A Smart Near-Real-Time Urban Groundwater Digital Twin-Based Information System for Monitoring, Forecasting, and Pump Control

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Abstract

In response to climate variability challenges, urban planners and water authorities increasingly rely on near-real-time urban groundwater information systems that integrate sensor data, predictive modelling, and geospatial analytics. Within smart-city frameworks, Digital Twins (DTs) provide solutions for integrating these data streams into unified operational monitoring and decision-support environments. This study proposes a DT framework for dynamic groundwater table (GWT) monitoring and control during rainfall and drought fluctuations. The contribution consists of (1) a DT-based approach enabling near-real-time GWT monitoring and operational control, (2) an integrated architecture linking sensors, weather data, machine learning-based GWT prediction from rainfall data, 3D geospatial visualisation, and actuator control for water pumps, and (3) a municipal decision support prototype demonstrated in the city of Enschede. The DT visualises historical, current, and anticipated GWT conditions and enables threshold-based actuation (activating or deactivating real-world water pumps), supporting operational groundwater management. This proof-of-concept demonstrates the potential of video game engines and DT for groundwater monitoring and control, supporting prescriptive operational decisions by detecting when simulated groundwater reaches the ground surface and triggering pump activation or deactivation. The findings highlight the potential of integrating Digital Twins for urban space maintenance and for managing climate change-related challenges, such as drought and water ingress, through prompt actions based on GWT behaviour.

1. Introduction

Globally, groundwater resources are under increasing pressure due to climate change, population growth, and urbanisation. Many regions are experiencing groundwater depletion, pollution, or flooding due to extreme weather. Climate change is intensifying hydrological extremes: longer droughts and heavier rainfall events. Cities especially struggle to balance flood prevention and water availability, since infrastructure was not designed for such volatility. As a response, cities worldwide are reimagining public spaces by integrating water reservoirs, green infrastructure, and nature-based solutions to mitigate climate impacts and manage groundwater table (GWT) fluctuations (Normeninstituut Bomen, 2022). However, the GWT's dynamic nature presents challenges, including water shortages during droughts and water ingress during heavy rainfall, highlighting the need for innovative solutions for urban water management (Reitsma, 2022; Climate Adaptation Platform Netherlands, 2022).

In the Netherlands, long-term weather data (KNMI, 2025) indicate a clear increase in annual precipitation, with recent records set in 2023. At the same time, severe and prolonged dry periods have become more frequent, as observed in 1996, 2003, 2018, and 2025. These extremes put pressure on urban groundwater systems, making both flooding- and drought-related complications more likely.

Conventional GWT management strategies remain limited in their adaptability to rapid changes in weather conditions. Reliant on fixed pump capacities and static control rules, they often fall short in extreme conditions. These limitations can lead to vegetation root stress, structural damage to buildings, and prolonged waterlogging (Climate Adaptation Platform Netherlands, 2022). To address these challenges, cities require systems that support continuous monitoring and operational decision-making for GWT management.

Existing DT-related water studies focus mainly on surface water forecasting, controlled environments, or descriptive platforms (Edington et al., 2023; Rápalo et al., 2024; Zhu et al., 2025). Also, a recent state-of-the-art review on underground DTs by (Zhu et al., 2025) categorized DTs by their functionality, ranging from descriptive to prescriptive systems. However, limited attention has been given to research connecting real-time GWT data with DTs for GWT management. Smart municipal-scale systems that combine near-real-time groundwater sensing, short-term prediction, interactive 3D visualisation, and operational control logic for groundwater infrastructure remain underexplored.

The findings from the reviewed studies indicate that DT applications in the water domain are advancing, demonstrating strong capabilities in modelling and forecasting. However, these approaches remain limited in their ability to support integrated, real-time decision-making for urban groundwater management, particularly in linking sensing, prediction, visualisations, and control within a single operational framework.

Therefore, the aim of this research is to assess the feasibility of integrating real-time GWT sensor data with weather information, to enable predictive and adaptive system behaviour. More specifically, it implements a data-driven urban infrastructure service that connects sensing, prediction, visualisation, and operational response. By incorporating predictive models, anticipated GWT levels for future timeframes can be estimated, enabling proactive planning and pre-emptive control of groundwater systems, such as activating or deactivating water pumps based on expected conditions. Rather than treating groundwater measurements as isolated monitoring records, the framework transforms heterogeneous urban data streams into smart data: information that is structured, contextualized, and made actionable for municipal decision-making. In this sense, the contribution is not only a Digital Twin prototype, but also a smart urban water management information system.

