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Advanced Digital Technologies for Sustainable Urban Water Management in South Tyrol

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Abstract

This study presents the initial findings from the ORCHESTRA project, which aims to enhance sustainable and resilient urban water management in South Tyrol. The project combines advanced digital technologies, such as digital twins, Artificial Intelligence (AI), and machine learning, with Nature-based Solutions (NbS) and green technologies to develop an intelligent, adaptive water management system. The application of digital twins is crucial as it provides real-time simulation and monitoring of urban water systems. Moreover, AI-driven analysis of IoT sensor data constitutes the basis for dynamic decision-making in the context of predictive water management and optimised network safety. The integration of digital technologies and green infrastructure will support sustainable urban development by contributing to informed urban planning while promoting resilience. Two case studies in Bolzano have been identified to demonstrate the practical application of digital twins and nature-based solutions (NbS). This research underscores the role of digital technologies in promoting sustainability within urban landscapes while advocating for a comprehensive, interdisciplinary approach to urban planning. Future steps include the expansion of the digital twin framework, alongside detailed cost-benefit analyses, stakeholders engagement, and the identification and resolution of implementation challenges to advance sustainable, intelligent, and resilient cities.

Highlights

- Real-time hydrologic-hydraulic digital-twin of Bolzano’s storm-water network fed by level and speed sensors.
- Twin-based scenarios show that adding green roofs and permeable pavements measurably lowers peak runoff.
- AI/ML models built on the sensor feed reliably forecast short-term water-level trends.
- The combined digital-twin and NbS framework provides a scalable “sponge-city” roadmap for climate-resilient Alpine towns

Introduction

Urban areas are increasingly facing the adverse effects of climate change and rapid urbanisation. The ongoing intensification of rainfall patterns, the increasing prevalence of prolonged periods of heat, and the relentless urban sprawl are pushing conventional pipe-based drainage networks beyond their design limits. The consequences of these phenomena include the disruption of the natural hydrological water cycle and an increase in the risk of flooding. Consequently, the inability of large impervious surfaces in conjunction with highly centralised grey infrastructure to absorb, store or safely convey the volumes generated by intense storms has resulted in an increase in flooding, periodic water shortages

and the intensification of urban-heat-island effects (Singh et al., 2023). The restoration of the natural hydrological cycle thus necessitates a transformation towards integrated, adaptive stormwater management techniques that encompass decentralised retention, adaptable control mechanisms and multifunctional public spaces (Oral et al., 2020). A notable approach, the Sponge City concept, exemplifies this strategy by promoting natural infiltration and retention of rainwater. The integration of Nature-based Solutions (NbS) within Sponge Cities, including features such as green roofs and permeable surfaces, when combined with advanced digital tools, has the potential to substantially mitigate flood risks, improve water quality and promote urban biodiversity.

Extreme precipitation trends and land use intensification have exposed the limitations of traditional drainage systems, leading to a growing interest in hybrid strategies that integrate nature-based solutions (NbS) and smart technologies into a cohesive management framework (Oral et al., 2021) (Sowińska-Świerkosz and García, 2022). In urban areas, NbS constitute deliberate, small-scale ecological interventions designed to restore natural processes such as infiltration, retention and evapotranspiration within the built environment (Eggermont et al., 2015). According to (Henriksen et al., 2022) and (Kõiv et al., 2024) EU legislation now requires municipalities to incorporate such measures into stormwater design by 2026. As demonstrated by (Pirouz et al., 2021) and (Tsatsou et al., 2023), the implementation of green roofs, permeable pavements, bio-retention cells and urban wetlands can collectively attenuate peak flows. Similarly, (Cohen et al., 2012) show that measures such as distributed infrastructure can also serve as a form of drought mitigation through local storage and reuse, effectively functioning as distributed "sponge" infrastructure. This approach has the dual benefits of simultaneously cooling neighbourhood microclimates and enhancing biodiversity (Alemaw et al., 2020). It is evident that the provision of a wide range of co-benefits, including the creation of habitats and the sequestration of carbon, as well as the enhancement of air quality and the availability of recreational amenities, has been demonstrated in the existing literature (Yang et al., 2022) (Xie et al., 2022) (Martín Muñoz et al., 2024) (Wan et al., 2022).

