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Can we scale Digital Twins of Nature-based Solutions for stormwater and transboundary water security projects?

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ABSTRACT

Nature-based Solutions (NbS) are presented as an alternative and decentralized solutions with different application scales for problems addressed to urban expansion as water quality reduction and floods. The usage of control strategies and mathematical modeling techniques has shown promising results for optimizing hydraulic and water treatment processes. The Digital Twins (DT) as process integration technology are widely used in industry, and recently these technique usages in urban water systems are showing effective results in both management and planning. However, there is a lack of proper literature definition for DT applied to NbS, especially for stormwater and transboundary water security projects. Thus, this paper sought through a literature review to access the existing conceptual challenges and the DT definition as a framework, identify how the mathematical modeling reported in the literature can improve the DT development, and evaluate the potential benefits associated with the application of DT in NbS.

Key words: digital approaches, Digital Twin framework, technological Nature-based Solutions

HIGHLIGHTS

- This review accessed Digital Twin (DT) applications to water-related structures and developed a technical framework to combine Nature-based Solutions (NbS) and DT techniques.
- The NbS DT development was divided into five different entities, which can be individually expanded and mutually connected.
- The technical aspects of each entity were accessed with the specifications to attend NbS techniques.

INTRODUCTION

Cities are becoming smart not only in terms of automating routine functions serving individual purposes, but also that it is possible to monitor, understand, analyze, plan and improve efficiency, equity and quality of life for the population, and in real time (Batty *et al.* 2012). Regarding urban drainage, technological solutions such as the Internet of Things (IoT), Big Data and Artificial Intelligence (AI) tend to improve the monitoring and control of drainage structures, being considered as alternatives to reduce the impacts caused by urbanization, as well as to mitigate the impacts of hydrological extremes caused by climate change (Giordano *et al.* 2014; Keung *et al.* 2019). In this way, the application of Nature-based Solutions (NbS) as alternative solutions in urban drainage for these same impacts has been growing (Kabisch *et al.* 2017; Oral *et al.* 2020).

NbS are defined as living solutions in which processes and structures are designed to meet different environmental factors while providing economic, social and ecological benefits (van den Bosch & Ode Sang 2017; Frantzeskaki 2019). Sustainable solutions for urban drainage such as bioretention, green roof, detention basin, wetland, and infiltration trench are widely

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known in the literature with different names, depending on the region (Fletcher *et al.* 2015). However, these sustainable solutions can be incorporated by NbS applied to urban drainage, since, according to the Adaptation Gap Report of the United Nations (UN) (Neufeldt *et al.* 2020), NbS are not only limited to structural actions, but also to adaptations that seek to revitalize and improve ecosystem services to manage risks and impacts on populations. In this way, NbS can be considered in broader contexts for sustainable urban drainage solutions.

Despite the different application scales, these devices work similarly through natural processes such as infiltration, biological activity and assimilation by plants. Thus, the water retention time is increased to reduce runoff in addition to promoting water treatment, thus improving the output quality (Dagenais *et al.* 2017; Mcclymont *et al.* 2020; Oliveira *et al.* 2021). However, despite the varied designs, these systems are currently designed to function passively, i.e., the system does not adapt to the inflow, outflow and water storage settings during an event to optimize hydraulic performance and to improve the treatment processes of water (Persaud *et al.* 2019).

The combination of NbS with technological solutions (e.g., real-time control) shows promising results where data obtained through real-time monitoring are used to optimize the water flow and treatment processes (Brasil *et al.* 2021). However, monitoring multiple devices can be complex and costly in systems without automatic data transmission, especially when monitoring water quality due to the necessary laboratory analysis (Glasgow *et al.* 2004). Thus, the use of collected data to calibrate mathematical models of NbS systems grows as these models evolve and can represent the physical and removal processes well (Tang *et al.* 2021).

Aiming at the integration between monitoring and data transmission, representation of the physical structures through mathematical modeling and techniques management, several areas related to urban water and sewage treatment systems developed a concept known as Digital Twins (DTs) imported from industrial manufactured products (Pedersen *et al.* 2021). DTs are digital representations of physical processes, in which the system is modeled with high fidelity to obtain responses to an event to control the performance of the variables involved (Tao *et al.* 2019; Sun *et al.* 2020). DTs were originally developed with the purpose of increasing the life cycle of products by exploring the functioning through information transmitted during the phases of use (Grives & Vickers 2016). But for stormwater and transboundary water security projects, where scales of governance are under complex interactions, DT applications in NbS are still incipient to enhance climate resilience of critical infrastructure (Brasil *et al.* 2021; Argyroudis *et al.* 2022; Kim & Choi 2022).