The paper presenting these findings is structured as follows. Section 2 establishes the design methodology applied throughout the research and introduces the case study; Section 3 shows the requirements that guided the design of the DT solution. Subsequently, Section 4 presents the solution's development, followed by its implementation in Section 5, which includes data integration, visualisation, and interaction processes. The DT is then evaluated in Section 6 through practical applications and expert validation, which provide feedback to iteratively refine the solution. Finally, the research discusses the limitations of the current implementation and highlights future research directions, including opportunities to extend DT capabilities through further improved predictive models, enhanced interoperability with local water authorities' systems, and expanded decision-making tools.

2. Methodology

The study follows a Design Science Research (DSR) approach to design, implement, demonstrate, and evaluate a prototype DT framework for near-real-time GWT monitoring and control. The methodological objective was to assess the feasibility of integrating heterogeneous data sources, interactive visualisation, short-term prediction, and actuator control within a single urban decision support system.

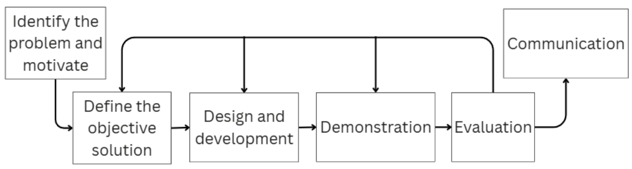

Figure 1. Design Science Research methodology by (Peffers, 2007).

The methodology consists of six iterative steps. First, the problem context was defined in collaboration with a local water authority, focusing on the limitations of static groundwater management practices under increasingly variable rainfall and drought conditions. Second, stakeholder requirements were identified and translated into technical and organisational design criteria. Third, a conceptual framework for the DT was developed to connect sensing, visualisation, prediction, and actuation. Fourth, a prototype was implemented by integrating groundwater measurements, rainfall data, a 3D geospatial environment, a basic predictive model, and IoT-based control logic. Fifth, the prototype was demonstrated in Enschede. Finally, the system was evaluated through technical verification and expert feedback to assess its feasibility, usefulness, and limitations as a decision-support tool.

Within this iterative process, stakeholders' feedback informed successive refinements of the prototype. The resulting evaluation should therefore be understood as a feasibility assessment of an integrated workflow, rather than as a comparative benchmark of prediction accuracy, interface usability, or control performance. This methodological positioning is important because the paper's main contribution lies in demonstrating how multiple components can be combined into a coherent smart-city information system for groundwater management.

The research is carried out in the city of Enschede, located in the east of the Netherlands, with a population of over 161,000 inhabitants (Visit Enschede, n.d.). Enschede was selected because its geomorphology makes groundwater management challenging. A thin, permeable top layer overlies a thick, poorly permeable clay layer that hinders natural drainage, particularly in areas where the terrain slopes away from the Glanerbeek River. Consequently, water accumulates in the lower-lying parts of the city, causing localised flooding and retention problems.

These geomorphological constraints, coupled with increasingly extreme rainfall and drought cycles in Enschede, create a dynamic hydrological environment that cannot be effectively managed with static or manual control procedures. This underscores the need for a predictive, data-driven decision-support system that can anticipate GWT fluctuations and adjust drainage infrastructure in response to evolving conditions, thereby supporting proactive planning and reducing the operational burden on water managers.

3. Requirements and objectives for a decision support DT for GWT management

Stakeholder requirements for the proposed Digital Twin system were identified through a series of interviews and inspiration sessions involving multidisciplinary participants, including representatives of the local water authority. This stakeholder analysis (see Annex A) provided the basis for a Hierarchical Requirements Decomposition, adapted from DiFranco (1977) and Bonnema (2016), which was used to structure the system's technical, organisational, and operational requirements. The analysis highlighted the need for near-real-time data integration, interface usability, scalability, compatibility with existing software environments, and a feasible implementation using available resources, particularly existing sensor datasets. It was the basis for shaping the design and use of the DT (see Annex B), helping to structure requirements and to provide constraints and interactions with details across various system levels. Next, the hierarchical requirements decomposition analysis helped clarify the technical and organisational requirements, such as real-time data integration, interface usability, scalability, and compatibility with existing software environments within the local water authority. Based on this analysis, the primary objective of the research was to develop a practical tool to monitor, visualise, and interact with the groundwater table in an urban environment. In the prototype presented in this paper, the system's decision-support function is limited to operational, threshold-based actions: monitoring groundwater conditions, anticipating short-term deviations based on rainfall inputs, and supporting pump activation or deactivation decisions when predefined groundwater ranges are exceeded.

The literature indicates that no comprehensive out-of-the-box software solution currently offers seamless integration with real-time data. Although some intermediary solutions attempt to bridge this gap, it is still necessary to customise and establish connections between real-time data and the model to meet each project's requirements, available data sources, and formats. Thus, essential components must be identified and interconnected to enable real-time data integration. Firstly, the collection and preparation of data are crucial, typically achieved through sensors that provide frequent updates on the relevant measurements. Secondly, a model capable of presenting the collected data interactively. And finally, the model's values must be refreshed within a time frame compatible with the data generation frequency, ensuring a synchronised and dynamic representation. Given this context, game engines stood out as suitable platforms due to their real-time data consumption capabilities, object-based triggering and compatibility with IoT protocols, as their capabilities aligned with these main requirements (Clausen et al., 2022; Gao et al., 2023; Gregory & Lemarchand, 2015; Horton et al., 2019; Kite-Powell, 2022).