On the other side, recent technological advancements in the domains of digital twins, the Internet of Things (IoT) and artificial intelligence (AI) have resulted in substantial progress in the field of machine learning (ML), thereby providing the necessary capabilities to achieve this objective (Song, 2022) (Köster, 2021). High-fidelity hydraulic and hydrological models, continuously updated by dense sensor networks, can now simulate a wide range of "what-if" scenarios, predict network states minutes to hours in advance, and trigger proactive control actions. Advancements in sensing, communication and analytics technologies have revolutionised water infrastructure management (Aivazidou et al., 2021) (Mullapudi et al., 2017). Digital representations of sewer networks, open channels and catchments, utilise continuous sensor data streams and update model states in near real time, enabling optimisation, scenario testing and early warning functions (Brasil et al., 2022). Incorporating artificial intelligence and machine learning algorithms, these twins have the capacity to predict system behaviour during extreme events and automatically implement control rules that reduce peak flows or divert them to storage (Mullapudi et al., 2017) (Cea and Costabile, 2022) (Shishegar et al., 2019).

Despite the EU Climate Adaptation Strategy's call (European Commission, 2021) for digitally enabled, self-learning, resilient, urban water systems, their deployment is limited by several obstacles and notable research gaps. Specifically, the lack of open frameworks linking ecological infrastructure with cyber-physical controls and few tools for adjusting nature-based solutions to evolving weather. These issues are further accentuated by inadequate monitoring and a shortage of site-specific performance data. Addressing these gaps will require interdisciplinary collaboration among engineers, ecologists, data scientists and policymakers, and this study moves that effort forward.

This study presents the first results of the ORCHESTRA project, which combines nature-based solutions with an AI-driven digital twin to evaluate flood-mitigation and microclimate benefits in two living laboratories, the peri-urban Via Fago catchment and the highly impervious NOI Tech Park, providing a comprehensive framework for future urban planning and sustainable development in the face of evolving environmental challenges.

Methodology

Integrated Approach

This study uses an integrated approach combining Nature-Based Solutions (NbS) with advanced digital technologies to improve sustainable urban water management in Bolzano, South Tyrol. A multi-phase research design was adopted to support a robust climate-resilient stormwater strategy. Initially, a systematic review of relevant literature and technical guidelines was carried out to identify the Nature-Based Solutions (NbS), such as green roofs, permeable pavements, bioretention cells and urban wetlands, suitable for mitigating urban flooding in alpine conditions. Each solution underwent a SWOT analysis to assess its relevance to Bolzano's climatic context, land-use constraints, regulatory framework, and compatibility with sensor-based control systems. Accordingly, the implementation of NbS has been strategically planned to restore natural water cycles and support climate adaptation.

In parallel, digital technologies were utilised to establish a comprehensive monitoring and management framework. Digital twins of Bolzano's urban water system have been developed to enable real-time monitoring, performance optimisation, and predictive analysis, with continuous updates through data from a network of IoT sensors. The installation of ultrasonic level sensors and electromagnetic flowmeters was conducted at key drainage nodes, which were selected through the utilisation of field surveys and GIS-based terrain analysis. These sensors recorded data at five-minute intervals over several months under varying rainfall conditions, thereby producing high-resolution datasets on water depths and discharges. The collected data was utilised to inform an EPA-SWMM hydrologic-hydraulic model, which formed the core of a cloud-based digital twin. Each NbS was virtually modelled, incorporating permeable pavements and bio-cells as low-impact development (LID) elements utilising depth-dependent retention curves. This facilitated the assessment of their hydrological performance under both historical and projected storm scenarios. Machine learning algorithms, specifically gradient-boosted regression trees and LSTM neural networks, were applied for predictive flow optimisation, and system efficiency. Continuous data assimilation updated model states in near real time, while model accuracy was validated using root-mean-square error metrics. The investigation demonstrated that sensor-integrated hydraulic simulations, enhanced by machine learning forecasts, offer a robust basis for quantifying the impact of Nature-Based Solutions (NbS). These tools enable the anticipation of flood peaks and support adaptive management strategies, promoting long-term sustainability in urban water systems.

