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Smart water campus – a testbed for smart water applications

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ABSTRACT

The Internet of Things concept includes low-cost sensors in combination with innovative wireless communication technology, supporting a large-scale implementation of measurement equipment in the field of urban water infrastructure (UWI). At present, the potentials of such smart solutions are often unclear, making it difficult for decision-makers to justify investments. To address this shortcoming, the Smart Campus is represented as an innovative testbed for smart and data-driven applications in the field of network-based UWI. During the last few years, the campus area of the University of Innsbruck has been comprehensively equipped with a variety of low-cost sensors for monitoring and controlling the UWI in high resolution (1–15 min). The experiences showed that the quality of service is influenced by the choice of communication technology and the installation location, thereby affecting the desired applications. Additionally, water distribution and urban drainage network including nature-based solutions have been integrated into an overall monitored system extended by measures to involve the urban population. This integrative approach allows the usage of synergies for the implementation and supports cross-system improvements (e.g., smart rainwater harvesting). However, an integration of different participants also implies new requirements for the project team (e.g., including social science).

Key words: information and communication technologies, integrative management, real-time monitoring, university campus, urban population, urban water infrastructure

HIGHLIGHTS

- The campus of the University of Innsbruck is presented as an innovative testbed for smart and data-driven applications, integrating a water distribution network, urban drainage network and nature-based solutions into an overall monitoring network.
- Wired communication technologies provide a high quality of service, while the amount of packet losses for low power wide area networks is strongly depending on the installation place.
- For a first step into smart applications with involvement of the urban population, scavenger hunts and information boards were used to particularly inform and involve children and students.
- Fault detection in real-time (e.g., water leakages and stagnation problems) and innovative applications for cross-system improvements (e.g., smart rainwater harvesting) are presented as exemplary applications.

INTRODUCTION

Smart cities are increasingly emerging worldwide, combining economic, institutional, social, and technical approaches in combination with existing infrastructure to improve quality of life (Keshavarzi *et al.* 2021). Reliable information and communication technologies (ICT) are essential for the exchange of measurement data and control commands, enabling also information and integration of urban citizens (Ahad *et al.* 2020). Especially the internet of things (IoT) concept allows the development of communicating items and enables new possibilities in monitoring and controlling the urban water infrastructure (UWI) (Singh & Ahmed 2021). For example, low-cost sensors in combination with innovative wireless communication technologies can be easily installed even at remote and underground structures, thereby supporting a large-scale implementation of measuring equipment in existing infrastructure.

To gain real experiences with ICT, digitalisation projects are implemented worldwide. In the following, some selected projects are presented as exemplary IoT-based measurement networks in the field of UWI. In the project 'Smart Water', 75 digital water meters and valves were installed to monitor and control a water distribution network (WDN) in an urban area in Thessaloniki in Greece (Antzoulatos *et al.* 2020). Thereby, water consumption data were transmitted via a long-range wide-area network (LoRaWAN) and Wireless Meter-Bus (WM-Bus) on hourly time steps, and this information was afterwards used for the implementation of innovative services, e.g., to manage peak demands. For urban drainage networks (UDNs), the project 'Open-storm' showed the potential of digitalisation by improving the efficiency of detention volumes and by monitoring urban floods in several case studies in Michigan in the United States (Kerkez *et al.* 2016; Bartos *et al.* 2018). System states like precipitation and filling depth were measured in a temporal resolution of 2–3 min during storm events, and based on this information, valves setting was adjusted to optimise the performance of retention ponds. In the project, measurement data and control commands were exchanged using cellular communication. Furthermore, Ebi *et al.* (2019) installed a private LoRaWAN network in the pilot study 'Urban water observatory' located in Switzerland, using more than 60 sensors to monitor the performance of an UDN in a temporal resolution of 1 to 5 min. Abbas *et al.* (2017) implemented a smart sewage system at the university campus of Lille in France. UDN data, e.g., filling depth, velocity, and turbidity, with 1 min resolution and hourly water consumption data were transmitted via cellular communication and used afterwards for the numerical modelling of wastewater flows.

In a modern and integrative concept for UWI, the centralised approaches of WDN and UDN are extended by decentralised and public solutions like nature-based solutions (NBS). Examples of NBS are green roofs, infiltration trenches, and raingardens with the aim to restore the natural water cycle on a local scale (Ruangpan *et al.* 2020). Subsequently, recent research has also focused on the development of smart NBS solutions (Xu *et al.* 2020). Additionally, there is also a transformation from purely technological solutions to smart city approaches that include the urban population ('Citizen Science') noticeably. However, as stated by Derkzen *et al.* (2017), the function of the different elements of the UWI is often unknown to the urban population and thus limiting the efficiency of implemented approaches. Therefore, it requires a sufficient and targeted measure for the involvement of the urban population, as the willingness for personal measures increases with a better understanding of the system and the associated problems (Veronesi *et al.* 2014).

The aim of this work is to present the Smart Campus as an innovative testbed for smart applications in the field of UWI. To the authors' knowledge, this is one of the first studies integrating urban drainage and water distribution networks including nature-based solutions into one overall monitored system. This has the advantage that synergies (e.g., ICT, data management) can be utilised for the implementation of the measurement network, whereas the collected data can be used for cross-system improvements. An exemplary application therefore is an automatic irrigation of NBS based on actual system conditions in WDN. Additionally, the main focus is also on the information and involvement of the local actors (e.g., urban population, students, infrastructure operators, decision-makers). The detailed objectives of this work can be described as follows:

- Describing the technical implementation of different measurement devices and ICT at the Smart Campus
- Evaluating the performance of applied ICT in terms of quality of service and discussing their suitability for different applications
- Developing and implementing innovative approaches to inform and to involve local actors
- Presenting selected evaluations of the measurement data to demonstrate the potential of smart applications (including cross-system improvements).

MATERIAL AND METHODS

As a case study, the Campus Technik of the University of Innsbruck has been comprehensively equipped with a variety of low-cost sensors for quantitative and qualitative measurements in the field of urban water infrastructure (UWI) since 2017. The campus has an area of eight hectares including several university buildings and a forecourt with NBS in the form of sunken planters and green swales planted as rain gardens. About 1,000 employees work at the campus and approximately 6,000 students are studying there. The campus area, called 'Smart Campus', is part of a pilot project for smart water cities integrating water distribution and urban drainage network including nature-based solutions into one overall monitored system.