4. Framework design: A decision support DT for GWT management

The resulting system integrates four main functions: (1) near-real-data retrieval, involving the automated collection and preparation of GWT measurements and rainfall data from their respective sources; (2) dynamic and interactive geospatial visualisation achieved through a triangulated groundwater surface generated from sensor observations; (3) basic GWT prediction, where a model estimates future groundwater levels based on rainfall input; and (4) IoT actuator control, enabling decision support for activating or deactivating pumps when the GWT exceeds predefined thresholds. The implementation of these sections is further described in Sections 5.1-5.4. Groundwater measurements from Twents Waternet and rainfall data from KNMI are automatically collected and pre-processed through a code-based workflow. These data are then used to update the Digital Twin, which represents both the urban context and changing groundwater conditions within a 3D spatial model. When groundwater values move outside predefined operational ranges, the system can support decisions to activate or deactivate pumps. In addition, rainfall-informed forecasting can be used to anticipate short-term changes in groundwater, thereby supporting more proactive management.

To achieve this proactive management, near-real-time data is collected through a network of sensors distributed across the city to measure the GWT depth. This data continuously updates the Digital Twin, which represents the city and the GWT levels within a 3D spatial model. Simulations are then executed within the game engine side of the DT, whose real-time interactive capabilities help identify whether the conditions are met to control the IoT actuators (water pumps) that regulate GWT levels in the real world. If the GWT exceeds established ranges, pumps across the city can be activated to lower it. Conversely, if the GWT level is too low, the pumps can be deactivated to allow for natural recharge. Therefore, these actions generate changes in the real world that are subsequently remeasured to feed back into the iterative operation of the DT (see Figure 2).

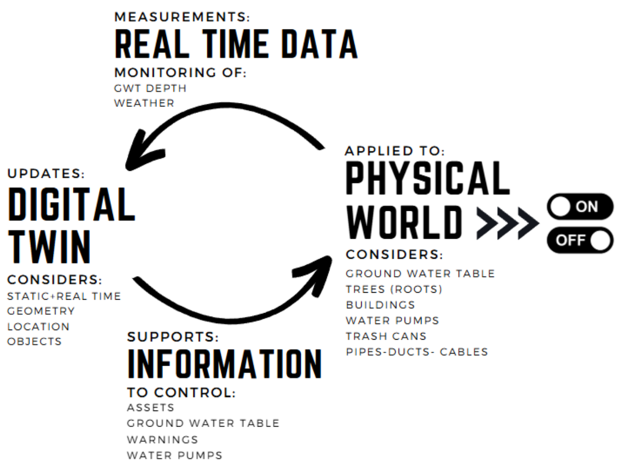

Figure 2. Closed-loop Digital Twin architecture.

Additionally, an optional analysis that incorporates weather data, such as rainfall forecasts, into a predictive model can be used to estimate GWT levels for future time windows, enabling proactive planning and allowing users to develop pre-emptive solutions rather than reactive responses.

4.1 Near-real-time data retrieval

The framework required an automated acquisition layer that periodically retrieved groundwater and rainfall observations and synchronized them before updating the DT. Based on expert knowledge, groundwater changes occur slowly; therefore, a measurement frequency of 1 per second would be excessive, whereas 1 per hour is sufficient to capture and visualise changes in the GWT. For this reason, the system is more accurately described as near-real-time rather than strictly real-time.

4.2 Dynamic and interactive geospatial visualisation

The interactive modelling environment was implemented using a video game engine because such platforms combine real-time rendering, scripting flexibility, and support for external communication. Within the proposed framework, the game engine serves as the host environment for interactive visualisation, and execution of control logic, while external services provide data retrieval and IoT communication where necessary. The choice of this environment was guided by practical requirements rather than by the platform itself being the central focus of the research contribution.

Moreover, a Delaunay-triangulated mesh was selected as the representation of the GWT because it allowed efficient on-the-fly updates while preserving the spatial relationships between sensor locations. In the adopted method, each sensor acts as a node in a three-dimensional mesh, with its groundwater value represented along the vertical axis. The triangulated surface thereby provides a continuously updated visual approximation of groundwater conditions across the study area.