Therefore, this article aims, through a literature review, to develop a technical framework for future DT applications in NbS. Also, this article focuses on the conceptual development of the framework since there is a lack of seminal literature on practical application using the integration of NbS and DT to the best of our knowledge. To this end, the concepts of DT were reviewed through the literature and its evolution in different areas, as well as the proposition of new specific terms for DT applied in NbS. It was also identified how DT entities can operate in NbS structures. Finally, the potential benefits of these applications at each stage were discussed based on the literature on DT and NbS.

DT HISTORY AND DEFINITIONS OF WATER-RELATED STRUCTURES

The first definition of DT was devised by the National Aeronautics and Space Administration (NASA) with the purpose of integrating multi-physics, multi-scale and probabilistic simulations of vehicles or systems using the best available physical models (Glaessgen & Stargel 2012; Negri *et al.* 2017). However, this definition was limited to development and research in the aerospace industry to simulate the effects of different aspects of the developed vehicles. Over time, the DT term began to be used by the industry for the purpose of managing the life cycle of products. This concept, initially proposed by Grieves & Vickers (2016), aimed to define the necessary structures to achieve the DT benefits, namely the physical object, the digital object and the connection between the two parts. According to the authors, the connections must flow from the physical object to the digital, or vice versa, interconnected by a unified repository between the parts.

Then, several important works were developed with a focus on Industry 4.0, IoT and the use of DT as an interface for these technologies (Tao *et al.* 2019). Gabor *et al.* (2016) sought to develop a system architecture with the simulation purpose in a physical–digital space, proposing an interface structure with the purpose of developing scenarios at different scales of time and space. Autiosalo *et al.* (2020) stated that DTs must have several resources between the axes of physical–digital objects, such as data management, statistical analysis, transmission structures and their respective connections, with simulation being one of several resources of digital objects. Thus, the concept and definition of DT is still in a constant process of evolution, not having a literature consensus (Wanasinghe *et al.* 2020).

As more studies were developed, DTs were used in areas focused not only on manufacturing products in industry, but also for optimizing production, equipment and machine layouts (Tao *et al.* 2017). Outside the scope of industry, DTs were also developed for different areas, such as healthcare, meteorology, education, energy sector and city planning (Mohammadi & Taylor 2018; Tao *et al.* 2018; Rasheed *et al.* 2019). Specifically, for urban water systems and sewage treatment systems, DT is a new concept (Pedersen *et al.* 2021). Fuertes *et al.* (2020) built a DT for a water distribution system through the integration of a Big Data platform containing several data sources, such as remote sensing, field installed sensors, remote operation through Supervisory Control and Data Acquisition (SCADA) and a computerized maintenance management system, coupled with hydraulic models and statistical data analysis models. As a result, the authors obtained a development framework for DT applied to water distribution systems capable of optimizing processes, in order to collect data from various sources, allowing real-time communication with the system's hydraulic model, in addition to predicting future scenarios.

Curl *et al.* (2019) referred to DT as the next-generation water treatment technology, exemplifying at a water treatment plant in the city of San Diego. Still in the implementation phase, the DT was able to simulate the controls and schemes of the water and sewage treatment plant, optimize operations through dynamic models and make it possible to forecast the system states, in addition to offering an interface between operators and the physical process. In a report on digital water, the International Water Association (IWA) points to DTs as transformative digital solutions, being important for the visualization and monitoring of system conditions, as well as for predicting realistic scenarios (Sarni *et al.* 2019).

Specifically for urban water systems, Pedersen *et al.* (2021) developed DT definitions for complex systems with frequent changes characteristic of these structures. The authors then propose the term 'living DT' specifically for this context, as urban water systems tend to be dimensioned for long periods and undergo constant spatial and temporal changes in their infrastructure due to the connection with urban transformations. According to the authors, the simulation processes currently applied form a kind of disconnected puzzle, where the applied models are disconnected from the observations, which, in turn, are disconnected from the analyses that differ from the physical processes. With this, this separation provokes the individual correction of each part of the structure, not seeking integration aimed at simulation, as in the case of a living DT.

