Digital Twin-Based Living Lab Model for Social Problem-Solving

Bridging Technology, Education, and Sustainability in the Asia-Pacific Region

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Abstract

As climate change triggers a surge in water-related disasters—ranging from severe flooding to water pollution—across the Asia-Pacific region, there is an urgent need for innovative research and development frameworks that transcend the limitations of conventional closed-laboratory research. This study proposes a digital-twin-based living lab model currently established by the Korea Institute of Civil Engineering and Building Technology (KICT) at the Andong River Experiment Center (REC) in the Republic of Korea. This model integrates a computing continuum architecture with zero-shot learning artificial intelligence to address tangible challenges, such as the detection of riverine floating debris and flood prediction. Furthermore, this study analyzes how these experiential education programs operated by the REC for students and citizens drive the popularization of science and technology, while contributing to the achievement of UN Sustainable Development Goals (SDGs) 4 and 13. Finally, we present a roadmap for technology transfer and cooperation to enhance the climate resilience of UN ESCAP member states.

Introduction

Water resource management in the 21st century has been confronted with an unprecedented landscape of uncertainty. Conventional frequency analyses, which are based on meteorological data accumulated over the past century, no longer serve as reliable indicators for predicting future rainfall patterns. The Asia-Pacific region is one of the areas globally most vulnerable to natural disasters. In this region, rapid urbanization combines with accelerating climate change, significantly amplifying the unpredictability of water management.

According to reports by the UN ESCAP (2023), water-related disasters such as floods, droughts, and typhoons are evolving beyond environmental shocks into complex social disasters that threaten regional economies and exacerbate poverty (Seddik and Sovacool, 2025). In particular, the discord between the intense, concentrated rainfall characteristics of the monsoon climate zone and aging water resource infrastructure makes disaster response increasingly challenging.

Decision-making based on rigorous scientific data and precise simulations is essential to establish effective climate adaptation policies. However, a significant number of developing member nations - Lao People's Democratic Republic (Lao PDR), Cambodia, Nepal, and Bangladesh - face profound difficulties in implementing preemptive disaster management because of the absence of high-cost experimental facilities, a shortage of specialized personnel, and issues regarding data reliability.

Against this backdrop, the Andong River Experiment Center (REC) of the Korea Institute of Civil Engineering and Building Technology (KICT) proposed an experimental solution that combines physical infrastructure with digital technology. The REC has evolved beyond a simple research facility into a Living Lab—an ecosystem in which various stakeholders participate in verifying technologies and solving social problems in an environment that closely mimics a natural river.

The objectives of this study are to introduce REC's Digital Twin-Based Living Lab model in detail and identify how this model simultaneously achieves technological innovation and social education. Specifically, this study focused on 1) computing continuum technology that bridges physical experiments and virtual models, 2) concrete case studies of river debris and flood management using artificial intelligence (AI), 3) the achievements of educational programs designed for the popularization of science, and 4) strategies for diffusing these technologies throughout the Asia-Pacific region.

Andong REC

Technologically supporting the sustainable use of natural resources requires verification at a scale identical to that of actual rivers, specifically through prototype empirical experiments. The REC of KICT is an empirical research facility specifically established to resolve such engineering challenges.

Located in Andong-si, Gyeongsangbuk-do, the Republic of Korea, the center is

Figure 1: View of the River Experiment Center (REC) (Source: River Experiment Center, KICT)

a hydraulic experimentation facility capable of reproducing the hydraulic and hydrological phenomena of actual rivers on a real scale. It was constructed on a site with a total area of 192,051 m² site. Although most hydraulic experiments rely on reduced-scale models—thereby necessitating the acceptance of errors such as the scale effect[1]—the REC has a large-capacity pumping station capable of supplying water at a maximum flow rate of 10 m³/s (10 tons per second) and three large-scale experimental channels. This infrastructure enables the replication of natural river flows without distortion. This implies the capability to artificially generate flood events, optimizing the facility for simulating extreme rainfall events that are becoming more frequent owing to climate change.