The technical architecture of ICT networks can be described by layers, whereby each layer fulfils certain tasks. In this work, the technical framework of Oberascher *et al.* (2022) is applied with the focus on perception (monitoring of environmental data and operational status), communication (exchange of monitoring data and control commands), middleware (data and code management), and processing (analysis) layer.

Perception layer

A multitude of parameters (e.g., soil moisture, water level, surface temperature, water pressure, water consumption, climate data, etc.) is measured and transmitted mostly in high resolution in intervals of 1–15 min. For more information about the spatial and temporal resolution of measurement data, refer to Figure 1.

In total, the measuring network currently includes 12 water meters and six pressure sensors for the water distribution network. Furthermore, two combined weather stations with precipitation, wind, air temperature and humidity as well as two stations with precipitation measurement are installed on the campus grounds. For urban drainage, five stations with soil moisture and soil temperature sensors, seven level sensors as well as one pressure sensor for sewer and green infrastructure and two temperature sensors for wastewater are installed. Additionally, a smart rain barrel as an IoT-based solution for smart rainwater harvesting (for more information refer to Oberascher *et al.* (2021)) is under operation during the summer months. Finally, three weather stations (referred to as E1, E3, and E4) and one water meter (referred to as E2) at single-family houses with distances between 5 and 8 km around the campus area are included in the project to test communication technologies also over longer transmission ranges. For more information about the measurement devices used, Table 1 summarises the main characteristics.

Communication layer

The data flow from the individual measurement devices to the joint database is illustrated in Figure 2, whereas the implementation of the ICT network took place in two phases. The first implementation phase was in spring 2017 and was characterised

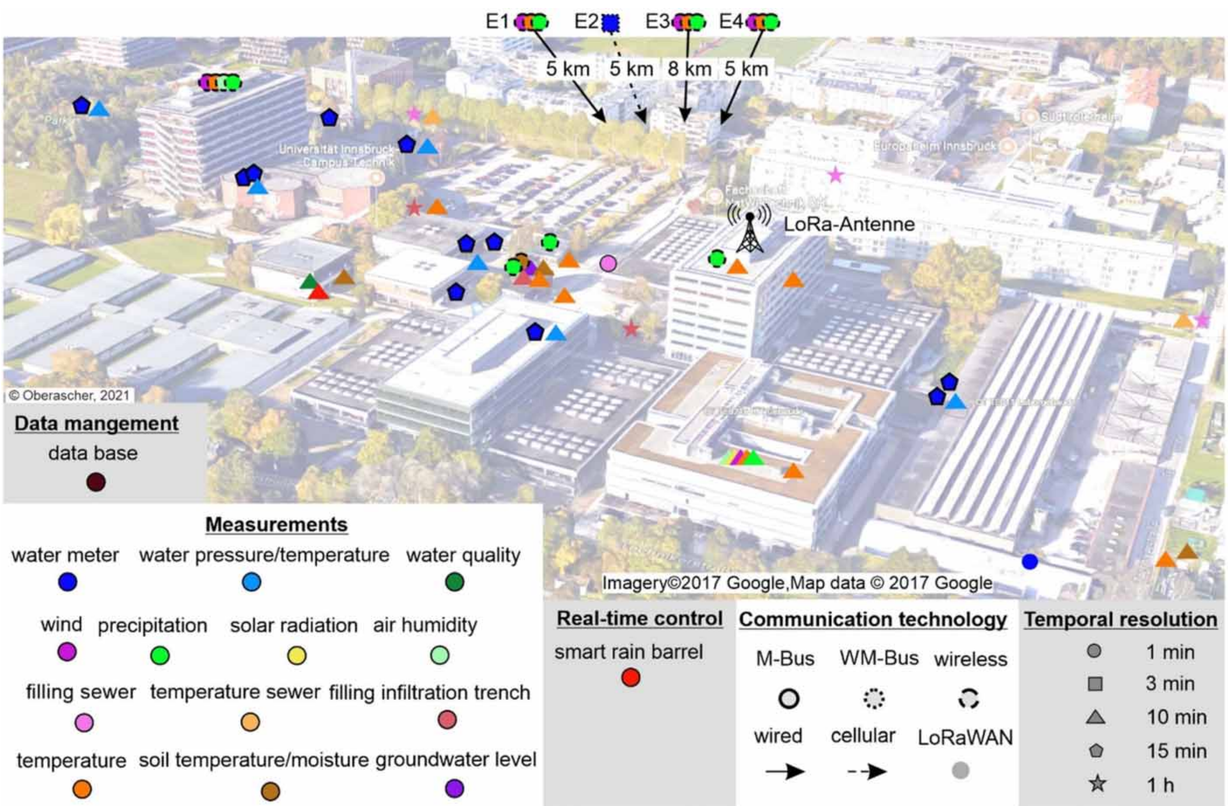

Figure 1 | Overview of the 'Smart Campus' with measurement locations including the measured parameters (indicated by colour), temporal resolution (highlighted by shape), and used communication technology (specified by frame). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2022.369.

Table 1 | Description of the used measurement devices at the smart campus

Device	Company	Measured parameters	Temporal resolution	Communication technology	First operation since	Number of devices
DL-ATM41	Decentlab GmbH	• Air temperature • Barometric pressure • Precipitation • Relative humidity • Vapor pressure • Solar radiation • Wind direction • Wind speed	10 min	LoRaWAN	July 2019	1
DL-MBX	Decentlab GmbH	• Water level	10 min	LoRaWAN	June 2019	1
DL-PR21 Temperature Sensor	Decentlab GmbH	• Water pressure	10 min	LoRaWAN	January 2020	6
DL-PR26	Decentlab GmbH	• Water pressure	10 min	LoRaWAN	June 2019	1
DL-TRS12	Decentlab GmbH	• Electrical conductivity • Soil moisture • Soil temperature	10 min	LoRaWAN	October 2020	3
MeiStream® Water Meter	Sensus	• Water flow	15 min	M-Bus	December 2017	3
Mehrstrahl-Patronenzähler	Bernhardt	• Water flow	3 min	WM-Bus	April 2017	1
Mehrstrahl-Nassläufer BM	Bernhardt	• Water flow	1 h	LoRaWAN	–	1
Mehrstrahl-Nassläufer BM	Bernhardt	• Water flow	15 min	M-Bus	December 2017	8
Rain collector with mountable base #7857	Davis Instruments	• Precipitation	1 min	Proprietary	April 2017	3
Smart Water v3.0	Libelium	• Conductivity • Oxidation–Reduction Potential • pH • Temperature	10 min	LoRaWAN	September 2020	1
Soil Moisture/Temperature Station #6345CS	Davis Instruments	• 4 × Soil temperature • 4 × Soil moisture	1 min	Proprietary	June 2017	1
TEK 766	Tekelek	• Water level	1–6 h	LoRaWAN	June 2019	4
Temp V3	Adeunis	• Temperature	10 min	LoRaWAN	September 2020	12
Vantage Pro2™ #6152	Davis Instruments	• Air temperature • Precipitation • Relative humidity • Wind speed • Wind direction • Wind speed	1 min	Proprietary	April 2017	1
Vantage Vue® #6250	Davis Instruments	• Air Temperature • Barometric pressure • Precipitation • Relative Humidity • Wind speed	1 min	Proprietary	February 2017	3