Other important elements of urban drainage are related to the management and design of networks. Thus, a second category of DT is needed to encapsulate urban water systems, called 'prototype DT'. A prototype DT, according to Grieves & Vickers (2017), can be used to optimize the design and construction process, since, due to the high cost of these operations, it is not possible to perform physical experiments at the application scale before construction without having a DT of that element. Thus, DT prototypes are predictive but not interrogative.

TECHNICAL FRAMEWORK OF DT APPLIED TO NBS

There is no specific conceptualization for the use of DT in NbS applied to urban drainage. So, to develop a technical framework, the DT may follow the particularities of the definitions proposed by Pedersen *et al.* (2021), having a specific DT for simulations (living DT) and a DT focused on size and design (prototype DT). However, unlike urban drainage, NbS depend on natural processes involving the soil and vegetation used, as well as the processes of clogging and biological activity of water treatment (Le Coustumer *et al.* 2012; Persaud *et al.* 2019). A generalized example of the design of an NbS can be seen in Figure 1, and Examples of how the digital twin framework should be developed can be found in the Supplementary Material. Therefore, both DT instances must be connected to evaluate these processes in both working simulations and design simulations.

In this context, NbS are subsystems that complement the traditional urban drainage, as they are techniques applied in a decentralized manner. Furthermore, the same system can contain different techniques applied at different scales, such as green roofs, bioretention cells and detention basins. To obtain credible results, these techniques must be inserted and analyzed together with the urban drainage, forming an extremely complex system (Shishegar *et al.* 2021). Therefore, similarly to what happens in industrial processes, working with a DT hierarchy, where the urban drainage DT contains and relates to other NbS DTs, can reduce the complexity of the system from monitoring, simulation and management.

Despite the various conceptual models and frameworks developed to define the architecture of a DT, there is still no consensus related to the application (Liu *et al.* 2021). Related to DT applied to urban systems, Autiosalo *et al.* (2020) and Pedersen *et al.* (2021) developed a star-shaped framework, where data from the center of the application are connected to other attributes. Tao *et al.* (2019) developed a framework consisting of five different dimensions: the physical entity, the digital entity, the data entity, the service entity, and the connections between the dimensions. To define the DT framework

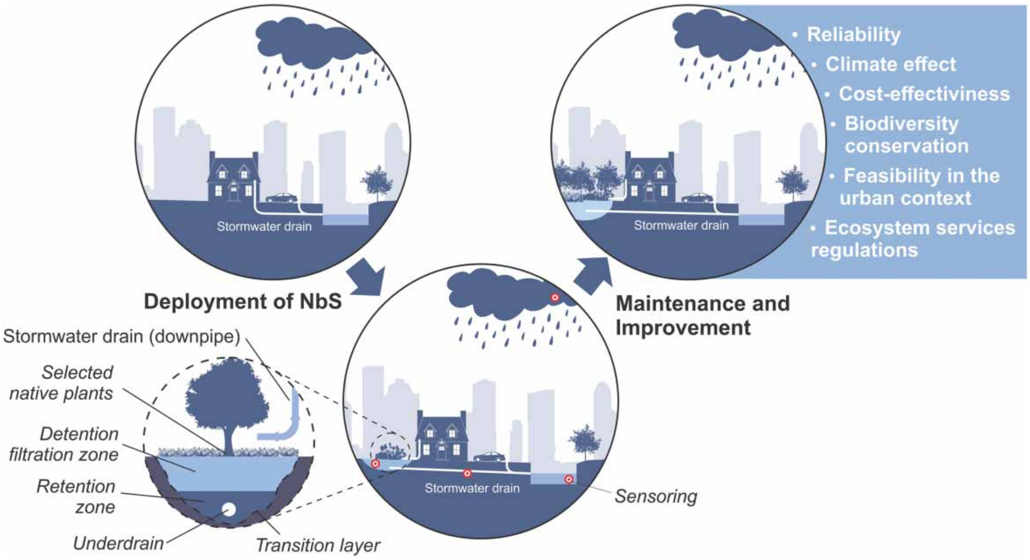

Figure 1 | Examples of deployment, sensing and monitoring, maintenance, and operation of Natural-based Solutions (NbS) for stormwater through DT.

applied in NbS, the five dimensions will be adapted to the star shape defined for urban environments. The dimensions proposed for the framework can be seen in Figure 2.

