more precise terrain mapping. In addition, it is possible to acquire data very quickly compared to drones, which have many restrictions with respect to flight time and mission area. In this project, aerial LiDAR mapping was performed with a point density of 25 points/m² or more. The characteristics of the employed LiDAR sensor are shown in Table 2. LiDAR reality modeling was performed for the 173 km extent of the Sumjin River and major local rivers. The occlusion area was minimized with multidirectional aerial photographs. To construct 3D LiDAR data, a DSM (digital surface model) and a DEM (digital elevation model) for the topography and river facilities were extracted. A survey for ground control points was conducted to determine the exact coordinates and elevation of the whole geospatial distribution of the mapped river.

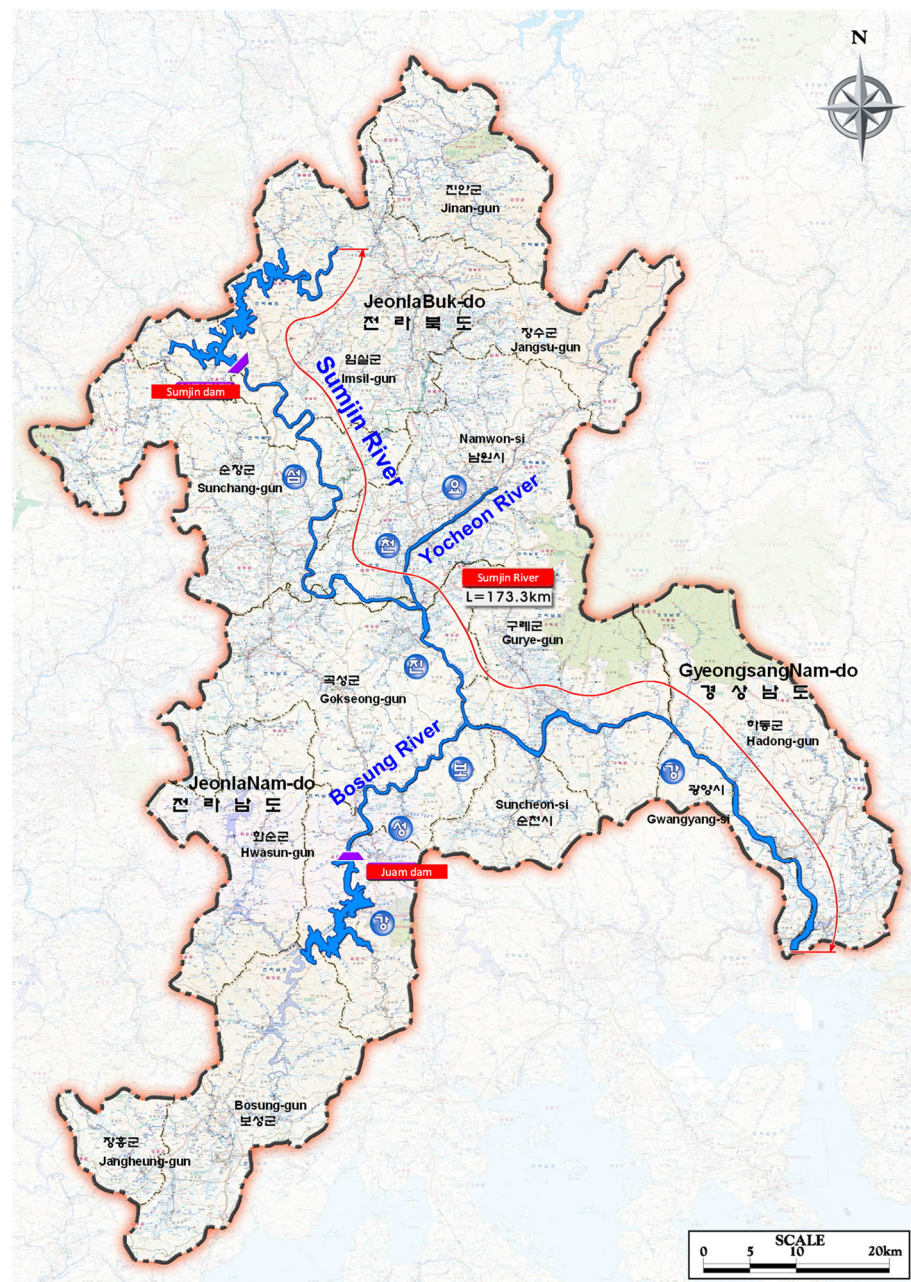


Figure 3. Geographic area of the digital twin watershed platform (K-Twin SJ).

Table 2. Specification of aerial LiDAR for river mapping.

LiDAR	RIEGL VUX-240	Field of View	75 Deg.
Max. measurement rate	1.5 million points/s	Max. data acquisition rate	1.8 MHz
Max. scan speed	400 lines/s	Accuracy ¹	20 mm
Max. operating flight altitude	1400 m	Precision ²	15 mm

Notes: ¹ Accuracy is the degree of conformity of a measured quantity to its actual value. ² Precision is the degree to which further measurements show the same result.