The success of large-scale experiments and the accuracy of digital twins depend entirely on the quality of the input data (Fuller et al., 2020). The REC is equipped with state-of-the-art instrumentation, including Acoustic Doppler Current Profilers (ADCP), underwater laser particle-size analyzers, 3D laser scanners, and ultra-precision Real Time Kinematic (RTK) GPS, to ensure this quality. These instruments measure variables, such as bed fluctuation, vegetation resistance, and flow velocity distribution, down to the millimeter scale. This provides the foundational data necessary to replicate reality within digital space, serving as a critical element in bridging the gap between physical reality and digital models.

Theoretical background and technical framework

In the water sector, a Living Lab refers to an open ecosystem in which technology suppliers (researchers) and demanders (citizens and the government) interact in a real-world environment to achieve innovation (Hossain et al., 2019). The REC functions not as a closed laboratory, but as an open outdoor testing ground. It serves as a platform that simulates various disaster scenarios and shares the results with the local community and educational sector, thereby enhancing the social acceptance of new technologies (Song and Sung, 2025).

The digital twin of the REC operates on a computing continuum architecture (Beckman et al., 2020), which integrates resources across three distinct layers to optimize performance and responsiveness.

- **Edge Layer (Field Site):** Internet of Things (IoT) sensors and intelligent closed-circuit televisions (CCTVs) installed throughout the river channels collect raw data. Lightweight AI models are deployed directly on these edge devices to perform initial analysis (for example, initial recognition of debris objects), enabling immediate data processing at the source.
- **Fog Layer (Local Center):** The data collected from the edge is transmitted to a local server. Here, data preprocessing and short-term predictive modeling are performed. This layer acts as an intermediary, reducing the latency and filtering data before reaching the central cloud.
- **Cloud/High-Performance Computing (HPC) Layer (Central Analysis):** Complex tasks such as computational fluid dynamics simulations and long-term climate change predictions are performed using HPC resources. The results of these intensive calculations are input back to the edge layer, thereby enabling

1 Scale effect denotes the deviation of experimental results in a reduced-scale model from those in the full-scale prototype, leading to potential distortions in the experimental results compared to real phenomena.

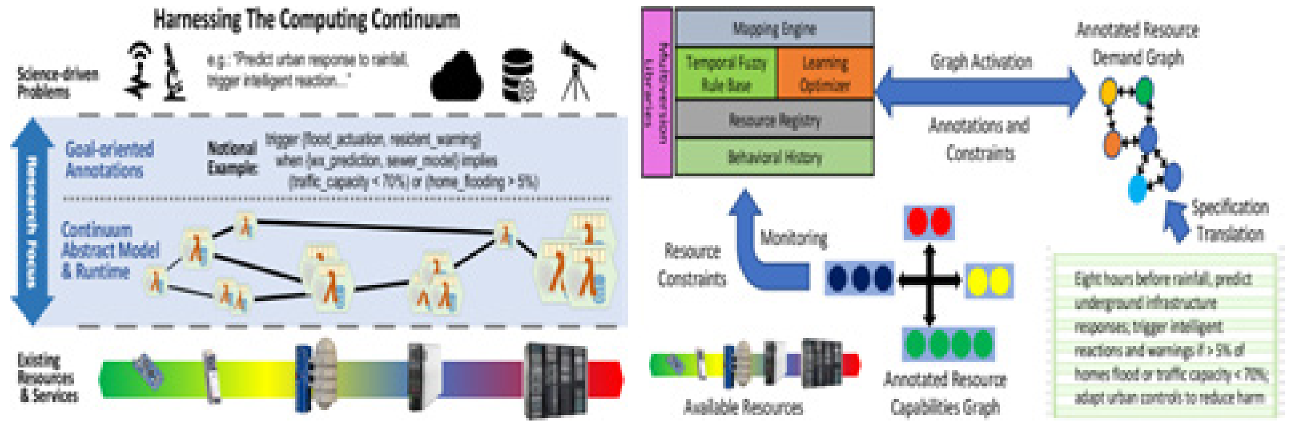

Figure 2: Computing continuum (Beckman et al., 2020)