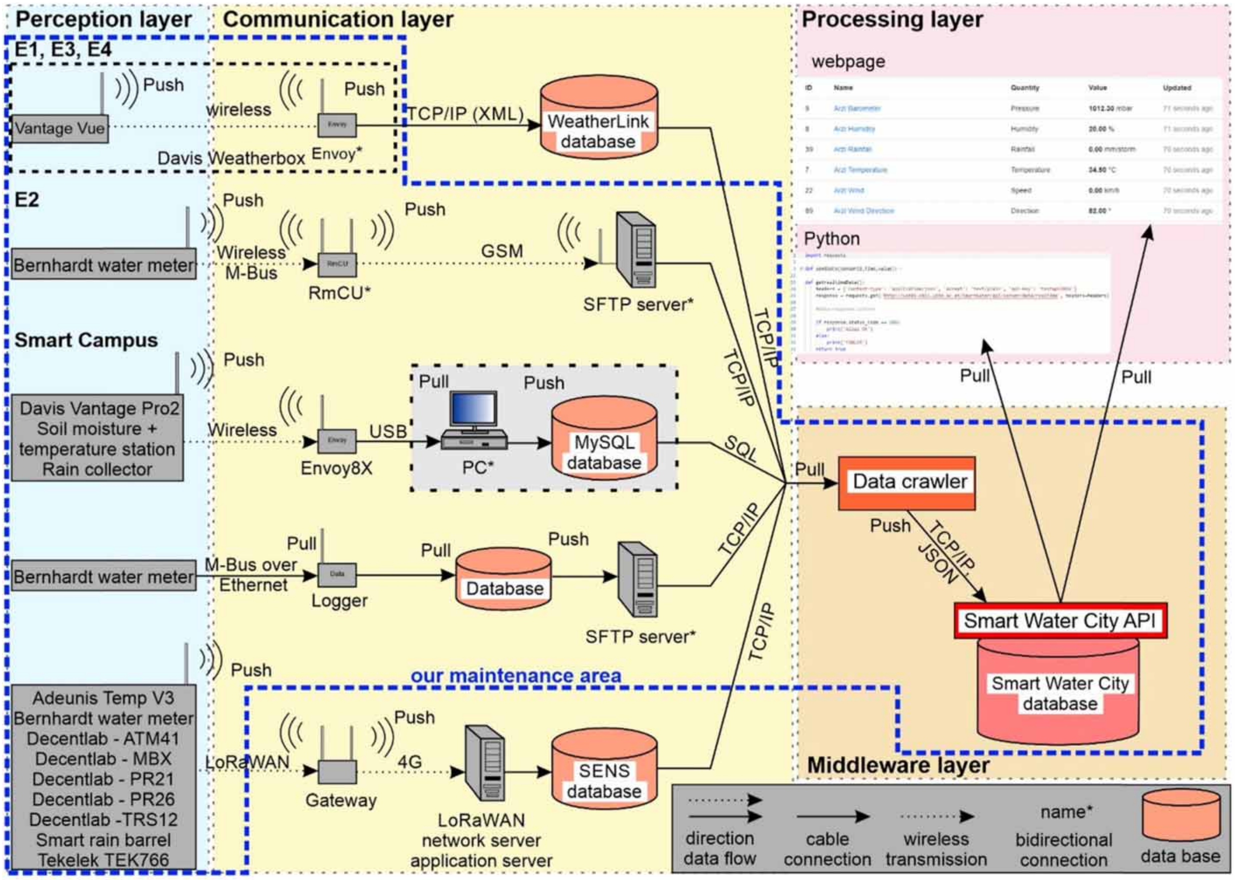

Figure 2 | Illustration of the data flow from the individual measurement devices to the central database with connection to analysis tools subdivided into the different layers.

by testing different communication technologies and systems. In this period, all devices from Davis Instrument, Bernhardt and Sensus were installed. Weather and water consumption data are transmitted via a proprietary wireless technology (Davis Instrument) and (W)M-Bus (Bernhardt and Sensus), respectively. Additionally, a joint database has been established, which is required for some systems specialised approaches (e.g., Windows MySQL database for all devices of Davis Instrument at the Smart Campus). Therefore, the development was primarily done by a working group member with expertise in computer science.

In contrast with the first implementation phase, the second expansion stage was mainly implemented by personal with expertise in environmental and civil engineering. Subsequently, the aim was to simplify the applied systems by using 'plug-and-play' sensors. In this context, a private LoRaWAN network was set up in summer 2019, which is operated by the Austrian LoRaWAN and IoT solution provider Sensor Network Services GmbH (SENS). Since then, the monitoring network has been continuously extended by different measurement devices from Decentlab and Adeunis.

Middleware layer

The aim of the middleware layer is (1) to integrate different measurement data into a joint database and (2) to ensure interoperability between different storage techniques, analysis modules, and visualisation techniques using a common Application Programming Interface (API) (Antzoulatos *et al.* 2020; Pedersen *et al.* 2021). This API is implemented as a REST service, which has the advantage that web addresses can be used for access and query of the stored data. For the Smart Campus, the programming code was implemented with Python programming language. Additionally, the open-source database management system PostgreSQL (https://www.postgresql.org/) was used for the joint database. Each entry consists of an identification number of the corresponding sensor, a timestamp and the measurement value. Furthermore, the coordinated universal time (UTC) was used for the time and date to avoid problems with time shifts during summer and winter time for central European time.