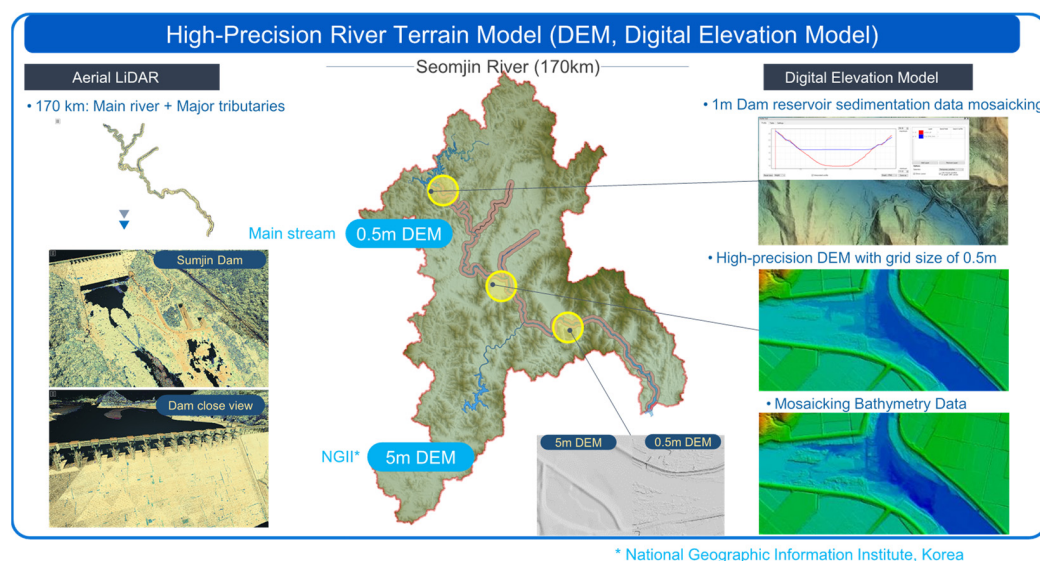


Figure 4. Generation of digital elevation model (DEM) for Sumjin dam and river watershed.

To generate the necessary 3D geospatial information for the digital twin of the Sumjin River basin, a 5 m grid DEM provided by the NGII was initially utilized. However, to improve accuracy and enhance understanding of river levees and enable hydraulic/hydrologic analysis, a higher-resolution 0.5 m grid DEM from an aerial LiDAR survey was merged with the existing dataset. Additionally, a 1 m DEM derived from a previous sedimentation survey was incorporated to capture the spatial characteristics of the river bed within the dam reservoir. These refinements improved the precision and quality of the 3D geospatial information, facilitating more effective analysis and decision-making within the digital twin system.

2.2.2. Water Infrastructure Drone Reality Modeling

Various facilities affect the flow of water in the Sumjin watershed. Typical examples are dams, river crossing bridges, and weirs. Photogrammetry-based reality modeling was performed for the Sumjin dam, bridges, and weir structures. Drone photogrammetry models were created for three dams, 85 major river bridges, and three weirs in the watershed. Afterward, separate data reduction and simplification sketches of 3D models were conducted to upload them on the digital twin platform.

Drone images were obtained with a GSD (ground sampling distance) of 2.0 cm. The work was completed during the dry season when the bridge facilities were exposed above the water as much as possible. Since the 3D models generated through drone photogrammetry are high-precision, large-capacity data, it is difficult to directly apply them to the digital twin platform. To visualize the digital twin platform covering the entire water system within a reasonable loading time, it is necessary to manually reduce the data capacity of the models. Therefore, the large-capacity 3D mesh models for the dams, bridges, and weir facilities were simplified through pattern-based sketching (Figure 5). Note should be taken that technical know-how was required in the process of acquiring raw data and reducing the density of the model for digital twin visualization.

In addition, drone 3D modeling of the levee was conducted in the vulnerable area where the river's main channel and its tributaries join. April Tag, which can automatically recognize patterns in post-processing software, was used for the ground control point.

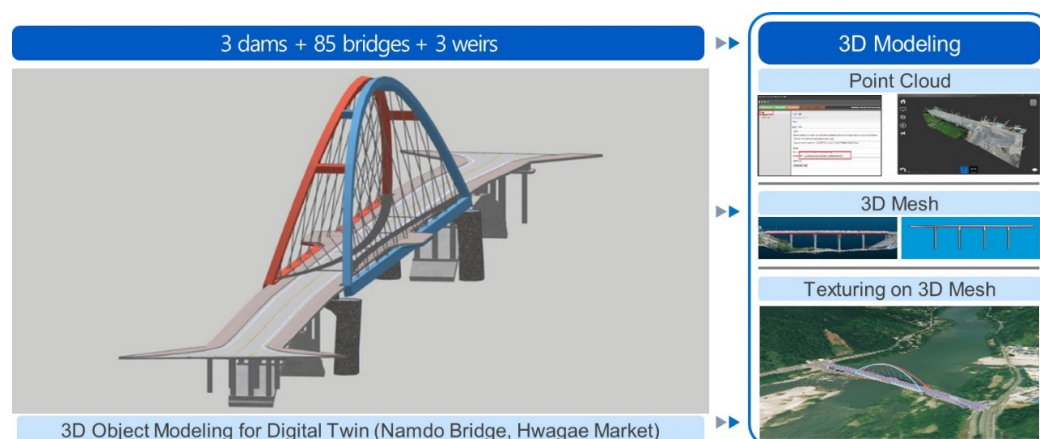


Figure 5. Drone-photogrammetry-based 3D object modeling for digital twinning.