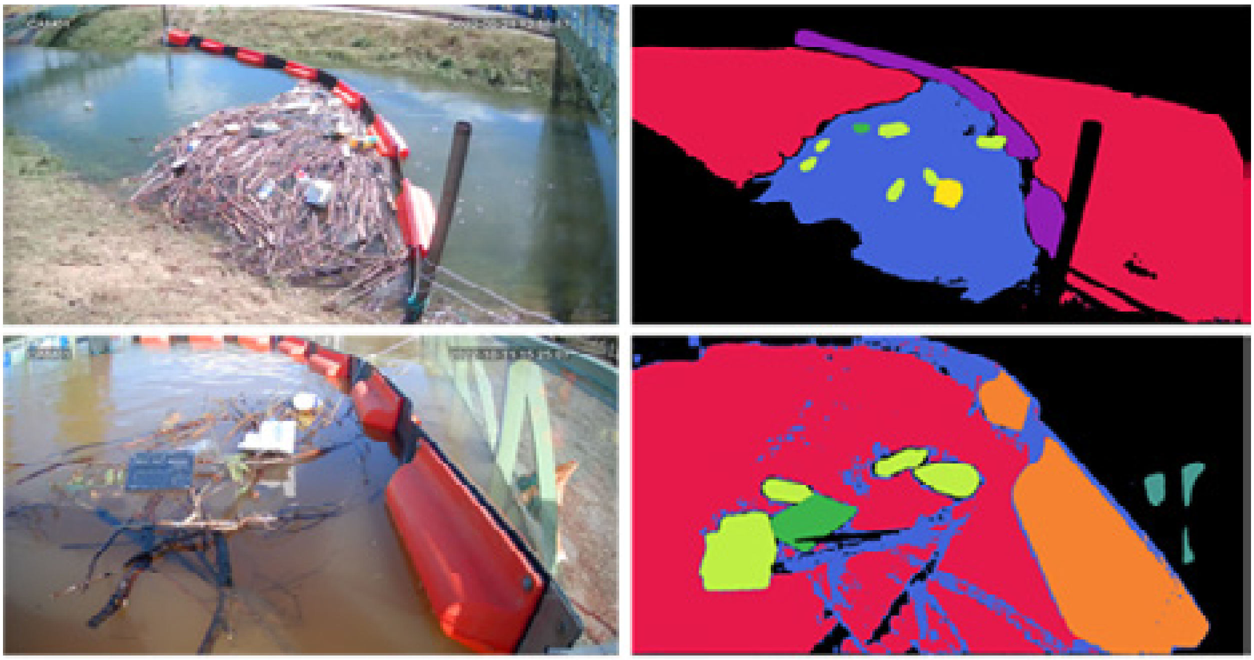

Figure 3: Waste detection using VLM (zero-shot learning) (Source: SimLab of Hanbat National University)

real-time response mechanisms (Buyya & Srirama, 2019).

A critical challenge in disaster management is that disaster data have a low frequency of occurrence, which makes it difficult to obtain sufficient training datasets for AI. To overcome this problem, the REC introduced zero-shot learning techniques. This approach combines large language models with vision models to identify new types of river debris or anomalies that the system has not previously learned using only text prompts for identification. This methodology significantly decreases the costs associated with data labeling, opening the possibility of low-cost AI solutions suitable for developing nations (Li et al., 2017).