The realisation of the middleware layer is based on the services of the Information Technology Services (IT-Center) of the University of Innsbruck. For example, the database used and the virtual machine running the programme code for the API and the web platform are hosted by the IT-Center. This has the main advantage that these system parts are within the firewall of the University of Innsbruck for data security. Additionally, there is a contract with an external IT company, which supports the team with necessary security updates.

Processing layer

This layer contains the data validation and quality assessment of the measured data (including gap filling methods) and afterwards, tools for data analysis as a basis for decision-making for different kinds of applications. Up to now, the focus has been the assessment of different sensor types and communication technologies for applications in the field of UWI. Therefore, two methods for data analysis and visualisation were implemented. The first option is via a website, which provides an overview of all measured environmental parameters including a visual representation of the time series. Non-sensitive data, in fact – everything except measurement data of the water distribution network, is freely available under https://umwelttechnik-swc.uibk.ac.at. Second, programming languages such as MATLAB® or Python are used for more advanced analysis. In this context, an example code for data analysis and visualisation of the temperature data written in Python can be downloaded via the website.

RESULTS AND DISCUSSION

Performance of applied communication technologies

For performance assessment, the indicator 'quality of service' is applied, which is determined as the ratio of successfully transmitted data packets and the total number of transmitted data packets on a weekly basis. Following, a quality of service of 100% corresponds to perfect data transmission without any packet losses, whereas a value of 0% refers to the situation when no data is transmitted. Figure 3 provides an overview of the quality of service of the used communication technologies. For the analysis, long-term data gaps caused by assignable malfunctions (e.g., sensor out of service) were manually removed to be able to compare the transmission losses.

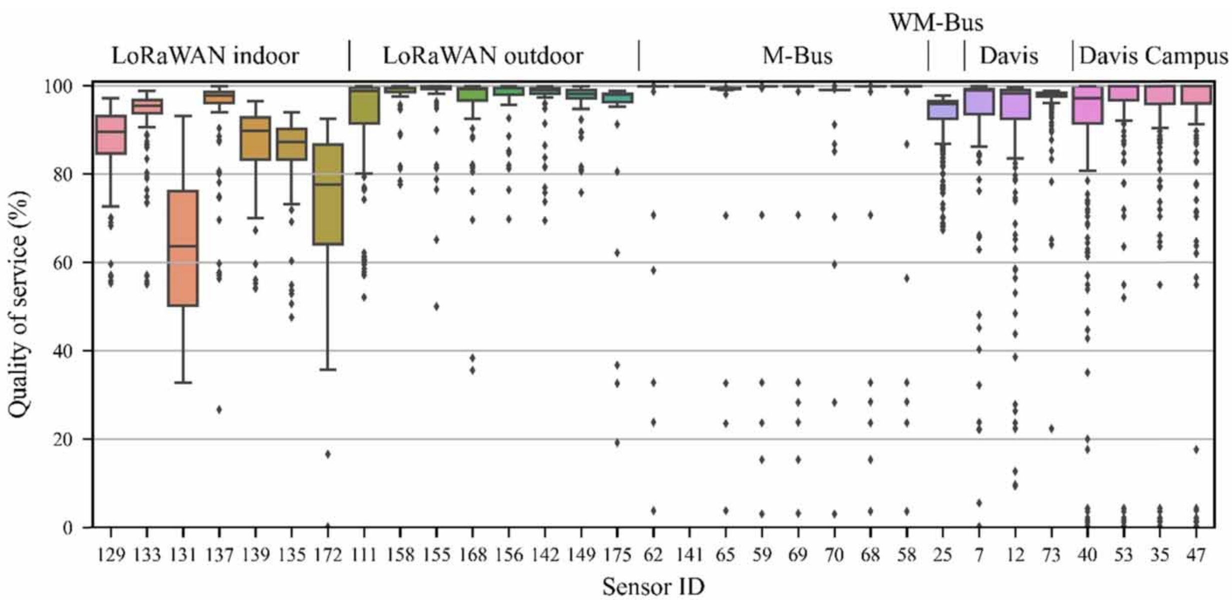

Figure 3 | Performance evaluation of applied communication technologies calculated by dividing successfully transmitted packets and the expected number of transmitted data packets on a weekly basis.

In western Austria, the water meters are usually installed in the basement. Additionally, M-Bus or WM-Bus are commonly applied as a European standard for the remote reading of water meters. First trials with WM-Bus at the Smart Campus showed that it was not possible to receive the WM-Bus signals outside the buildings (probably due to thick concrete walls and interferences from other devices also transmitting in the public frequency bandwidths), therefore the project team decided to use M-Bus. At the university, an underground collector corridor connects all the buildings at the Smart Campus, which simplified the installation of cables. Additionally, there is also a building management system already implemented and it was only necessary to connect the digital water meter with the building management system. However, the buildings are separated by fire compartments, which also meant more effort for permissions and installations. In contrast, WM-Bus is used for the single-family house equipped with a digital water meter as the received signal strength was sufficient due to a lower distance between the water meter and the data logger. As expected, M-Bus has the highest quality of service of the used communication technologies with almost 100% probability of transmission. In contrast, WM-Bus has a quality of service of approximately 93%, meaning that 7% of all packets are lost in the applied configuration.

For the weather station, two different systems at the single-family houses and the Smart Campus are used. The first system, the Vantage Vue® #6250, is more or less a stand-alone version requiring a wired connection to the internet. Afterwards, the data can be crawled from the manufacturer's website. Subsequently, this system is very well suited for application-oriented users. In contrast, the second system (including all the devices from Davis Instrument) at the Smart Campus is intended for integration into a larger system. Additionally, the data cannot be stored directly into the joint database, therefore requiring the combination of different systems (e.g., Windows MySQL database) as also shown in Figure 2. Furthermore, a transmitter was installed to improve signal strength and to reduce packet losses. Following, this system requires more programming efforts and is therefore may be less suitable for non-IT-savvy persons. Data communication works in both systems via proprietary communication technology, and the quality of service is 92 and 91% for the weather stations at the single-family houses and at the Smart Campus, respectively.