From the results, it is confirmed that drone photogrammetry and helicopter LiDAR reality modeling for digital twin construction is very useful in terms of precision and accuracy. Precision refers to how precisely the constructed model represents the spatial arrangement of the information used in the model, i.e., the narrowness of the spacing between the spatial information used for model construction. To illustrate, we performed reality modeling using photos with a physical distance of 2 cm per pixel, which was the precision of drone mapping. Additionally, when generating DSM (digital surface model) and orthophotos from the reality-modeled 3D information, we achieved a resolution of approximately 1 cm/pixel or finer, which was due to the overlap (approximately 80%) of the captured photos during the construction of the reality model. Accuracy is a metric that indicates how accurately the constructed reality model represents the actual geographic coordinate space. In this study, we performed positional correction of all reality model results using RTK-GPS measurements. The horizontal precision of the RTK-GPS used was $8 \text{ mm} \pm 0.5 \text{ ppm}$, and the vertical precision was $15 \text{ mm} \pm 0.5 \text{ ppm}$. According to the error propagation principle, the precision of the RTK-GPS does not directly translate to accuracy. When inspecting each model using validation points set by RTK-GPS, a maximum horizontal error of 3 cm and a maximum vertical error of 5.3 cm were observed.

2.3. Data Connection

Hydraulic and hydrologic water management data are linked to the GIS-based 3D geospatial information (Figure 6). Water management data connected to the digital twin platform include dam operation, weather, river monitoring, and CCTV images. More specifically, real-time synchronized data include dam operation data (e.g., reservoir water level, inflow rate, discharge rate, water storage), river water level, rainfall, and CCTV video. These data are also used as input for the flood analysis model. River water levels and CCTV images are visualized based on location. They are also displayed on a smart big board.

More specifically, to broadcast synchronized real-time data, a digital twin platform server gathers data on dam operation, weather conditions, and river monitoring using existing separate platforms. The twin platform developed seamlessly connects with existing databases, allowing to integrate data at 10 min, 1 h, and 1-day intervals in real-time. Additionally, CCTV (closed-circuit television) footage is recorded in real-time through a separate platform using a DVR (digital video recorder), and video streaming services are made available through RTSP (real-time streaming protocol) and HLS (HTTP live streaming) protocols. The platform we developed retrieves the streaming CCTV footage from the analysis server, applies AI models for interpretation, and stores and delivers the results on the server. Two types of CCTV with different resolutions were accommodated. One was a video with a resolution of 800×600 pixels at 30 fps (frames per sec), and the other was a video with a resolution of 1920×1080 pixels at 30 fps.



Figure 6. Real-time river water level measured on the digital twin platform.

2.4. Dam and River Monitoring Drone System

A drone inspection system that can surpass the limits of existing manpower surveys is useful for on-site monitoring or constraint investigation of the dam and the river basin during flooding. However, drones that are able to fly even in rain and strong winds and that can withstand being submerged in water in case of an unwanted emergency landing are rare. In this project, an unmanned automated drone system was developed (Figure 7). We developed a drone with wind-resistant and waterproof performance that can fly in conditions of 10 mm of rainfall and 10 m/s of strong wind. In addition, by making a drone station to enable automatic vertical take-off and landing, a regular monitoring system for the watershed is implemented. There is an automatic charging function and a long-distance waypoint mission flight function using LTE (long-term evolution) communication. In addition to optical and thermal imaging cameras, it also has a speaker function to broadcast notifications when an event occurs.

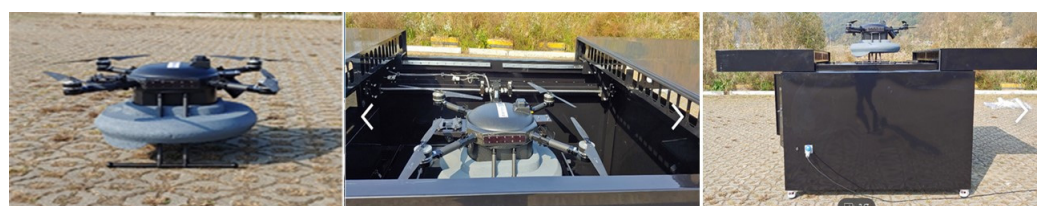


Figure 7. Development of drone and drone-station system for dam and river monitoring.