The adoption of digital twin technology for water disaster management in the Asia-Pacific reveals a stark digital divide. While advanced economies such as Singapore and Japan leverage city-scale, real-time integrated platforms (Smart Nation and Digital Government Office (SNDGO), 2022; Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2022), developing member States are hindered by systemic infrastructure and capacity bottlenecks. Consequently, a distinct multi-tier structure has emerged wherein mid-tier nations employ partial solutions—such as early-stage digital twin applications in basin-scale flood modelling systems in Thailand (Hydro–Informatics Institute (HII), 2021)—while lower-tier nations continue to struggle with fundamental data fragmentation and sensor maintenance (World Meteorological Organization (WMO), 2021).

Crucially, the direct transfer of high-end digital twin models to developing economies has proven unsustainable, as the primary barrier is not hardware availability but operational continuity. High-fidelity models depend on continuous, high-precision data streams, yet resource-constrained environments frequently suffer from equipment malfunctions and data gaps (World Bank, 2020). Moreover, long-term projects often fail due to a shortage of the local technical expertise required for regular sensor calibration and system repair.

To successfully expand digital twin adoption, stakeholders must therefore shift from a strategy of "high-end replication" to "context-appropriate adaptation." This approach necessitates deploying low-cost sensor networks augmented by AI-based data enhancement to overcome hardware limitations, while simultaneously adopting modular architectures that allow for scalable growth rather than demanding immediate, full-system integration (Fuller et al., 2020). Finally, investment must be reoriented from capital-intensive facilities toward sustainable training programs focused on basic hydraulic measurement and model operation.

Considering these pronounced disparities in digital twin readiness, particularly the persistent challenges related to data continuity, sensor maintenance, and institutional capacity in lower-tier economies, the need for empirically grounded and operationally feasible implementation models becomes evident. Accordingly, the Andong River Experiment Center offers a rigorous case study through which the integration of large-scale physical hydraulic experiments with digital twin methodologies can be examined for their applicability to real-world water disaster management.

Case studies for social problem-solving

Case 1: AI-based automated detection system for floating river debris

Plastic waste in Asian rivers represents a severe problem; during floods, it obstructs bridges and drainage outlets, causes overflows, and eventually flows into the ocean, thereby destroying marine ecosystems. Traditional visual monitoring is limited in its ability to cover vast areas and is highly labor-intensive.

To address this issue, the REC research team, in collaboration with Hanbat National University, is developing an intelligent-monitoring system that integrates the YOLO v5 object detection algorithm with vision language models.

- **Experimental setup:** Various floating objects, such as plastic bottles, Styrofoam, and driftwood, were introduced into the experimental channels. Video footage was secured using CCTVs and drones. Data were collected for 3 years (2023-2025) under various environmental variables (daytime, nighttime, illuminance, light intensity, angle of light), including changes in lighting conditions and adverse weather scenarios, to ensure robustness of the system under varying conditions.
- **Real-time detection:** The developed AI model successfully detected and classified floating debris, with an average accuracy exceeding 90% (Source: SimLab of Hanbat National University).
- **Volume estimation and decision support:** Beyond simple detection, the system utilized pixel segmentation technology to calculate the volume of trash in real time. This capability enables local governments to implement data-driven administration, such as optimizing the dispatch schedules of collection trucks and prioritizing the management of locations with a high debris influx (van Lieshout et al., 2020).

Case 2: Flood simulation and vegetation management guidelines

Vegetation in natural rivers (trees and grasses) is ecologically vital; however, during floods, it acts as an obstacle to water flow, causing water levels to rise. Balancing vegetation conservation with flood safety (hydraulic control) is a persistent challenge in river management.

The REC conducted real-scale vegetation channel experiments for 5 years (2021-2025) in cooperation with the Aalto University in Finland and Deltares in the Netherlands.