At the end of the first stage, a self-operated LoRaWAN network was set up including first trials of the signal strength at different installation places. In the second implementation phase, the operation LoRaWAN network continued without the assistance of a computer scientist. Following this, a cooperation with a local IoT solution provider, who offers LoRaWAN connectivity including gateway, network server and application server, was started. Therefore, newly installed measurement devices can be easily activated and can be crawled afterwards from a web platform. This solution requires much less effort and IT knowledge from the user side, as well as providing personal support. At the Smart Campus, LoRaWAN is used for multiple measurement devices installed in buildings, manholes and the outdoor area. As expected, there is a noticeable difference between outdoor and deep-indoor installation (e.g., basement) places regarding packet losses. Installation places with visual contact with the antenna have on average a quality of service of 95% which is reduced to 82% for installation places in cellars and manholes. As can be seen, especially deep-indoor installation places have a high variance. At the Smart Campus, the distance between devices and the antenna is between 50 and 300 m, whereas no direct correlation between distance and packet loss can be identified. For example, the façade material of the buildings is much more significant, as the sensor with the highest amount of packet losses (37%) is installed in a building with a combined metal and glass façade near the antenna. This is in accordance with the findings of Ragulis *et al.* (2017), who found that energy-saving glasses include thin metal coatings and can thereby significantly decrease signal strength.

Summarising, the quality of service depends on the ICT used and in case of wireless communication technologies, also on the installation place. An efficient ICT requires therefore coordination with the requirements of the intended application. For example, packet losses are in general low in wired communication networks, and therefore suitable for applications having a high requirement on timely and complete datasets (e.g., controlling network elements or peak-hour pricing). Especially wireless technologies operating in public frequency ranges (e.g., LoRaWAN) are subject to packet losses, whereas the quality of service depends on the used communication technology and installation conditions. Therefore, this should be considered before implementation and these technologies are more suitable for delay-tolerant and incomplete data sets (e.g., large-scale monitoring of environmental parameters). However, compared to wireless technologies, wired technologies require considerable effort for installation especially in already existing buildings. To tackle this challenge, Oberascher *et al.* (2022) provided a comprehensive review of smart applications and usable ICT in the field of network-based UWI, which can be used as a first decision-making tool.

Additionally, for wireless technologies there are also 'plug-and-play' sensors available, meaning that the measured data are nearly automatically transmitted to the manufacturer/provider's website and can be used from there. Subsequently, this supports water engineers, who neither want to spend much time nor have the knowledge to install and operate a communication network. Especially for LoRaWAN, there are already some operators on the open market offering connectivity for large-scale implementation of measurement devices. If using this service, the sphere of influence is greatly diminished as one is dependent on third-party services.

Involvement of urban population

As described in the introduction, smart cities combine different approaches to improve quality of life, whereas the integration of the urban population is an essential part of the development of new operating concepts. An example therefore is the smart rain barrel concept as a multi-actor partnership. For more information, refer to the next chapter. For the success of these measures, a sufficient participation of the urban population is essential. However, as described by Derkzen *et al.* (2017), especially the functions of NBS are partly unknown to the population. Therefore, a sufficient information about the functioning including future challenges is required in a first step, as the willingness to participate in such approaches increases if the people are aware of the future problems (Veronesi *et al.* 2014).

To overcome this limitation, innovative approaches were implemented at the Smart Campus with the aim of explaining the functioning of the implemented NBS to the urban population. Initially, it was planned to use the number of participants as an indicator to evaluate the effectiveness of the approaches. However, the global COVID-19 crisis and the corresponding measures (e.g., distance learning, no public events at the campus area) decreased public participation drastically. Therefore, the focus is on a qualitative description of the implemented approaches.

Information panel in combination with a website

At the Smart Campus an information panel has been set up, showing a cross-section through the adjacent NBS and explaining how it works (Figure 4). Additionally, a QR-Code was added to the information panel, which forwards interested persons to the website https://umwelttechnik-swc.uibk.ac.at/ui/about_en/green_infrastructure for further information. Besides NBS, the website also presents other elements of the urban water infrastructure including a short description of the functionality. On average, the website has about three to four visits per day (English and German version).

Figure 4 | Information board installed at a raingarden with a QR-Code to the website for more information.

Scavenger hunt

Additionally, many elements of the UWI are underground and therefore not 'visible' to the population. To address this issue, a scavenger hunt under pedagogical guidance was planned and organised for a university event in spring 2019 to particularly address children and families. In the scavenger hunt, different elements of the UWI were integrated including an explanation of the function to further raise awareness about the 'hidden' UWI. The hints included (1) general (e.g., functioning and structure) and detailed (e.g., water consumption and amount of rainfall in Austria) information about the UWI, (2) a task including exercises (e.g., 'Follow the path of the rainwater to the infiltration system') and experiments (e.g., 'cleaning of muddy water in layered soils'), and (3) selection of possible solutions, whereby the right solution leads to another element of the UWI. As an example, Figure 5(a) shows the answer options for the above-mentioned experiment and the correct answer leads afterwards to a hydrant used for fire-fighting water with the next hint. The scavenger hunt lasted about 30 minutes and about 45 families participated during the half-day. The treasure (diamonds and golden chocolate coins) was hidden in a treasure chest with a combination lock (Figure 5(b)), which was a particular attraction for (younger) children and motivated them to participate.

Implementation of innovative applications

Through high-resolution data, the system conditions in water distribution, and in wastewater and drainage infrastructure are known in real time. Consequently, the Smart Campus represents an ideal test bed for innovative technical applications in the field of UWI. Following this, some interesting analyses and exemplary applications are presented.

Temporal progression of surface temperature in urban environments

Urban growth causes an increase in impervious surfaces, thereby affecting the local microclimate. Especially, impervious and dark surfaces have higher temperatures due to reduced evaporation and higher absorption of solar radiation, which can lead to urban heat island effects in cities (Deilami *et al.* 2018). Subsequently, nature-based solutions (NBS) are frequently used as a countermeasure, as NBS have positive effects on urban microclimate through increasing shading, evapotranspiration, and water storage (Norton *et al.* 2015).

In this context, Figure 6 illustrates surface and air temperatures for different installation locations during a hot period in September 2020, extended by solar radiation and precipitation data. As can be seen, there is a clear correlation between solar radiation and measured temperature, resulting in a clear distinction between day and night hours. Furthermore, cloudy (07.09.) and sunny days (08–10.09) can be distinguished as well. As expected, impermeable surfaces have a higher maximum temperature than green areas, e.g., the maximum temperature of bitumen roofs, stone paving, and areas under trees are 70, 36, and 26 °C, respectively, during the observation period. Interestingly, minimum temperature during the night hours is partly the opposite and bitumen roofs have a lower temperature than green areas (e.g., 8 °C compared to 12 °C). Consequently, impermeable surfaces have a higher difference between day and night hours (e.g., up to 60 °C), whereas variations are much lower for green areas (e.g., up to 15 °C).