3. Simulation in a Cyber-Physical System

3.1. Flood Simulation

Flood simulation is a key feature of the digital twin watershed platform (K-Twin SJ). The platform is configured to perform a flood analysis by linking dams and rivers into one system. For the flood analysis, three types of software were installed: K-Drum for rainfall-runoff analysis, K-River for river flow analysis, and K-Flood for river overflow analysis (Figures 8 and 9). These flood simulations are designed to be performed based on sensing data such as the real-time water level and dam operating conditions combined with geospatial information. In addition to current conditions, it is possible to simulate the flood analysis according to forecast scenarios when weather information or dam operating conditions change.

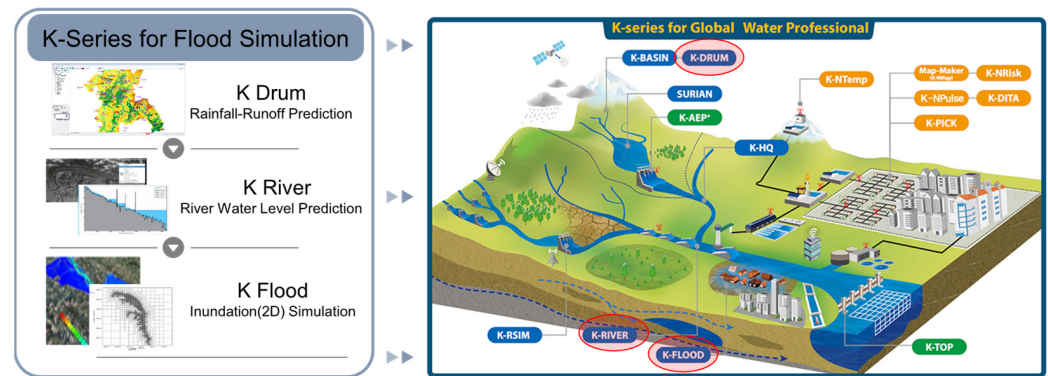


Figure 8. Three types of flood analyses and simulation models running on the digital twin platform.

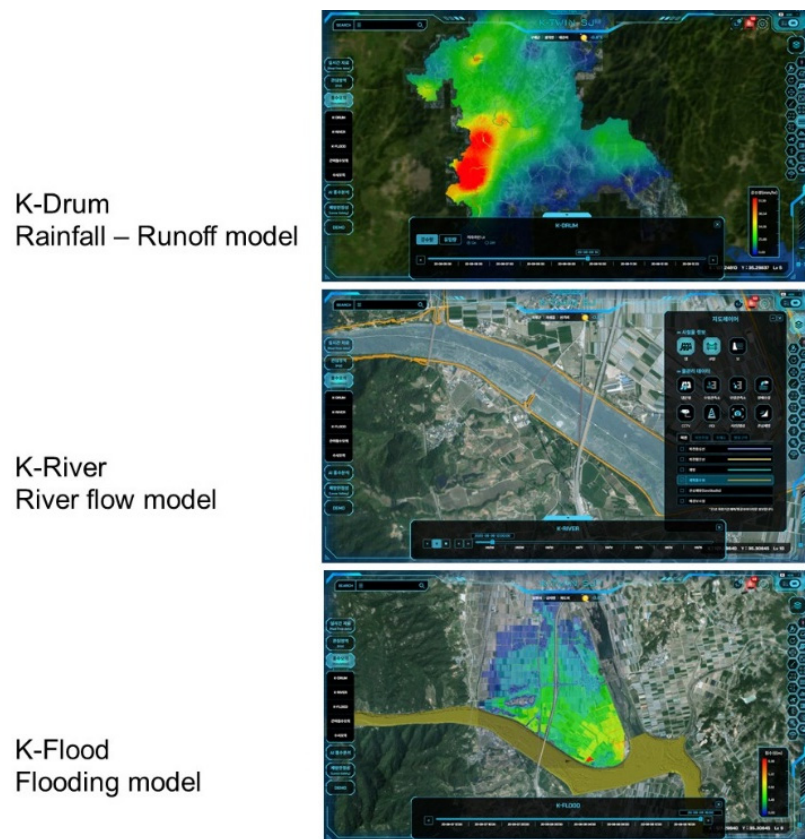


Figure 9. Visualization of three types of flood simulation.

In addition, the flood simulation module is equipped with a function to predict the river water level according to the dam operation scenario based on the AI learning model and to optimize the decision-making on the dam discharge rate through the spillway. For the AI flood analysis, a smart flood prediction scheme was developed by applying the BAS model (big data, AI, simulation). This model creates a hypothetical model using flood-prediction-related mathematical/hydrological knowledge and 3D geospatial information and increases the accuracy of flood prediction data through model learning linked with the collected data (Figure 10).