4.3 Basic GWT prediction

A very basic Machine Learning (ML) approach was employed through a Decision Tree Regressor model to predict GWT dynamics. The rationale behind the choice comes from the need for a solution that can efficiently handle the substantial dataset generated by numerous sensors while providing quick insights into GWT changes. Additionally, the amount of groundwater drained daily from the city, whether by natural processes or human intervention, was not publicly known and is typically required for physical models. Therefore, the use of ML introduces a way to approach GWT prediction with fewer parameters than traditional methods.

The integration of this model into the video game engine and data collection would enable the generation of forecasts of GWT changes. Importantly, the predictive model was designed in a modular manner, allowing users to choose and substitute it as needed. Therefore, if another predictive model yields better results than the selected model for this study area, it can be easily replaced with the most favourable one. While the primary focus wasn't on developing the predictive model itself, a machine learning algorithm was implemented to demonstrate proof of concept. The DT visualised both current and anticipated changes in the water table, aiding the identification of areas where pumping may be necessary.

4.4 IoT actuator control

To achieve IoT-enabled water pump control for real-world interactions, seamless integration of three main elements was necessary: actuators, data, and a visualisation/control interface (Gao et al., 2023). Therefore, a triggering event must first be identified and captured, after which an appropriate response action is determined and communicated to the actuator, enabling

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it to activate or deactivate in accordance with the defined control logic.

For demonstration purposes, the implemented threshold corresponded to groundwater reaching the terrain surface, representing an intuitive flooding condition. However, in operational deployments, thresholds would be set by water experts based on their local groundwater management policies and infrastructure constraints.

Different actions were identified for high- and low-GWT scenarios, including adjusting theoretical water-extraction rates and implementing flood-prevention measures. In the Digital Twin, a script was generated to capture the triggering event and dynamically respond with actions based on GWT depth. The game engine's collision detection and triggering capabilities facilitated the development of a method to transmit commands over the internet to an external IoT handler website.

For the implementation case, a small-scale actuator was selected as a proof of concept. The IoT protocol control had to be managed through the game engine, along with a webhook service. This setup was configured to use signals generated by the video game engine to control a smart actuator. Although the implemented actuator is small-scale, the experiment demonstrates the feasibility of coupling environmental monitoring and predictive interpretation with physical responses. Future operational deployment would require more robust control logic, secure communication protocols, device authentication, and institutional governance mechanisms for safe infrastructure operation.

5. Use case and implementation

The Enschede case study demonstrated the feasibility of the proposed DT framework in a municipal groundwater management setting. This section presents how the framework was deployed using available local datasets and infrastructure. The implementation follows the workflow described in the previous sections, near-real-data retrieval, dynamic and interactive geospatial visualisation, a basic GWT prediction and IoT actuator control within a unified DT environment; verifying that all components of the DT interacted properly.

Applying the generated conceptual framework to the case of the city of Enschede provided insights into the strengths and limitations of the developed DT and highlighted areas of improvement. These insights play a crucial role in refining and adjusting the DT and in identifying additional features to consider to enhance the DT's applicability in future iterations.

The prototype was implemented using Unity and C#. Python scripts automated the data acquisition and preprocessing stages. QGIS was used for geospatial preprocessing including Delaunay triangulation and terrain preparation. Additionally, IoT communication between the Digital Twin and the physical pump prototype was established using webhook-based communication through an online automation service.

Moreover, the implementation results served as a basis for discussing the extent to which the resulting system functions as a practical monitoring and decision-support environment, through a feasibility assessment of the integrated workflow rather than as a full benchmark of prediction accuracy or interface performance.

5.1 Implementation of near-real-time data retrieval

The data used for the Digital Twin development was sourced from various providers, including Twents Waternet, the Dutch website for precipitation monitoring Buienradar, the Royal Netherlands Meteorological Institute (KNMI), the Netherlands Cadastre, additional open/private data sources, and historic GWT data. These datasets provided groundwater measurements, rainfall observations and forecasts, terrain information, sensor locations, and contextual geospatial data required by the DT (Table 1). The IoT-based control of the water pump involved integrating real-world equipment data into the Digital Twin prototype.

Source	Data type	Temporal resolution	Spatial role	Function in the DT
OpenStreetMap	Building footprints / base map data	Static	Urban spatial context	3D visualization and spatial reference for the DT environment
Cadastre / sensor registry (sensor locations)	Sensor coordinates	Static	Infrastructure location	Defines monitoring network and spatial positioning of groundwater sensors
Twents Waternet	Groundwater level measurements	Hourly (delayed)	Point-based environmental monitoring	State monitoring of groundwater table (GWT) conditions
KNMI / Buienradar	Rainfall observations and forecasts	Hourly / forecast	Regional meteorological input	Short-term anticipation and input for groundwater prediction model
IoT pump system	Pump status / control signals	Real-time	Infrastructure actuation	Actuation layer controlling groundwater pumping

Table 1. Data sources, their roles and characteristics

A flexible data retrieval workflow was developed to locate, download, organise, and store the most recent groundwater data available from the Twents Waternet portal. These files contain groundwater-table measurements collected by distributed sensors in the study area and provide the basis for state updating within the Digital Twin. A key design feature of the workflow is that refresh intervals can be configured according to operational needs and source availability. In principle, retrieval can be scheduled at intervals ranging from seconds to hours; in practice, however, the effective refresh rate is constrained by the update frequency and validation procedures of the source data.
In addition to groundwater observations, rainfall data were incorporated to support short-term forecasting and anticipatory decision-making. The integration workflow synchronised these heterogeneous datasets, translated them into a format suitable for the 3D model environment, and refreshing the displayed state at intervals compatible with data availability.