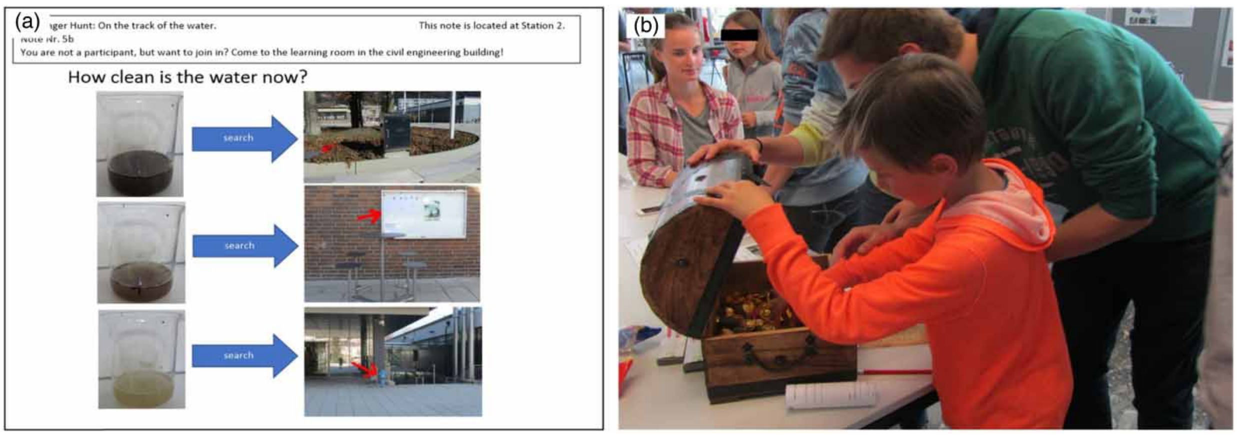

Figure 5 | Scavenger hunt with (a) answer options for the experiment 'cleaning of muddy water in layered soils' and (b) treasure chest as a particular attraction.

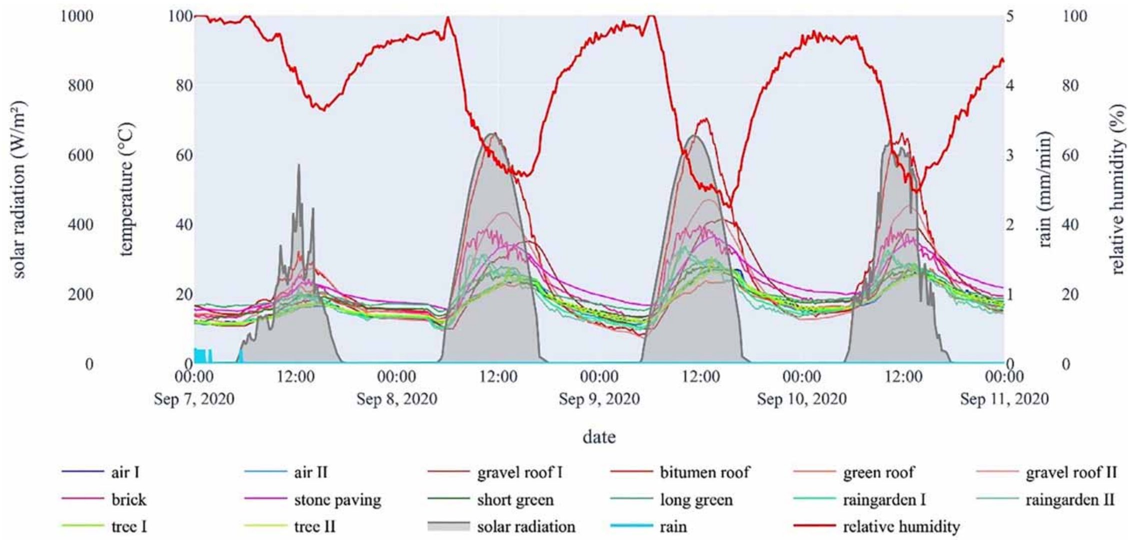

Figure 6 | Temperature for different surface areas and installation places during a sunny period in autumn 2020.

Summarised, the exemplary comparison between different surface types showed very well the potential for green infrastructure to improve the ambient temperature in urban areas. However, functioning irrigation during dry periods will be essential for the management of NBS. Using drinking water for irrigation will increase the pressure on the water supply system and there is a risk of resource conflict with other urban water users (e.g., domestic and commercial water demand) (Norton *et al.* 2015). Subsequently, a sufficient irrigation will be a limiting factor for NBS and may require the combination with innovative stormwater management approaches (e.g., the SRB concept).

Smart rain barrel (SRB)

The SRB is an IoT-based microstorage for advanced rainwater harvesting and the main parts of the SRB are shown in Figure 7. The SRB consists of a conventional rain barrel, extended by a filling level sensor to measure the actual filling depth and a remotely controllable discharge valve to release stormwater before precipitation events. Measurement data and control commands are transmitted via the low-power wide area network LoRaWAN (Oberascher *et al.* 2021). At the Smart Campus, a prototype is under operation during the summer months from April to September. The SRB installed has a catchment area of approximately. 80 m^2, and the roof runoff is drained to an infiltration trench afterwards.

The control strategy consists of two parts. First, high-resolution weather forecasts provided by the Austrian National Weather Service are used to analyse the future weather development. The weather forecasts extracted from the integrated