Case study

The empirical component of the study focused on two hydrologically contrasting districts of Bolzano (see Figure 1). The selection of these locations was driven by the objective of assessing the efficacy of nature-based solutions and real-time digital monitoring in diverse urban contexts.

The first test site, Via Fago, is located within a narrow peri-urban corridor on the northern edge of the city: this area is characterised by the alternating presence of residential areas and wooded slopes that serve as natural drainage corridors for several steep, ephemeral streams. Despite the presence of vegetated traffic islands, street-tree pits and private gardens, which serve to create isolated areas of permeability, the discontinuous coverage is unable to impede the substantial unit-runoff volumes generated during convective summer storms. Municipal regulations further restrict the implementation of hydraulic conveyance by prohibiting direct discharge to the combined sewer, and instead obliging property owners to dispose of runoff on site. Consequently, the locality presents an example of a town catchment where infiltration-type NbS must shoulder most of the retention burden yet must do so within fragmented public space and under severe limits.

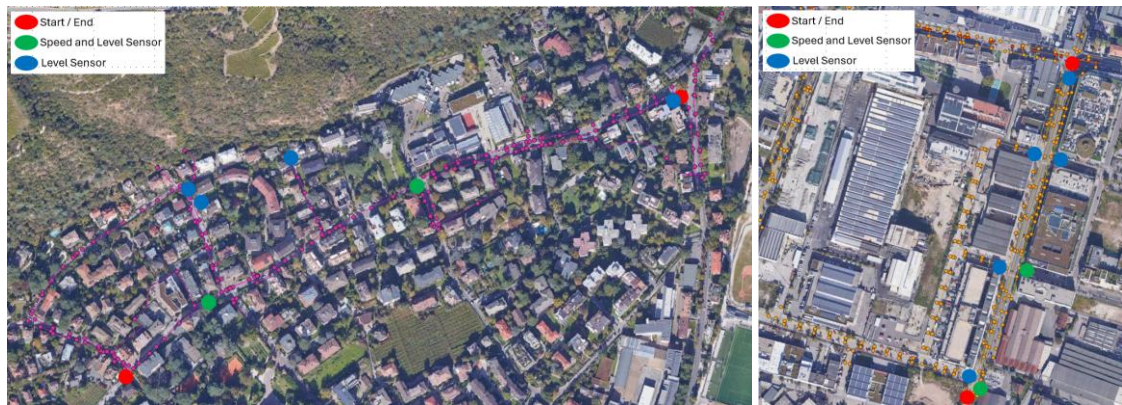


Figure 1. (left) Case study via Fago (right) Case study via Galvani.

By way of contrast, the second case study near the NOI Tech Park innovation district is in the densely built southern plain and is characterised by large, low-rise industrial blocks, asphalt service yards and an overall imperviousness exceeding ninety per cent. The ground-level vegetation is sparse, and the urban-heat-island effect phenomenon is known to elevate summer surface temperatures. In several instances, permeable paving and honeycomb turf have been employed for parking areas. The architectural typology, however, provides substantial structural capacity for extensive or semi-intensive green roofs. However, the cumulative retention effect has not been taken considered, since, by regulation, water must be dispersed on private land and not reach the public drainage system. Both areas were instrumented with ultrasonic level sensors and electromagnetic flow meters positioned at hydraulically representative nodes of their respective drainage networks. This methodological approach enabled the generation of two complementary data sets: the first set captured hillside inflow dynamics, while the second set captured large-roof hydrographs. These observations are utilised by a coupled hydrologic–hydraulic digital twin, which has been developed in EPA-SWMM and is hosted on a cloud platform that ingests five-minute sensor updates. The objective of this study was to simulate the hydrological influence of the interventions under observed storms, as well as to design rainfall scenarios of varying return periods.

Results and discussion

This chapter presents the preliminary outcomes of the ORCHESTRA project which explores the feasibility of a hybrid and digital model for sustainable urban water management in Bolzano. The integration of digital-twin technology, artificial-intelligence-of-things (AIoT) and nature-based solutions (NbS), has enabled the development of a digital platform that replicates the city's stormwater infrastructure. When paired with dense IoT sensor arrays and machine-learning analytics, the platform enables real-time hydrological forecasting and adaptive operational strategies. Initial simulations indicate that this integrated approach enhances hydraulic resilience to extreme rainfall, reduces peak runoff, and improves system reliability in comparison with conventional static designs. The modelling framework was evaluated across a range of scenarios to improve predictive accuracy, identify long-term maintenance requirements, and inform design guidelines tailored to specific locations. While these findings affirm the technical viability of the approach, the study also identifies key empirical and operational challenges that must be addressed before municipal-scale implementation can be undertaken. Furthermore, it highlights the potential transferability of these guidelines to other dense Alpine municipalities that are pursuing climate-resilient stormwater strategies.