The study area contains 277 groundwater sensors distributed across the City of Enschede, each associated with a unique identifier and a corresponding location. These identifiers serve as references to specific monitoring neighbourhoods, enabling precise identification and categorisation of these locations for data collection and analysis. Therefore, the sensor dataset can be combined with weather data from the same geographic locations to build a comprehensive Digital Twin model for predicting and visualising groundwater behaviour. The location of the sensors in the study area is visualised in Figure 3.

5.2 A dynamic 3D mesh for GWT visualisation using Delaunay triangulation for efficient real-time updates

Implementing a Digital Twin requires coordination to function as a coherent system. This coordination was achieved through the game engine, which served as a central hub within the interactive environment, managing data retrieval, temporal synchronisation,

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state updates, visualisation refreshes, prediction execution, and the transmission of actuator-control messages. In this way, the game engine hosted the main interaction environment, while external services were incorporated as needed for automation and communication. The implementation illustrates that a functional Digital Twin for urban groundwater management does not emerge from visualisation alone, but from the coordinated integration of sensing, data transformation, predictive interpretation, and response logic. At the same time, the prototype required substantial custom scripting and configuration to enable interoperability between components. This highlights both the flexibility of the approach and the current absence of fully integrated off-the-shelf solutions for this type of municipal groundwater application.

The Delaunay Triangulation was implemented using the sensors' X and Z positions in the study area, as these remain constant over time. Therefore, to determine how to draw each triangle forming a GWT mesh in the game engine, the Delaunay Triangulation tool in a GIS software was employed (see Figure 4). Each point ID was grouped with two others to form a triangle, and the GWT's depth value served as the Y-axis value during the triangle generation process in 3D.

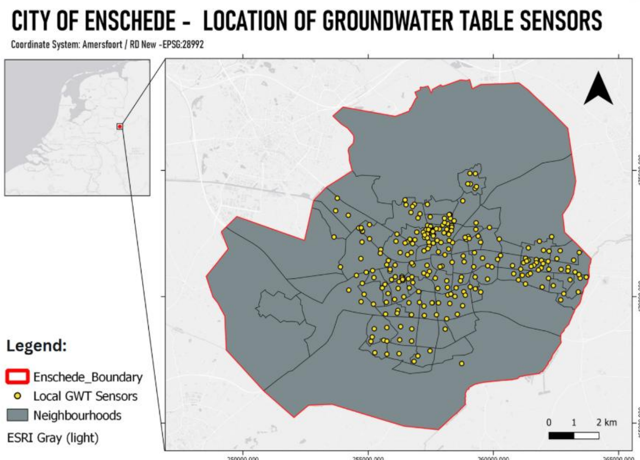

Figure 3. Study area and sensor locations across the city of Enschede, the Netherlands.

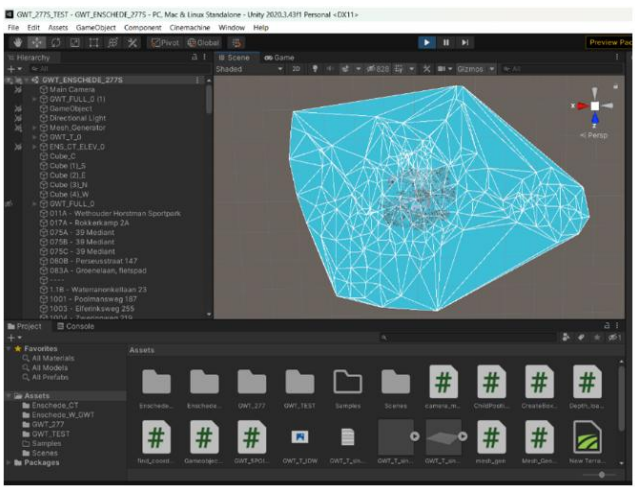

Figure 4. Translated the location of sensors to the video game engine environment.

The location of the sensors was important when generating the dynamic GWT within the game engine. As these points had to match the locations of the study area's surroundings, procedural modelling was used to convert the shapefile points into 3D coordinates compatible with the game engines, preserving their positions in the real world.