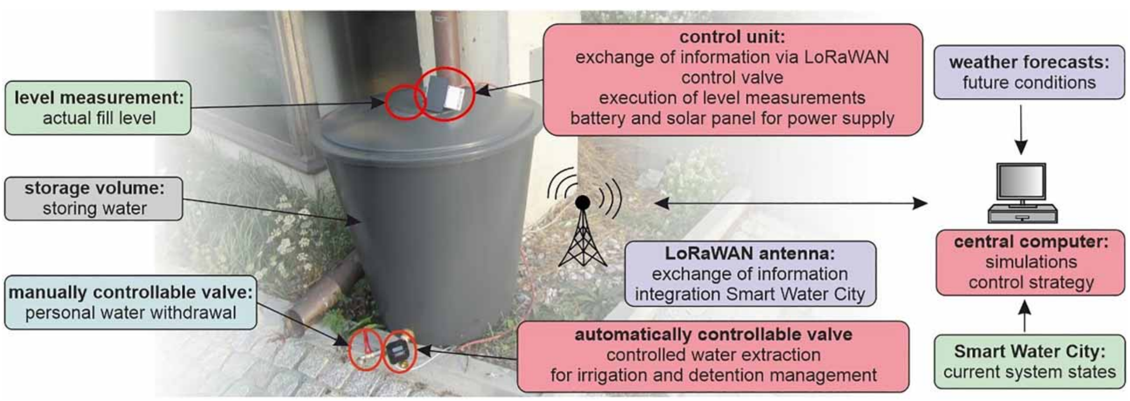

Figure 7 | Prototype of the smart rain barrel (SRB) with key elements. This figure is reproduced with small alterations from Oberascher *et al.* (2021) under an Attribution 4.0 International license (CC BY 4.0).

nowcasting through comprehensive analysis (INCA) system are received every 30 min for the next 24 h in 15 min steps. If the estimated rainfall volume exceeds the available storage volume, and the following control commands can be transmitted via LoRaWAN to the SRB: (1) the required filling depth to fully capture the predicted precipitation amount, or (2) time of minutes to close the discharge valve before the predicted peak intensity. Second, a soil moisture sensor is installed near the SRB, which can be used to determine and monitor the irrigation requirements (e.g., the start of irrigation process, increase soil moisture) during dry weather. Therefore, the SRB concept (maybe in combination with bigger storage volumes) can be used as a smart application to address the challenges associated with NBS in terms of irrigation. Furthermore, the SRB concept is intended for a multi-actor partnership between the network operator (e.g., bears the costs and is thereby allowed to empty the rain barrel in case of forecasted rain events) and the property owner (is responsible for the maintenance and can use the rainwater during dry weather periods).

Drinking water temperature during exit restrictions

The evaluation in Figure 8 shows the drinking water temperature during the COVID-19 exit restrictions in spring 2020. The combination of low withdrawal quantities and an unfavourable pipe installation in a boiler room resulted in drinking water temperatures between 26 and 30 °C. According to valid standards, e.g., ÖNORM EN 806-2 (2005), cold water temperature should not exceed 25 °C 30 s full opening of taps, as hot water favours the formation of germs, e.g., legionella bacteria. In this context, smart systems also represent a possible measure to tackle this issue. For example, smart devices (e.g., smart toilet flushes, smart faucets, smart irrigation for NBS) can be automatically opened to release drinking water in case of high drinking water temperatures. Subsequently, this increases the drinking water quality by reducing residence time in the pipes.

Water loss management

Water losses in water distribution networks cause a major challenge for a smooth operation, being on average between 16 and 30% in Europe (EurEau 2017). As a measure, online monitoring can help to detect leakages in real-time reducing the amount of water losses. In this context, Figure 9 shows a documented real pipe burst in the water distribution network at the Smart Campus. Therefore, the difference between measured inflow and consumption can be an indication of possible leaks in the network. As not all buildings are equipped with a water meter, there is always a difference between inflow and consumption noticeable. However, a sudden increase in both inflow and difference quantity can be seen very clearly on 03.03.2020. Normally, such an incident can only be discovered after the occurrence of local damage (e.g., undermining of streets) or increased water quantities for billing. Additionally, water pressure sensors installed at the campus showed a significant reduction in water pressure during the pipe burst. The pipe burst was finally repaired 3 days later by installing a temporary bypass pipe. The total water loss in this case was estimated to be approximately 1.000 m^3, whereas no further damage was caused, e.g., by penetration of water into surrounding buildings.

Further discussion

Applying the IoT concept means a change from a few measurement points to a large-scale implementation of measurement devices distributed over the area. This development is mainly forwarded by using low-cost sensors in combination with wireless communication technologies operating in public frequency ranges. Subsequently, sources of errors increase and can

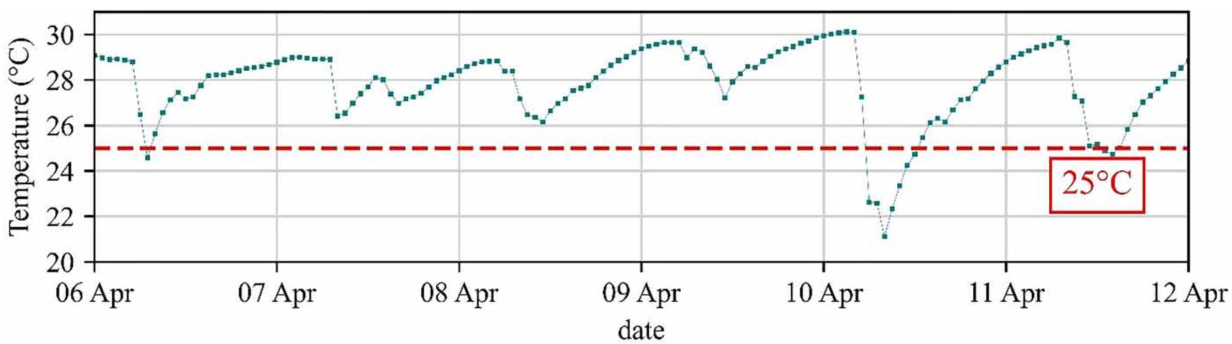

Figure 8 | Drinking water temperature during the exit restrictions in spring 2020.