- **Methodology:** Vegetation zones with varying densities and arrangements were created, and flood flows were discharged through the zones. Variations in the flow velocity and water levels were measured in 3D.
- **Application:** The data were used to calibrate the roughness coefficients of the numerical models. The accuracy of the floodwater level prediction models was significantly improved by precisely calculating the flow resistance caused by vegetation.
- **Outcome:** The experimental results, regarding the flow resistance of density variation, provide a scientific basis for establishing vegetation management guidelines that minimize flood risk while preserving ecosystems. By quantifying changes in the roughness coefficient based on vegetation, this work continues to be researched under the national research and development projects of the Korean Ministry of Environment (e.g. Nature-based Solution project) and is cited as a benchmark case for climate-adaptive river management in Korea.

Science popularization and educational impact

The living lab at the KICT REC functions as a comprehensive platform that integrates research and development with Education and Civic Engagement. This integration plays a pivotal role in the diffusion of the social value of technology.

The REC operates systematic educational programs targeting elementary, middle, high schools in the Gyeongsangbuk-do region, as well as university students from across the nation.

- **Experiential Learning:** Students step out of the classroom and into the real-scale river experiment site. They operate drones to scan the terrain and virtually experience the downstream impacts of dam construction simulated through digital twin. For instance, on November 19, 2025, the REC hosted 39 students from Andong Seohu, Namseon, and Gilju

Figure 4: Andong Integrated Education X AI Digital Collaboration Program (Source: River Experiment Center, KICT)

Figure 5: Demonstration of drone-based river monitoring systems at the REC Open Lab event (Source: River Experiment Center, KICT)

Figure 6: Simulation for workload planning integrated with AI (Source: SimLab of Hanbat National University)

Elementary Schools. These students participated in drone operation and digital twin simulations (Figure 4).

- **Connecting theory to reality:** These programs demonstrate how abstract scientific principles are applied to solve actual social problems (floods and droughts), thereby cultivating students' scientific interests and problem-solving capabilities.
- **Sustainable Development Goal (SDG) Contribution:** This contributes directly to UN SDG 4 (Quality Education). REC helps bridge the educational gap by providing opportunities to experience cutting-edge technology, particularly for students in regional cities.

The REC regularly hosts Open Lab events. Local residents are invited to observe demonstrations of flood prevention technologies and communicate directly with researchers, thereby increasing their understanding of water management policies. This represents the practice of Citizen Science, where citizens function not merely as beneficiaries, but also as active monitors and participants (Buytaert et al., 2014).

Regional strategy: Cooperation and diffusion in the Asia-Pacific region

The REC aims to share its established infrastructure and accumulated knowledge with UN ESCAP member countries to enhance the climate resilience of the entire region. However, this strategy focuses on technology transfer, recognizing that it is difficult for developing nations to immediately construct large-scale experimental facilities that require massive budgets. This approach involves packaging validated low-cost IoT sensor packages and open-source analysis software, coupled with joint research and workforce training to enhance social problem-solving capabilities.

Therefore, a three-phase cooperation roadmap is proposed.

- Phase 1: Standardization and baseline establishment

  Utilizing real-scale experimental facilities at the REC, we will verify and standardize the performance of AI flood prediction models and low-cost sensor networks specifically specialized for the Asian-Pacific monsoon climate including India, Bangladesh, Pakistan, Viet Nam, Thailand, Philippines, Indonesia, China, the Republic of Korea, and Japan. This establishes a reliable baseline for the technologies deployed across the region.

- Phase 2: Remote access and platform sharing

  We will open a cloud-based laboratory that will allow countries lacking physical experimental facilities to remotely access the digital twin system at the REC. Member nations can input their local river data and run simulations. This approach reduces cross-border travel costs and maximizes the efficiency of research collaboration.

- Phase 3: Education and operational model export

  Beyond simple technology transfer, we will provide structured operational know-how and educational curricula from the REC. By offering invitational training for policymakers and engineers and localized custom education, we will support capacity building to enable member countries to independently construct sustainable water management ecosystems (Antonesi et al., 2025).