Physical entity

The physical entity is composed by the NbS applied to urban drainage and the sensors used by it to monitor these structures. The first step in developing the physical entity is to decide which types of data to collect (Tao & Qi 2019). As NbS have several techniques with different scales and operating principles, the variables must be analyzed for individual cases; however, some parameters related to the flow must be monitored regardless of the technique, namely the inflow and the outflow in the device, the water internal level and the precipitation. Other meteorological variables that can directly or indirectly influence

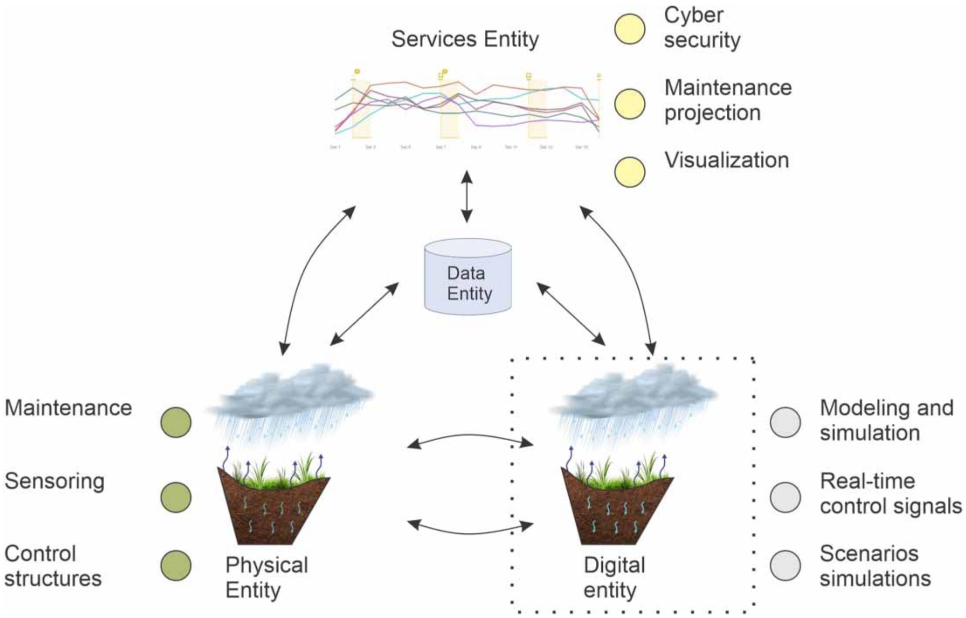

Figure 2 | Technical framework for DT applied to NbS. The entities are representations of the subsystems within the DT applied to the NbS for the developed framework. The connections entity is represented by the arrows that indicate the flow of data between the other entities.

the devices are solar radiation, wind speed, soil moisture, variation in water infiltration over time, plant wilting point, among others (Le Coustumer *et al.* 2012; Salazar *et al.* 2018; Persaud *et al.* 2019), although the time scale of influence of these aforementioned variables (i.e. daily, hourly) is usually less refined compared to flows and level measurements (i.e. sub-hourly).

Another determining factor is the optimal number of sensors to be distributed across the structures. Few sensors can make predictions inaccurate, while too many sensors can make monitoring economically unfeasible and overload storage systems with unnecessary details (Tao & Qi 2019). In addition, for essential variables, it is important to have sensors with redundancy, since, in case of failure, there will be no serious damage to the collected data.

In addition, the DT applied to NbS, unlike other structures, there is a need to monitor water quality, since one of the main benefits of applying NbS is the improvement of urban water quality through natural processes (Fletcher *et al.* 2015). Although there is a continuous evolution in water quality monitoring techniques using sensors, these tend to be expensive and have a shorter service life when compared to sensors that monitor water quantity data (Glasgow *et al.* 2004). A widely used alternative to monitor the water quality of NbS is to carry out laboratory tests during a period, where through the collection of this data, models can be calibrated and validated (in the case of DT, the digital entity), so, sporadically, new tests are carried out to know if there was any change in the modeled results. This approach, despite not working in real time, as needed for a traditional DT, can enable qualitative monitoring of these devices.