The models were generated in a georeferenced environment first and later exported with a local reference within the model, helping them retain their scale and position (Figure 4). As both the buildings and the sensors were created using the same reference system in the procedural modelling software, it was easier to align them when they were ported to the game engine (see Figure 5).

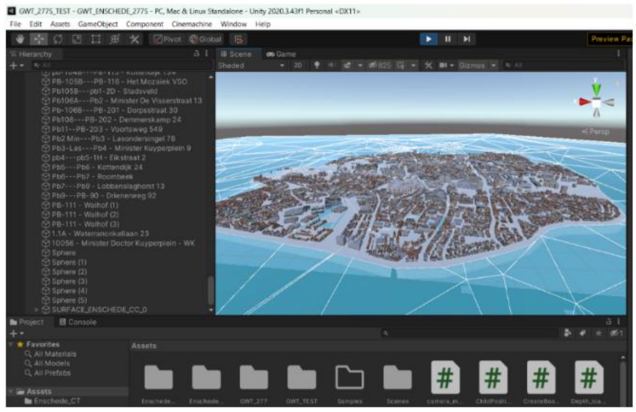

Figure 5. A combination of a city model and the 3D Delaunay Triangulation of the GWT.

5.3 A basic regression-based predictive model (Decision Tree Regressor) to test modular forecasting capabilities

After the data were prepared to train the machine learning model, a basic groundwater-level prediction using a Decision Tree Regressor was performed. This prediction was based on hourly rainfall data (Rainfall Hourly - RH) obtained from the KNMI API, which generated the predicted GWT level per sensor to update the groundwater height of the 3D mesh in the game engine, enabling the simulation of a basic dynamic future scenario for triggering detection and actuation.

5.4 IoT actuation using smart switches to activate and deactivate small water pumps, establishing communication between the DT and real-world devices through a webhook interface

The terrain surface played a crucial role in the Digital Twin, enabling real-time tracking of interactions between the GWT mesh and the surface, with hitboxes triggering actions. To obtain this terrain representation, a Digital Terrain Model (DTM) *.TIF file obtained from AHN4 with a spatial resolution of 0.5m matching the project's coordinate reference system RD New (EPSG:28992) was imported, covering the study area, which allowed the creation of a precise 3D depiction of the natural terrain without the presence of buildings or trees. This accurate representation complements the GWT representation and the 3D buildings, making it ideal for the Digital Twin application in this research.

The neutral state of the code occurs when the updated GWT depth mesh remains below the surface, in which case only monitoring actions are performed by visualising GWT changes. If the GWT mesh rises above or touches the surface, then a predefined maker event trigger from the game engine is activated and sends an HTTP POST request to a webhook service that connects the game engine to the physical actuator through an IoT manager website. In this case, the command "WaterpumpON" is executed, activating an internet-enabled smart plug that is waiting for instructions. The smart plug is directly connected to a small water pump situated in a controlled environment. Conversely, when the GWT mesh drops back below the surface, another maker event trigger happens. This executes the command "WaterpumpOFF", turning off both the smart plug and the water pump (see Figure 6).

Additionally, for ease of visualisation, when the water pump is activated and deactivated, a (red) cylinder and an animated water pump are shown as beacons (as seen in Figure 6) to indicate the location where the groundwater has entered the range to activate the water pump. This helps users quickly identify the affected areas while navigating a large three-dimensional environment, such as an entire city. To reflect the physical actuator status in the digital environment, the beacon appears when the command "WaterpumpON" is active. When the collider exits the trigger zone, it removes the cylinder beacon and the animated water pump model as the "WaterpumpOFF" command is activated.

However, while real-time data visualisation can be implemented adequately due to the game engine's capabilities, it can sometimes be hindered by two factors: (1) The dependency on Twents Waternet's data refresh rates, as the data undergoes a verification process before being made available for download. Otherwise, a direct connection between the sensors and the Digital Twin could help streamline processes such as data preparation and formatting, reducing these delays. (2) The slow changes in groundwater over time make it difficult to visualise the Digital Twin in action. Therefore, a historical scenario option was implemented to load values that can test different cases that may trigger the described events and assess possible thresholds.

Figure 6. Video game engine and water pump actuator states. Left: Water pump ON when water touches the surface. Right: Water pump OFF when groundwater is not touching the surface.

6. Evaluation

An evaluation was conducted with staff from the Municipality of Enschede. The evaluation focused on assessing the feasibility of integrating heterogeneous sensing, prediction, visualisation, and actuator control into a coherent Digital Twin-based municipal decision-support prototype, rather than benchmarking the performance of individual components. Consequently, quantitative prediction metrics (e.g., RMSE, MAE, or R^2), usability studies, and communication latency measurements, were considered outside of the scope of this proof-of-concept. These evaluations constitute important future work prior to operational deployment. In order to assess the feasibility of the proposed proof-of-concept, four qualitative evaluation objectives were considered: (1) technical integration feasibility, (2) operational decision-support feasibility, (3) stakeholder usefulness, and (4) transferability and scalability.