Furthermore, the REC implements an empowerment program that fosters regional cooperation and shared growth by partnering with local government bodies, including municipal education offices. Under this initiative, the REC opens its research infrastructure to the regional community to co-organize hands-on learning activities and capacity-building workshops. This collaborative framework not only advances SDG 4 by broadening access to quality Science, Technology, Engineering, and Mathematics (STEM) education but also supports SDG 13 by equipping local stakeholders with the technical and institutional expertise to address climate-related water challenges. By synthesizing education, public-sector collaboration, and open infrastructure, the program offers a practical pathway for regions to enhance both climate resilience and long-term sustainable development.

Lessons learned and recommendations

Experience across the Asia-Pacific region indicates that the primary barrier to digital twin adoption is not technological capability, but operational sustainability.

- Data scarcity vs. Model precision: High-fidelity models frequently fail in developing member States because necessary field data—specifically regarding water levels, flow velocity, debris movement, and vegetation roughness—is either non-existent or fragmented (Hrachowitz et al., 2013).
- Infrastructure fragility: Projects relying on expensive, high-maintenance sensor networks are often discontinued within one to two years due to systemic constraints, including unstable power grids, hardware malfunctions in harsh environments, and a critical shortage of technical staff (Rogers & Tsirkunov, 2019).
- The "Over-Engineering" trap: attempting to deploy full-scale, high-end systems immediately often leads to resource exhaustion. Sustainable operations must take precedence over advanced technical features to ensure long-term viability.

To address these challenges, member States and technical partners should adopt a context-appropriate, phased deployment strategy.

- Adopt a "Remote Validation" model: Countries lacking domestic experimental facilities should utilize regional hubs, such as the Andong River Experiment Center, to generate high-quality calibration data. These large-scale physical experiments provide a reliable substitute for missing field data, reducing model uncertainty without requiring expensive local infrastructure.
- Shift to lightweight and hybrid technologies: Governments should move away from fragile, capital-intensive hardware toward robust solutions like CCTV-based monitoring combined with edge-AI modules. This approach offers high operational impact with minimal reliance on continuous internet connectivity or specialized maintenance.
- Structure systems with layered architecture: Digital twins should be distributed across layered resources utilizing edge devices for immediate processing, local servers for data aggregation, and reserving national/cloud HPC only for complex simulations. This prevents over-investment in high-end infrastructure.
- Implement phased and modular deployment: Avoid "all-or-nothing" implementation by beginning with specific, high-value modules (e.g., flood-level prediction or roughness calibration). This step-by-step scaling builds capability before expanding to fully integrated systems.
- Standardize through regional collaboration: Developed modules should be standardized and shared through APCTT and ESCAP networks. Collaborative development will reduce duplication and allow member States to adopt "plug-and-play" solutions tailored to common hydrological problems.
- Institutionalize through community engagement: Technology cannot survive in a vacuum. Establishing student programs and "Open Laboratories" fosters public understanding and institutional acceptance, increasing the likelihood that digital twins will be integrated into long-term disaster management protocols.

Conclusion

The most powerful weapon tool humans possess is scientific evidence of the colossal threat of climate change. We must move away from uncertainty-driven assumptions or overly conventional engineering designs and adopt an attitude that acknowledges the complexity of nature by measuring and analyzing it with precision.

The Andong River Experiment Center is at the forefront of this scientific inquiry. The water and plants flowing here are not merely the subjects of the experiment; they constitute a testing ground that reveals optimal solutions for the coexistence of humanity and nature.

Furthermore, the case of the Andong REC demonstrates how the convergence of digital twins and living labs can solve complex social problems during a climate crisis. Technical innovation based on the computing continuum has heightened the precision of disaster management, whereas education and civic participation through the Living Lab have proven the social value of science and technology.

An organic connection among Technology, People, and Cooperation is essential for a sustainable future in the Asia-Pacific region. The KICT REC is poised to become a pillar in building a network that makes Asia safe and resilient to floods and droughts by actively sharing its proven technology platforms and educational programs with ESCAP member nations. We propose that policymakers and research institutions participate in this cooperative model to implement cross-border climate action (SDG 13).

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