An advantage of NbS' physical entities compared to other DT structures is that these techniques are embedded in the urban environment. For this reason, it is possible to explore the possibilities of citizen science either by monitoring through social perception or through awareness of the use of these techniques for educational purposes (Restemeyer & Boogaard 2021). Furthermore, in conjunction with the digital entity, the use of data related to the physical entity can be obtained through Kalman filters to improve the use of real-time and catchment area models (Estrada 2018).

Finally, it is in the physical entity that the maintenance of structures takes place. As NbS use several natural processes in their operation, some factors must be observed from the standpoint of preventive maintenance. The clogging effect, for example, can reduce the device's infiltration and storage capacity, causing a decrease in performance (Le Coustumer *et al.* 2012). Thus, the communication between the services entity and the physical entity must occur to detect the change of these variables and determine the optimal period for maintenance. Another essential factor for NbS is the health of plants, as they are responsible for part of the water treatment in the devices (Angle *et al.* 2003; Wolf & Lundholm 2008). Therefore, it should be ensured a minimal water level at the NbS in dry periods. Additionally, the maintenance should be planned in consonance with the service entity by checking the conditions of the plants based on the forecasted dry period and, if necessary, carrying out an on-site intervention. It is also necessary to guarantee the valves' integrity, as they are responsible for retaining or releasing water from the devices based on the simulations performed by the digital entity, and, in case of failure, they can generate unexpected flow downstream of the devices.

Digital entity

Due to the high availability of works that use mathematical modeling and simulation of scenarios about NbS (and urban drainage), it is necessary to differentiate these applications from the development of a DT. Wright & Davidson (2020) sought, through the definitions of DT, to point out the main differences between the models. They found that DT mainly needs the following: (i) an object model; (ii) an expansive set of data (i.e., a set that evolves over time) related to the object and (iii) a means of updating and adjusting the model according to the data. A fundamental aspect about the parts listed is that the DT needs to be associated with an object that exists; otherwise, a DT without a Physical Twin is considered as a model. Another important factor is that the dataset is critical to accurately describe the object's change over time, updating and adjusting the model to current system conditions.

However, the differences mentioned above are related to the manufacture of industrial products. For the specific areas of hydrology and hydraulics, there are models and frameworks in which they incorporate all the factors mentioned above to be considered as DT, e.g., monitoring of dams (Oliveira & Alegre 2020) and monitoring of hydrological disasters (Al-Sabhan *et al.* 2003). These models incorporate several functionalities, in addition to simulation, as in the DT; however, there is no uniformity between the developments because of the lack of encapsulation of these technologies. Therefore, defining DT for these systems is important to classify already-used models that comply with the criteria, in addition to stimulating the development of new models with the encapsulation of technologies promoted by the DT.

Some authors point out that the DT should have a specific focus on models and simulations, while others seek a more integrative approach across all DT axes (Weyer *et al.* 2016; Qi & Tao 2018; Tao *et al.* 2019). However, in either approach, mathematical models are fundamental to simulate the physical system. Physically based models consist of observing one or more physical phenomena of interest and developing fundamental mathematical equations, simplified or not, to represent the behavior of this phenomenon (Beven 1989). For the development and validation of these models, it is important to follow an experimental stage, where the physical behavior of the problem is verified through laboratory or field tests, and the solution is solved using an analytical or numerical method (Perlade *et al.* 2003). On the other hand, well-developed DTs tend to have a large amount of data, so the use of data-driven models is also possible assuming that the data manifests the physical behavior of the system (Rasheed *et al.* 2020). In this process, tools that use AI, such as machine learning and artificial neural networks, can benefit the techniques by predicting the system's behavior against events, anticipating the action.

For the digital entity development, it is necessary to model the flow and quality of the water entering the NbS from the drainage, the infiltration and water treatment processes within the NbS, in addition to representing the eventual outflow back to the drainage. For this framework, the main models will be evaluated considering two different approaches that must work in integration with the other dimensions. The first approach concerns the modeling of drainage in conjunction with NbS, that is, models that transform rainfall into surface runoff up to the entrance of NbS. However, some techniques such as green roofs do not require this procedure, as entry only occurs through precipitation under the roof. The second approach is related to the modeling of the isolated NbS of the drainage system. This approach is a simplification of the idea that only a part of the system is more suitable for distributed applications of several NbS.