6.1 Technical integration feasibility

Did sensing, synchronisation, prediction, visualisation, and actuator control work together?

From the results of the case study implemented for the city of Enschede, it was observable that all components operated together within the DT workflow. Sensor data were synchronised, groundwater levels were predicted using rainfall data, and the results were effectively visualised in the DT environment. Additionally, when groundwater levels reached established thresholds, the system successfully activated the connected water pumps. Therefore, these results demonstrated the feasibility of integrating the monitoring, prediction, visualisation, and actuation components, even when individual modules could still be further refined for operational deployment.

6.2 Operational decision-support feasibility

Did the prototype support the intended operational decisions?

This prototype enabled stakeholders to access up-to-date information on GWT fluctuations and to support operational decisions, including pump activation or deactivation based on predefined groundwater-level conditions. Additionally, it was considered valuable that the DT provides simulations in virtual environments that can interact with real-world elements, such as the actuation of small-scale water pumps. This capability enables stakeholders to evaluate groundwater level thresholds and assess system behaviour under varying conditions before implementing decisions in the real world. This characteristic can further enable testing of reaction times and system reliability, demonstrating the DT's potential to support informed investment and operational decisions regarding future infrastructure.

6.3 Stakeholder usefulness

Did experts consider the visualisation and monitoring meaningful?

Users noted that the freedom to move within the visualisation environment could be somewhat overwhelming, and that static localised views focusing on areas of concern would better support their monitoring tasks. Moreover, they expressed optimism about the possibility of monitoring an entire city through a single tool, which could help identify future areas of interest. However, there remains room for improvement in the user experience, as the current controls lack full intuitiveness and require a brief familiarisation period for the effective navigation within the 3D environment.

Despite these limitations, the case demonstrates how a smart-city groundwater management system can be constructed by combining sensor data, predictive logic, interactive geospatial visualisation, and infrastructure feedback. In this sense, the Digital Twin functions not only as a visualisation platform, but also as a smart data environment that transforms heterogeneous environmental measurements into actionable information for municipal groundwater management.

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6.4 Transferability and scalability

What would be required for other areas or production use?

The scalability of the project was considered promising, particularly through the integration of high-capacity, internet-connected water pumps and strategically placed sensors. Several cities in the Netherlands already maintain similar regional monitoring databases, enabling the methodology to be replicated elsewhere. Although equivalent datasets may not be available worldwide, similar systems can be applied in other contexts provided that groundwater sensors, periodic rainfall data, a DTM, and IoT infrastructure are available.

7. Conclusions

This paper presented a prototype Digital Twin framework for near-real-time urban groundwater-table management in which heterogeneous sensing, weather, visualisation, predictive, and actuator-control components were integrated into a single municipal decision-support environment. The study addressed a practical gap in urban groundwater management by exploring how distributed sensor measurements and external weather data can be transformed into a dynamic geospatial representation to support monitoring, short-term forecasting, and threshold-based operational actions.

The main contribution of the work lies in demonstrating the feasibility of integrating these functions within a coherent Digital Twin workflow. Groundwater observations from distributed sensors were combined with rainfall data, represented through a dynamic 3D mesh, supplemented with a modular proof-of-concept predictive model, and linked to IoT-based pump control logic. As a result, the prototype demonstrates how environmental sensing can translate into actionable smart data for municipal groundwater management.

The results should be interpreted carefully, as the generated groundwater surface represents an interpolated visualisation intended for operational awareness rather than a physically calibrated groundwater flow simulation. Therefore, the prototype is neither a complete hydrological simulation platform nor a production-ready infrastructure-control system. Rather, it is a feasibility-oriented demonstration of how monitoring, visualisation, prediction, and physical feedback can be combined in a smart-city context. Its strongest value lies in showing that interactive geospatial environments can support operational awareness and early action for groundwater management when coupled with synchronised environmental data and clear decision thresholds.

Future work should focus on improving predictive performance, strengthening interoperability with municipal systems, formalising secure communication with connected devices, and conducting more systematic evaluations with end users. Moreover, future research should focus on optimising system integration, clarity/usability of the DT, as well as further developing the predictions to enhance trust in the visualised results and exploring specific use cases to further expand the impact of this solution.

The study highlights the potential of DTs for urban groundwater management to serve as smart-city information systems, transforming data sources into interpretable and actionable support for municipal decision-making. Therefore, this research helps bridge the gap in GWT management by demonstrating the value of integrating DTs with near-real-time data and advanced analytics. The combined findings show that real-time data fusion and prediction enabled immediate pump control, and that DT visualisation fosters evaluation opportunities for pumping scenarios, supporting a dynamic approach to groundwater management.