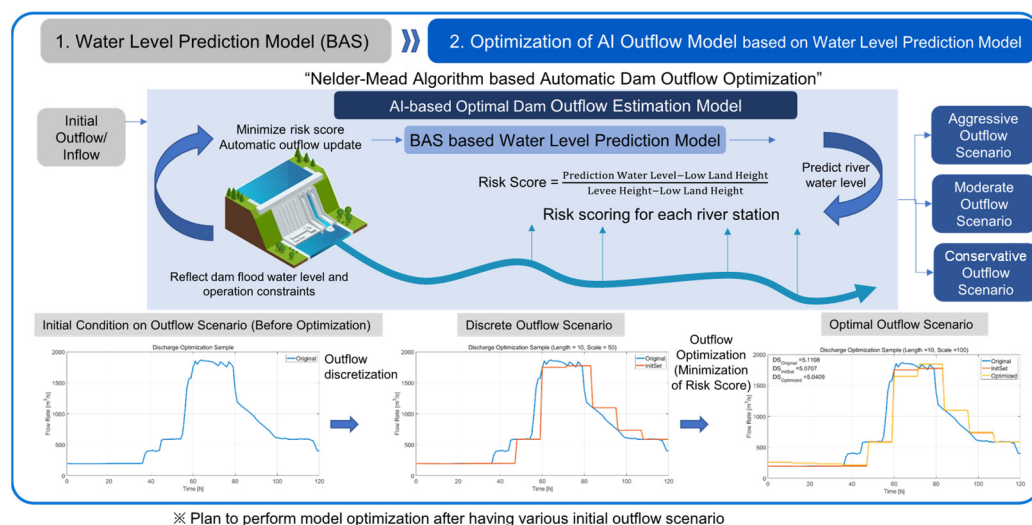
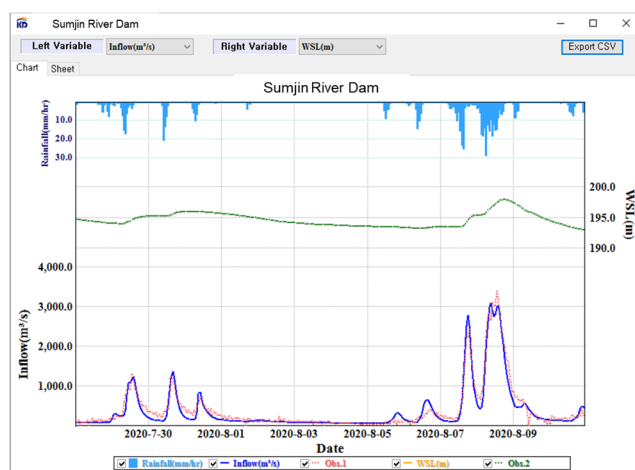


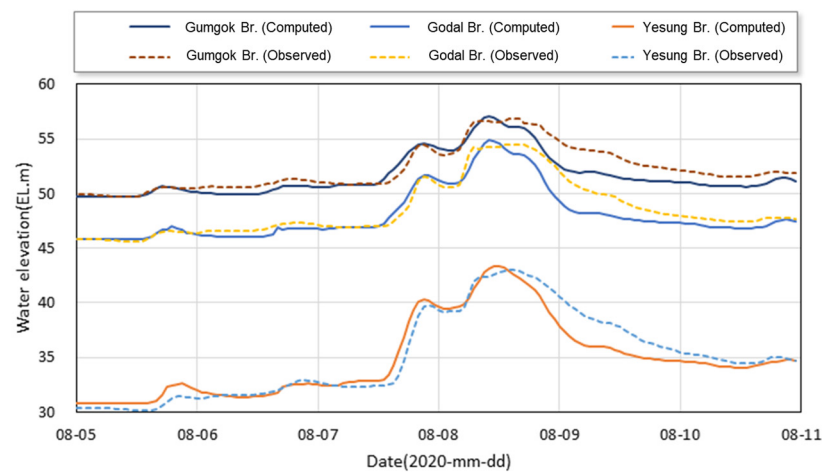
Figure 10. AI model to predict river water level and to generate optimized dam discharge scenarios during flood season.

To ensure the reliability of constructing the digital twin flood simulation model, validation was conducted using the flood record of the Sumjin River in August 2020 (Figure 11). The validation process involved comparing the data from the main observation points with the predicted results obtained from the digital twin. Specifically, the accuracy of the K-Drum rainfall-runoff model was evaluated by calculating the inflow of the Sumjin River dam, and its performance was assessed using Nash–Sutcliffe efficiency (NSE), which measures the model's ability to match the observed data. The NSE value for this model was found to be 0.95, indicating a high level of accuracy (Figure 11a). Additionally, the river level prediction using the K-River model exhibited behavior that closely resembled the observed water levels at three major points with water level observation stations during the flood event (Figure 11b). Furthermore, the K-Flood model, a two-dimensional flood inundation model, produced similar results to the actual extensive flooding that occurred in the Youcheon confluence area (Figure 11c). Overall, the flood simulation performance on the digital twin platform demonstrated good reliability for the August 2020 flood event.