Implementing the Sponge City Concept in South Tyrol

The evaluation of nature-based solutions for urban storm-water control in South Tyrol confirms the potential of permeable pavements and green roofs in enhancing flood resilience, mitigating the urban heat island effect and promoting biodiversity.

Case studies in Via Fago and NOI Tech Park demonstrated the transformative potential of nature-based solutions (NbS): at Via Fago, permeable pavements and green corridors has shown to improve

infiltration rates, reduced surface runoff and managed stormwater more effectively, and enhance both aesthetic and ecological quality. Similarly at NOI Tech Park through the installation of green roofs and permeable paving mitigates the urban heat island effect by decreasing surface temperatures and enhances water detention capabilities, improving stormwater management and detention and contributing to a more sustainable and comfortable urban environments.

While space-intensive measures like constructed wetlands, tree planting, and vegetated façades offer substantial hydraulic and thermal benefits, they are often difficult to retrofit in densely built areas. In contrast, permeable pavements and extensive green roofs have been shown to offer substantial runoff reduction and surface-temperature mitigation, while incurring comparatively modest spatial and maintenance demands. However, their performance depends on design specifics, seasonal conditions and initial investment. The findings of the research suggest that a hybrid strategy, combining targeted "green" interventions with existing "grey" infrastructure, is an effective solution.

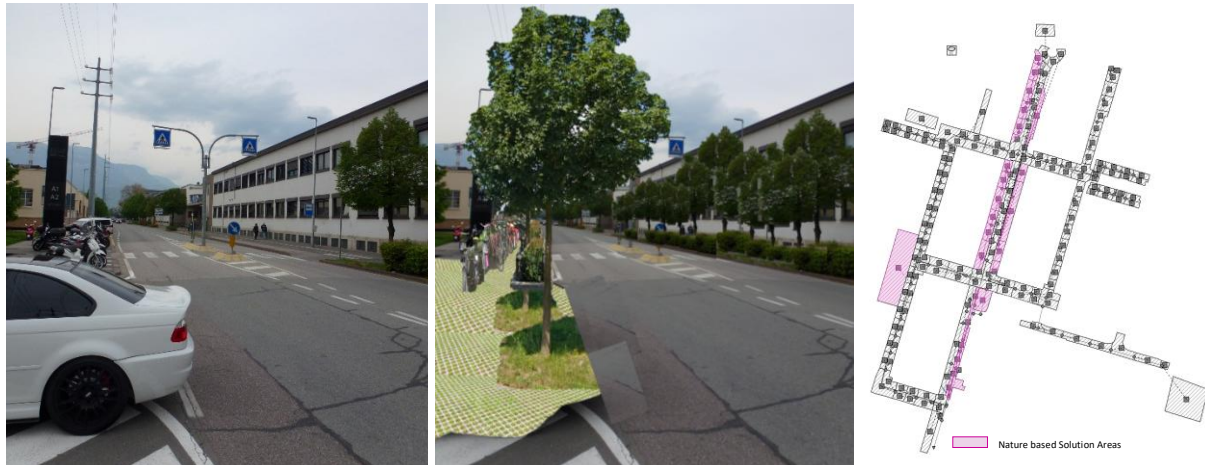


Figure 2. The redesign of a street next to NOI Tech Park - the EPA-SWMM model with areas being converted to NbS.

The benefits of selected Nature-Based Solutions (NbS) were quantified by modelling each configuration as a low-impact development (LID) element within an EPA-SWMM hydrologic-hydraulic framework (see Figure 2). Simulation experiments were conducted in the case study areas to assess the impact of vegetation on the attenuation of moderate storms, to assess the performance of Nature-Based Solutions (NbS) in mitigating peak runoff within selected urban areas in Bolzano: this involved replacing portions of impervious surfaces with green infrastructure as identified during the planning phase.