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Appendix A

Component Requirements	Description	Conditions	Constraints
Visualization	Enable the visualization of measurable data.	Visualization must be done in an intuitive manner, easy to use and interactive, avoid overloading both visually and resource wise.	Visualization within the available workflow and software in EMUN, but experimentation on external tools is allowed.
Predictive Model	Identify the required data and structure to train the predictive model.	The predictive model must be able to forecast at least 1 hour ahead of the measurement time. The predictions outlook could be extended, for example, to 6 hours, 24 hours or longer.	Data must be normalized and retain georeferenced capabilities to visually and geographically overlay it on the study area for analysis purposes.
Physical Model	After the predictive model forecast, a basic physical model should be implemented to predict GWT dewatering or recharge behavior.	The modelled behavior of the interaction of the drainage system with the groundwater must consider the established thresholds required to maintain optimal GWT levels the study area. For example, the system should prevent the GWT from rising above the required 0.70m clearance, measured from the ground surface to the water table.	The physical model must comply with the standards of the EMUN workflow to allow the ease of analysis of the results of the DT. These techniques should help detect patterns and make decisions.
Central Hub	Enable the visualization and interaction of the elements that compound the DT to support an iterative workflow.	The UI must feature a digital representation of the study area, with graphical dimensions tailored to meet EMUN specific requirements. Therefore, within this interface, the Digital Twin Prototype should depict the pipes and manholes near the Glanerbeek River, facilitating monitoring.	The Central Hub must be integrated as much as possible with the EMUN workflow and software, being the specified requirement to be done under ESRI's ARCGIS software.
Notifications for Action Suggestions	A notification system must be integrated into the DT to allow users to get feedback from the workflow results and make decisions.	Notifications must indicate the current groundwater state at the measured location: above the optimal level, within the optimal range, or below the optimal range. Depending on the state, the notification should clearly display the level of importance, specify the suggested action, and state the intended goal of that action.	The action must not be performed by the Digital Twin independently of the users approval, therefore a sort of confirmation dialog is encouraged.
Control of Actuators	Implementing the ability to control actuators based on the DT suggestions that consider the physical thresholds established by EMUN.	The DT User Interface must allow control under the centralized hub. Measurements to consider actions must be referenced from the average North Sea level Normaal Amsterdams Peil (NAP) in meters.	Due to budget constraints, only one controllable barrier will be strategically installed in the lowest manhole of the prototype.

Appendix B

User Needs	Evaluation Criteria	How to Address Needs
Clear visual representation The DT dynamically showcases visual representations of the GWT	**User Interaction** Clear, easy to understand an interact elements are present.	Have test sessions with EMUN staff to identify users' perception on the usability of the tool. Implement suggestions in future revisions.
Groundwater Forecasts The DT to forecast GWT levels ahead of time to support proactive decision making.	**Predictive Model Forecast** Minimum 1 hour ahead. Extendable to 6h, 24h, or longer depending on data and time availability.	Validate forecasts against sensor data at different time intervals. Track model performance and refine training datasets
Respecting Physical Thresholds The system must ensure groundwater never rises above EMUN's critical clearance below ground surface.	**Physical Model Threshold** Maintain 0.70m clearance (ground surface to GWT) in all scenarios.	Run simulations and compare results of predicted behavior of drainage with the ones made by water experts. Verify that the clearance threshold is respected.
Workflow Integration The DT needs to integrate with the existing workflows and infrastructure of EMUN.	**Central Hub Workflow Integration** Fully migrated to Municipality's workflow, servers and ArcGIS based infrastructure.	Conduct workflow integration tests with EMUN users. Migrate the whole system to their servers and equipment.
Clear and Actionable Notifications Notifications must clearly state groundwater status, urgency, and suggested actions.	**Notification Clarity and Validity** All notifications should state the GWT condition (above/ within/below optimal levels), suggested action and intended goal.	Conduct user evaluations to confirm clarity and usefulness. Verify user confirmation before an action is executed.
Responsive Actuator Control The system must allow fast and reliable control of barriers through the central hub after a decision is made.	**Actuator Control Responsiveness** Actuator commands ideally would be issued within 5 minutes after a decision is made.	Measure the response time from the moment an action suggestion is issued until the action is executed (including response time from users).
Prototype Scalability The prototype must demonstrate whether the DT can realistically be scaled to physical implementation.	**Prototype Efficiency** Allow the EMUN to simulate the use of the DT with actuators to identify its feasibility for a physical implementation.	Implement digital simulations of the actuators controlled by the DT. If these tests are successful, tests with physical actuators can follow. Once validated, the DT can be connected to test it with in-situ actuators that control the real barriers in the drainage system.