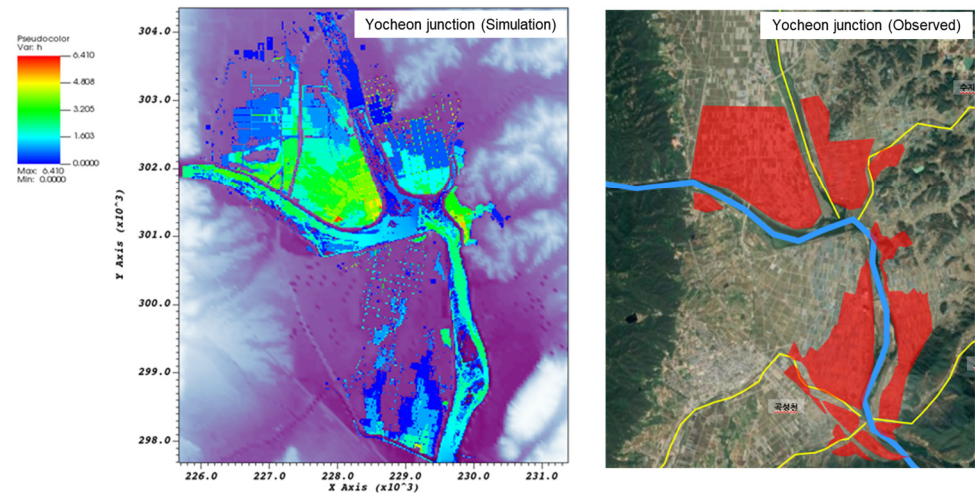


(a) Validation of K-Drum

Figure 11. Cont.



(b) Validation of K-River



(c) Validation of K-Flood

Figure 11. Validation of the flood simulation model on the digital twin platform.

3.2. Geotechnical Levee Safety Analyses

The digital twin platform is also equipped with a levee safety evaluation module. This is incorporated because flooding can result in piping or slope sliding of the levee.

The levee safety evaluation module in this project comprises two analysis modules. One is a seepage and slope stability analysis module implemented by GeoStudio. The other is a slope stability analysis module by FLAC with a user-defined interface solution. By selecting levees in the weak area, the first module manually performs a slope stability analysis and a seepage analysis reflecting water level conditions. Through the slope stability and seepage analyses, the possibility of slope sliding and internal erosion of the riverbank is evaluated (Figure 12). The user can then upload the result to the digital twin platform. The second module does not conduct a seepage analysis, but rather it computes the factor of safety for the slope stability semi-automatically. Once the levee to be evaluated is determined with the geometry, input water level, and material properties, a FLAC controller searches for a pending analysis and automatically creates command input files using the built-in FISH language so that recalling FLAC can run the analysis (Figure 13). The output results, such as the factor of safety, saturation, displacement vectors, seepage distribution, and effective stress contour, are stored in the database and displayed on the platform. The whole process can be automatically performed on the platform, or the user can apply different material properties and river water levels as inputs when another slope stability analysis is necessary for a parametric study.

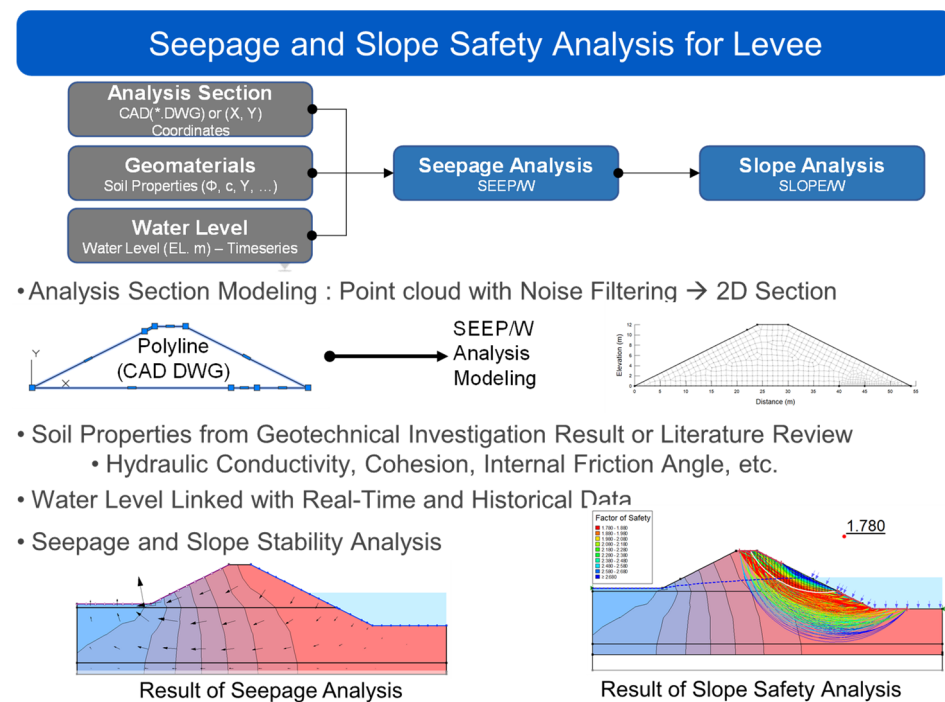


Figure 12. Levee safety evaluation by GeoStudio.