In the NOI Techpark area, NbS were implemented over a surface of 0.01053 km² within the total sub-catchment area of 0.0472 km², corresponding to approximately 22.3% of the total area. For Via Fago, 0.00132 km² of NbS were introduced within an area of 0.0113 km², accounting for approximately 11.7%. The results of the hydrological simulation indicated a substantial reduction in peak runoff, with a decrease of approximately 24% observed in the NOI Techpark area and a marginally lower yet still significant decrease in Via Fago. The findings suggested that the existing patchwork of vegetation and partial infiltration in the peri-urban catchment already serve to attenuate moderate storms. Conversely, the NOI Tech Park, which exhibited high levels of impermeability, demonstrated notable surface accumulation, suggesting an alternative response to storm events.

The modelling outcomes validate the earlier SWOT analysis, offering a quantitative foundation for the future implementation of the model on a large scale, informing future performance monitoring efforts.

Digital Solutions for Urban Water Infrastructure

A pivotal element of the present investigation concerns the application of contemporary artificial-intelligence techniques to the large, high-frequency data stream generated by Bolzano's pilot sensor network. The installation of ultrasonic level probes and electromagnetic flow meters was conducted at hydraulically representative nodes throughout the drainage system. Concurrently, data pertaining to rainfall intensity, temperature and wind parameters were collected over a period of five

minutes. Despite the present series encompassing a relatively brief period, inadequate for the complete utilisation of data-intensive deep learning methodologies, it offers a practical experimental framework for investigating the viability of machine learning-driven forecasting. This framework facilitates the comparison of data-driven predictions with hydraulic responses simulated by the EPA SWMM digital twin.

Data pre-processing involved the synchronisation of individual sensor feeds, after which three supervised learning approaches were evaluated. Initially, a Random Forest ensemble of 300 trees was trained to estimate ten-minute-ahead water levels at downstream nodes. Secondly, a gradient-boosted decision tree algorithm (XGBoost) was implemented to improve short-term prediction by minimizing residual errors iteratively. Thirdly, a univariate Long Short Term Memory (LSTM) neural network was developed for thirty minute lead times. All models were trained on 70% of the available time series, with the remaining 30% held out for validation.

Preliminary results show (Figure 3) that all models captured the overall hydrograph shape and the timing of peak stages with promising accuracy, despite the limited training period. The Random Forest ensemble provides the clearest insight into which inputs are the most significant: twenty-minute cumulative rainfall and upstream depth changes. XGBoost builds on this by slightly increasing the coefficient of determination and reducing the root mean square error by about ten per cent compared to the Random Forest baseline. The LSTM model exhibited strong performance during the rising limbs of multi-pulse events, benefiting from its temporal memory architecture.