Urban drainage system modeling coupled with NbS

Urban drainage systems have specific characteristics, such as large-scale architectures, nonlinear dynamics, hybrid dynamics, water storage and disturbances, in addition to constant changes and adaptations. García *et al.* (2015) opine that models can be classified depending on how detailed they are. For NbS techniques integrated with urban drainage, the level of integration necessary for the development of the DT must be considered. In this way, it is crucial to define the spatial scale that the technique is in, i.e., techniques with smaller spatial scales and more distributed in the catchment can work with DT applications in each device and then unified with urban drainage (e.g., bioretention). As for techniques with a larger spatial scale (e.g., detention basins), it is important to develop an integrated DT for the entire system, that is, the DT directly integrates urban drainage with the larger-scale NbS.

For systems integrated with urban drainage, information is needed about the catchment contributing to both pollution and runoff, the drainage network pipes, flow protections, and an understanding of the system. Thus, Bach *et al.* (2014) reviewed the main modeling techniques for integrated urban drainage models. The application of integrated models, despite being more complex, brings multiple benefits such as the possibility of controlling the system in real time, the reduction of combined sewage overflow (CSO), the accuracy of modeled data and the use of forecasting to prepare different scenarios (Bertrand-Krajewski *et al.* 1997; Schindler *et al.* 2010). For the implementation of combined modeling of the drainage system with NbS, the Storm Water Management Model (SWMM) is a model that stands out for its versatility, as it is a free software where it is possible to model urban drainage in an integrated manner with NbS, and has an alternative commercial software based on the SWMM that helps in the NbS modeling process (e.g., PCSWMM) (Elliott & Trowsdale 2007; Bach *et al.* 2014). Another model that stands out for DT applied to NbS is the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), because it is a model widely applied in the literature with free and open access and uses equations that seek to simulate the physical behavior of the system, such as Green-Ampt for infiltration and mass balance for hydraulic performance. Although it was not built specifically for NbS, there are several additional features developed by researchers to also associate a water quality module with nutrients (Khaniya *et al.* 2017).

Nbs modeling

There are several specific models for each NbS technique applied to urban drainage. Models related to bioretention systems (Brown *et al.* 2013; Randelovic *et al.* 2016; Shen *et al.* 2018; Gülbaz 2019), green roofs (Sailor 2008; She & Pang 2010; Vesuviano & Stovin 2013), permeable pavements (Kuang *et al.* 2011; Lee *et al.* 2015; Liu *et al.* 2020), detention basins (Oxley & Mays 2014; Liu *et al.* 2015; Bellu *et al.* 2016) and wetlands (Meyer *et al.* 2015). Despite the various models reported in the literature for each specific technique, for application in the DT, it is necessary to observe some specific characteristics about the scope of the model. For the development of a DT, a model should be physically based, it must have a temporal and spatial resolution suitable for application in DT, the simulation result should be applicable for other entities, it must run continuous simulations, and, for the specific case of NbS, it must model the water quality as well (Grieves & Vickers 2017; Bao *et al.*

2019; Nika *et al.* 2020; Rasheed *et al.* 2020). These features can be supplemented by more than one model running in parallel; however, the input and output flow of data must be coordinated to avoid compatibility issues between models.

To achieve the necessary robustness for the development of DT applied to NbS, it is necessary to develop new modeling techniques focused on the DT or improve the existing models. For this improvement to be possible, the use of models with an open repository is essential, as it allows different collaborators with different needs to share and develop new features for existing and tested models (Datta 2017).

Another important feature in DT models is the use of real-time control in NbS applications. Brasil *et al.* (2021) reviewed the literature on real-time control of NbS structures. The authors concluded that despite this application being of the recent origin, it was possible to obtain superior performance compared to the same devices running without real-time control. Even so, as it is a recent area in the study of NbS, few models can control the input and output structures of devices. Furthermore, real-time control algorithms can be used in NbS with the purpose of optimizing the operation of the devices to obtain good water treatment performances without loss of hydraulic capacity.

The application of DT implies keeping the digital functioning in parallel with the physical functioning, so the use of models that are focused on continuous simulations is more indicated than the ones focused on events. However, it is possible to work with real-time forecast scenarios, so that it is possible to optimize the physical system configurations based on this data (Wong & Kerkez 2018). To this end, tools that perform these predictions can be added to existing NbS models to optimize real-time control.