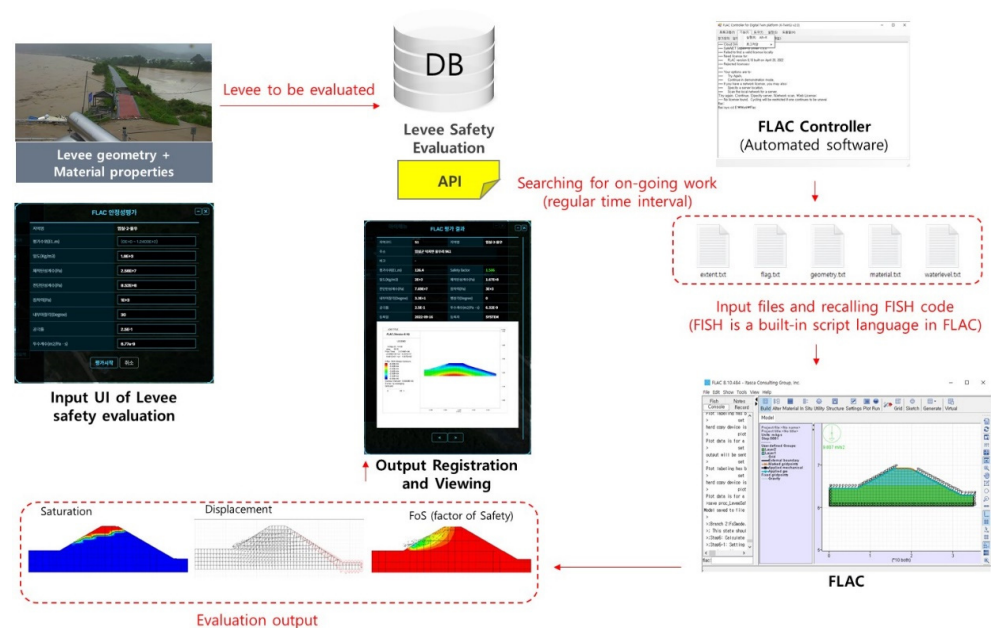


Figure 13. Slope stability analysis module to assess levee safety by FLAC with interface solution.

For this numerical analysis, drawing information on the levee is required. However, it is not easy to acquire drawing information in the actual conditions. Therefore, to support the generation of the analysis sections, we developed a vectorizing tool. After performing 3D modeling by drone photogrammetry, the model was converted into a 2D geometry section for analysis. In this process, a noise filtering technology was also developed to remove unwanted vegetation or noise on the slope. This slope pretreatment program was loaded into the digital twin platform as an independent module. AI learning is being carried out to improve the reliability of noise filtering by selecting 12 weak levees in the Sumjin River.

The validation of levee stability evaluation on the digital twin during flooding is a critical factor to consider. To assess the performance of the levee stability evaluation model integrated into the digital twin platform, we conducted validation for a specific levee section where slope sliding occurred in 2020. Figure 14 illustrates the occurrence of slope sliding on the levee during the August 2020 flood event. By utilizing the digital twin slope stability analysis, it was determined that the slope exhibited instability with a safety factor of 1.0, thereby confirming the occurrence of instability.

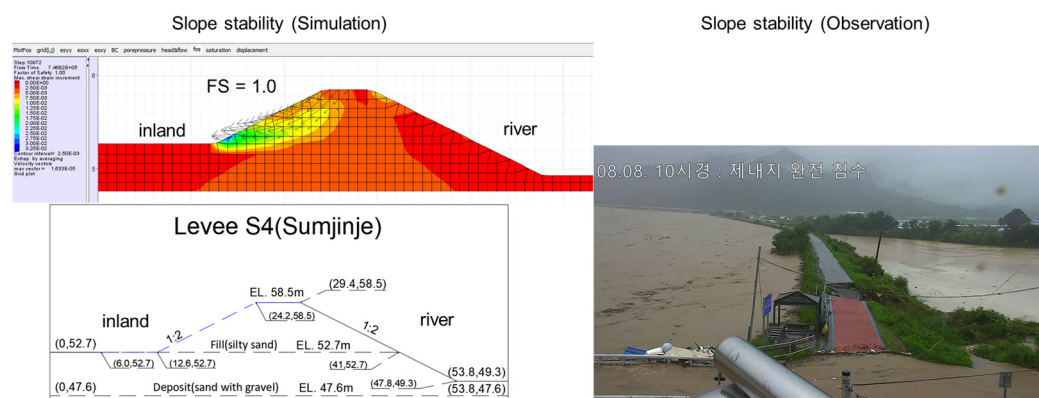


Figure 14. A validation of slope stability analysis module on digital twin platform.