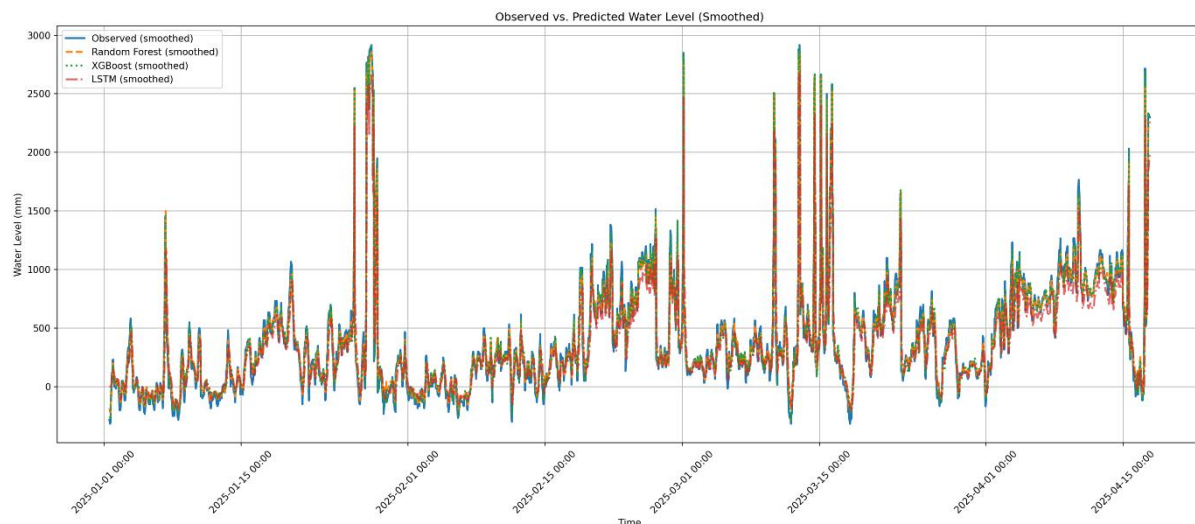


Figure 3. Comparison of Observed vs. Predicted values.

However, it should be noted that the network's accuracy is reduced when rainfall intensities exceed those observed during the network's training. Nonetheless, the application of machine learning and predicted water levels as boundary conditions in the SWMM digital twin results in flow patterns that more closely match observed discharges than the open-loop SWMM model. This demonstrates the value of a hybrid approach in addressing real-time uncertainties in hydraulic parameters and inflow conditions. The present findings, although provisional as the monitoring campaign currently encompasses a six month period (November to April), support the the potential of machine learning as a complementary module within a physically based digital twin, as the machine learning models have been calibrated and tested based on a restricted data set. This would facilitate the generation of rapid forecasts and adaptive control suggestions that cannot be derived from SWMM alone without extensive recalibration. Nevertheless, extended monitoring, ideally spanning a minimum of one year, is essential to expose models to a wider range of extreme precipitation events for cross-validation and benchmarking. Establishing a broader climatological dataset will enhance parameter optimization and strengthen the digital twin's decision-support capabilities. It is expected that the long-term convergence of sensor data, machine learning models and the SWMM's mechanistic basis will deliver a resilient, self-adapting management framework, capable of preventing surcharge conditions and

informing the cost-effective deployment of additional nature-based retention measures across Bolzano and similar Alpine municipalities.

Conclusions and future work

The integration of Nature-Based Solutions (NbS) and advanced digital technologies presents a promising approach for achieving sustainable and resilient urban water management in Bolzano and similar regions. Overall, the study highlights the powerful combination of digital technologies and nature-based solutions in enhancing flood resilience and fostering urban biodiversity and the qualitative improvements observed in the case studies underscore the effectiveness of this integrated approach in transforming urban landscapes into more resilient, intelligent, and sustainable environments. The ORCHESTRA project has formulated and tested an integrative framework that fuses Nature-Based Solutions with a decision architecture to support climate-resilient stormwater management in South Tyrol. Digital twins, informed by five-minute observations from a dense IoT sensor network and refined with machine learning analytics, captured real-time hydrological dynamics embedding a continuously calibrated EPA-SWMM model in two case study areas in Bolzano. Application to the contrasting pilot districts revealed tangible benefits and demonstrated that tailored portfolios to site-specific hydraulic constraints and micro-climatic targets of Nature-based Solutions (NbS) as green roofs and permeable pavements can attenuate peak discharges reductions during cloudburst events and reduce runoff via incremental retention. These results indicate that a data-driven, technology-enhanced NbS strategy provides a transferable blueprint for Alpine and sub-Alpine cities facing analogous climate pressures.

Despite these encouraging outcomes, several hurdles must be overcome before large-scale deployment becomes feasible: the necessity of long-term data sets to generalise model skill in the context of extreme events must be addressed and the implementation of continuous calibration procedures is essential to prevent the divergence between digital replicas and physical assets as without automated parameter-estimation routines and field audits, sediment deposition, seasonal vegetation growth and minor structural changes could cause model drift. Research will extend the monitoring process to encompass a minimum of one hydrological cycle with a wider spectrum of rainfall intensities, incorporating additional data streams. Finally, questions of life-cycle economics with more cost-effective solutions, to develop robust frameworks, long-term maintenance liability and stakeholder acceptance remain only partially addressed and must be integrated into future cost-benefit analyses to ensure widespread adoption and long-term sustainability.

Addressing these technical, economic and social dimensions will consolidate the role of digitalisation and ecological design in building climate-responsive, socially accepted and financially sustainable urban water infrastructures for Bolzano and beyond, fostering intelligent, resilient, and sustainable urban landscapes.

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