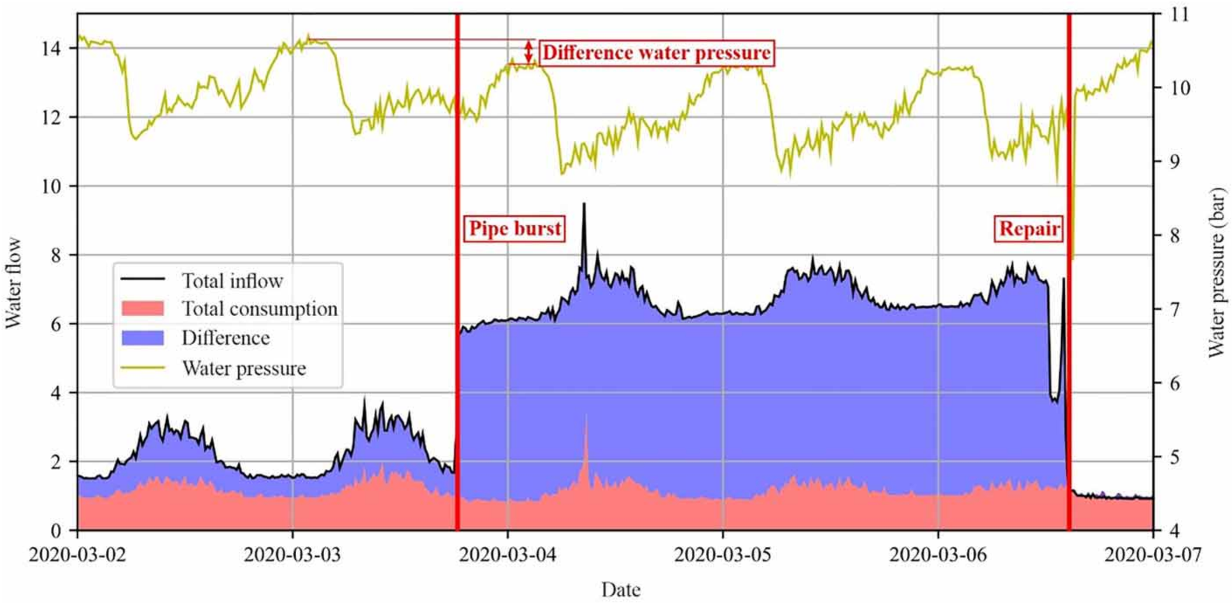

Figure 9 | Water leakage in the water distribution network at the Smart Campus.

include data uncertainty and data errors due to a lower measurement accuracy (quality of sensor design) or data gaps because of packet losses (quality of service). However, these data are afterwards used as the basis for decision-making and real-time control. Therefore, the importance of data validation and quality assessments is increasing and requires appropriate methods and tools for the fast processing of big data, e.g., by using artificial intelligence to tackle this challenge.

Up to now, a high-resolution measurement network has been established at the Smart Campus, requiring investment costs of material and personnel for the installation, operation and maintenance of the installed measurement devices. Considering only material, the investment costs for the Smart Campus are around €30.000 (excluded SRB). Additionally, battery-powered measurement devices are used for all wireless communication technologies, thereby further increasing the ecological impact. Subsequently, appropriate applications are required to achieve economic and ecological sustainability as one of the main pillars of smart cities. During this work, some exemplary applications for digital approaches are presented and their influences on the performance of UWI are discussed. However, detailed life-cycle analyses have not been performed to determine the ecological and economic impact of these technologies which would be required to answer the question 'are smart technologies in the context of UWI sustainable?'. Therefore, this topic should be addressed by future research. With reference to the Smart Campus, the added value represents a clear increase in knowledge in the development and implementation of smart systems, which can be used as the basis for future research projects in the field and as a showroom for practical implementations.'

Summary of the key lessons learned

Based on the experiences during the development of the 'Smart Campus', the following is a summary of the key learning lessons:

- The implementation of a measurement network requires a trade-off between installation expenses, maintenance efforts and quality of service. For example, cabled communication technologies (e.g., M-Bus) provide high reliability, but may imply challenges for installation in existing buildings. In contrast, wireless communication technologies are easy to install, while an operation in public frequency ranges (e.g., LoRaWAN, Wireless M-Bus) always includes packet losses.
- Additionally, real-world implementation of wireless communication technologies may differ from the perfect performance. For example, sources of interfaces can be structural (e.g., energy-saving glasses, concrete walls) or operational (e.g., other devices using the same frequency), which may reduce the signal quality significantly. Therefore, it is recommended to perform initial tests before installing wireless communication technologies on a large scale.

- Furthermore, the implementation requires detailed knowledge about information technologies (IT) (e.g., sensor development, communication technologies, databases, data security) and many working hours to realise a monitoring and controlling network, especially when combining different technologies.
- Therefore, if the focus of the project is on using the data (e.g., application-related), or the project members either do not want to spend much time nor have detailed knowledge about these issues, it is recommended to buy as many services as possible (e.g., measurement devices, connectivity, data security). Of course, these services are more expensive and also depend on third parties.
- However, the transformation of applications from purely technical approaches to an integration of a wide range of participants also implies new requirements for the project team and the realisation. For example, the importance of content communication increases to integrate different participants into the project, which is not necessarily a technician's strength. Therefore, an interdisciplinary approach should be pursued, e.g., by including social and educational scientists.

CONCLUSION

In this work, the Campus Technik of the University of Innsbruck (further called Smart Campus) is presented as an innovative testbed for smart and data-driven applications in the field of network-based urban water infrastructure (UWI). Therefore, the campus area has been comprehensively equipped with a variety of low-cost sensors for qualitative and quantitative measurements and a multitude of different environmental parameters (e.g., soil moisture, water level, surface temperature, water pressure, water consumption, climate data, …) are measured and transmitted mostly in high resolution in intervals of 1–15 min. By using this high-resolution data, system conditions in water distribution, in wastewater and drainage infrastructure are known in real time and exemplary applications and analyses are presented afterwards. For example, the data is used for fault detection in real time (e.g., leakages, increased drinking water temperature due to stagnation) or for innovative applications (e.g., smart rainwater harvesting in combination with green infrastructure to mitigate urban heat islands). Additionally, innovative approaches are implemented to inform the urban population about the functioning of the UWI with the focus on nature-based solutions.

Based on the obtained results, the following conclusions can be made:

- Smart applications enable new possibilities in operation and for fault detection in real time, but also implies new challenges for the project team. For example, the implementation of the monitoring and controlling network requires – up to now – sufficient IT knowledge, or the integration of different participants requires sufficient content communication.
- The following questions are relevant for the implementation of a monitoring and control network and should be carefully addressed before the project start: (1) 'Which applications are likely to be implemented?', (2) 'Which communication technology meets the requirements?', (3) 'Do the selected communication technologies work properly under the local installation conditions?', and (4) 'How should it be implemented (e.g., project team or third-parties)?'. In this context, refer to Oberascher *et al.* (2022), who presented a comprehensive analysis of data requirements and features of communication technologies to support efficient monitoring and controlling networks in the field of UWI.
- Furthermore, the installation and operation of a monitoring network result in both investment costs and the usage of mainly battery-powered measurement devices also increases the ecological impact. Therefore, appropriate applications and detailed life-cycle analysis are required to achieve the economic and ecological sustainability of digital approaches.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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