3.3. AI Intelligent CCTV Analysis

The platform contains an AI CCTV analysis system (Figure 15). It creates deep learning-based CCTV image analysis data that can be utilized to recognize and judge abnormal situations. By linking this with the digital twin, we are building a real-time system that quickly recognizes abnormal situations, supports comprehensive judgment, and enables preemptive responses. As types of object recognition, people, vehicles, and watermarks were trained. Two primary techniques are employed in AI-based intelligent CCTV analysis for the recognition of individuals, vehicles, and watermarks. The YOLOv4 model is utilized for the recognition of people and vehicles, while the YOLACT model is employed for watermark recognition. YOLOv4 is selected for people and vehicles due to the significance of object localization and the requirement for individual identification. In contrast, YOLACT is chosen for watermarks to bypass the localization step and treat them as a unified entity. The intelligent CCTV module achieves an image processing speed exceeding 1 fps, with object detection accuracy and watermark detection accuracy both surpassing 90%. In the future, this system can be linked with the early warning system.

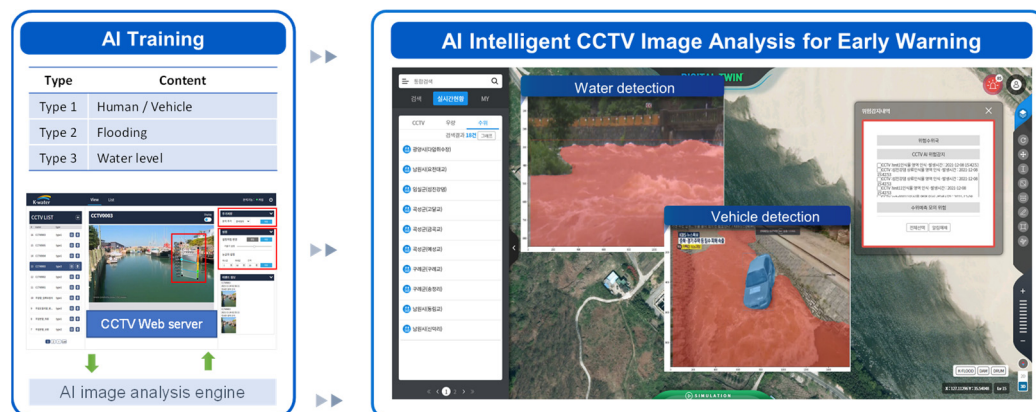


Figure 15. AI CCTV data analysis module.

4. Discussion

The K-Twin SJ, a digital twin dam and watershed management platform, was designed in May 2021 and realized in December 2022. User services began in April 2023 for internal customers at K-water (Korea Water Resources Corporation, Daedeok-gu, Daejeon, Republic of Korea). It is crucial to validate the platform's effectiveness as a decision-making tool in both normal water management and flood situations. Although it is a powerful digital platform for water resource operation and management, as well as water disaster reduction in case of flooding, it has only recently been launched, and sufficient validation will take time. This paper extensively discusses the individual and integrated solutions of the digital twin water management platform that connects dams and rivers as a single system. However, further research is required for future verification and validation. During the platform's development stage, limited models were verified. The flood model verification was based on the flood events that occurred on 7–8 August 2022 in the Sumjin River in Korea. This flood record was used to calibrate the rainfall-runoff model, river simulation model, and flooding model. The same flood-induced levee breach and piping/slope failure case histories were used for the calibration of geotechnical safety analyses of levees. Other modules implemented on the digital twin platform were also calibrated using the 2022 flood event. Despite these efforts, more data-driven validation and calibration are still necessary in the future. Quantitative and qualitative evaluations of the digital twin dam and watershed management need to be studied, focusing on enhancing productivity and efficiency in the decision-making process.

5. Conclusions

Water management combining dams and rivers is critical to efficiently accommodate better flood control decision-making. A 'digital twin' can be used to allow interaction between the physical and digital worlds of water management. It can also be a useful tool to improve the efficiency of the operation and maintenance of water infrastructure such as dams and rivers.

We introduce a digital twin water management platform, 'K-Twin SJ', for the entire 173 km long Sumjin River basin in South Korea. The project includes high-precision 3D geospatial informatization of the whole watershed, real-time water management data visualization, flood analysis simulation, AI dam operation optimization, AI slope geometry generation, levee safety evaluation, AI CCTV image analysis, simpler flooding potential prediction, and an advanced drone monitoring system. To create 3D geospatial information, high-resolution helicopter LiDAR mapping was conducted for the river. Reality modeling by drone photogrammetry and 3D data reduction was performed for three dams, 85 river bridges, and 3 weirs. Data from dam operation, weather forecasts, river water level stations, and CCTV were combined and visualized on the platform. An AI-driven intelligent CCTV image analysis was added to the platform for early warning. An automatic drone monitoring system was developed to supervise the dam reservoir and downstream river even amid rainfall and windy conditions. Seepage analysis and slope stability analysis for levees were integrated into the platform. To generate the as-built geometry of the levee, AI-based noise filtering and a vectorizing module were developed. Three types of dam and river simulations were implemented on the platform—a rainfall-runoff model, a hydraulic river flow prediction model, and a river flooding model. In addition, AI-driven smart flood prediction and an optimized dam discharge model were loaded to minimize flood damage to the downstream river and to secure dam safety.

Through the platform, data-based smart water management is implemented. By linking dams and rivers into one system, the digital twin platform will contribute to a multidisciplinary model that integrates various components to enhance the productivity of water management against flooding.

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