Service entity

The service entity is important for the visualization and operation process. In it, the decision-maker will be able to ascertain the functioning of the other entities, graphically visualize the processes and operate the opening or closing of valves, overwriting the commands carried out by algorithms of the digital entity.

Several triggers must be installed to verify the health of the system. Some of these triggers are implemented in the digital entity, where anomalies can be detected through modeled results from the input and historical data. The integrity of the sensors can also be measured in the physical entity, where it is possible to observe anomalies in the results when storing the data. These triggers must be implemented in the service entity, since it allows to visualize the entire system, and, through the decision-maker's observations, perform the necessary maintenance on the other entities.

Related to visualization, a service entity intended to receive the data from the data entity and display the observed data graphically with a temporal resolution compatible with the resolution of the monitored parameters. With so, the decision support systems (DSS) such as Business Intelligence (BI) can be used. BI seeks to combine the storage and knowledge of the system to produce sufficient information in decision processes (Arnott 2008). Although there are open-source BI services, that is, free to use and adapt, Microsoft PowerBI is the most used, as it has integrations with various software, programming languages, databases and cloud services.

NbS monitoring systems, as they are decentralized alternatives, require a spatial analysis distributed in the drainage area. Thus, the visualization of several NbS applied to different scales of urban drainage becomes a challenge. For the desired integration in the development of the DT, Geographic Information Systems (GIS) software can be used. In addition, the connection between GIS software and BI has been used in different areas to improve the integration of spatial visualization with a temporal visualization of the data (Lock *et al.* 2020; Munawar *et al.* 2020; Chishtie *et al.* 2022). A fundamental factor about DTs is data security, privacy and system integrity. As the service entity is responsible for the operation of the system, measures must be taken to guarantee the security of interception and modification of the states of unauthorized users. Mashaly (2021) cited three concepts that must be present in the DT: data encryption, authentication and blockchain technologies. Data encryption is necessary, so that only other entities can understand the received and sent data. Authentication is intended to ensure that the source of the data received is secure. The blockchain is useful to ensure data integrity. These concepts must be applied both in the connections between the entities and in the service entity since this is the general interface.

Data entity

The first step in building the DT is to collect all the data required by the other entities (Mashaly 2021). Additionally, storing and flowing data to other entities are essential for the correct functioning of a DT (Tao *et al.* 2019). The data entity must have a stable and constant connection to all other entities. The physical entity sends the data to be stored, the stored data are sent to the digital entity so that it can perform scenario simulations, and then the physical entity is controlled, in addition to sending the stored information for visualization in the service entity. Therefore, the data entity has a major importance for the functioning of a DT applied to NbS. This data flow can be seen in Figure 3.

A frequent concern with data is unifying their format for common use by all other entities (Schroeder *et al.* 2016). Mani *et al.* (2001) recommend the use of data in XML (Extensible Markup Language) format, since they are formats that can describe different types of data and are used in several applications. However, the type and format of data used in industrial applications differ from those needed for NbS applications. The data required for the NbS are usually presented in table format, with the columns being the observed parameter and the rows the observed period. Alternative solutions can be given to control commands that can be registered, in addition to the need for maintenance. For these cases, it is recommended to use relational databases, in which they can store and make available the required data, such as MySQL, which is an open-source software.

As storage solutions, DT can work entirely on cloud services, entirely with local storage or with both services (Alam & El Saddik 2017). Fully cloud services are solutions that require more robust servers that are often operated by third-party companies. They are secure options, as there is hardly any data loss, and they have easy access to data. However, for DT applications, it is important to check the maximum transmission capacity and latency, as these factors can limit data access, as well as guaranteeing internet connection throughout the process (Mashaly 2021). On the other hand, data stored locally is difficult to expand, as it is necessary to purchase new physical storage units, in addition to risking data loss if technical problems occur with these units. Therefore, it is recommended to perform data security backups, even if this reduces the storage capacity of the devices. A mixed approach is also possible, where the most recent data are in cloud services to be used by other entities, while historical data can be stored locally in backups, and used when necessary.

Connection entity

Connections between entities are of fundamental importance, since by the very definition of DT, the system must work in an integrated manner (Pedersen *et al.* 2021). NbS are usually applied in a decentralized way and in urban environments, which give characteristics that differ from applications of DT communication systems applied in industry. Furthermore, for the joint monitoring of urban drainage with NbS, several spatially distributed sensors are needed, collecting information from different variables.

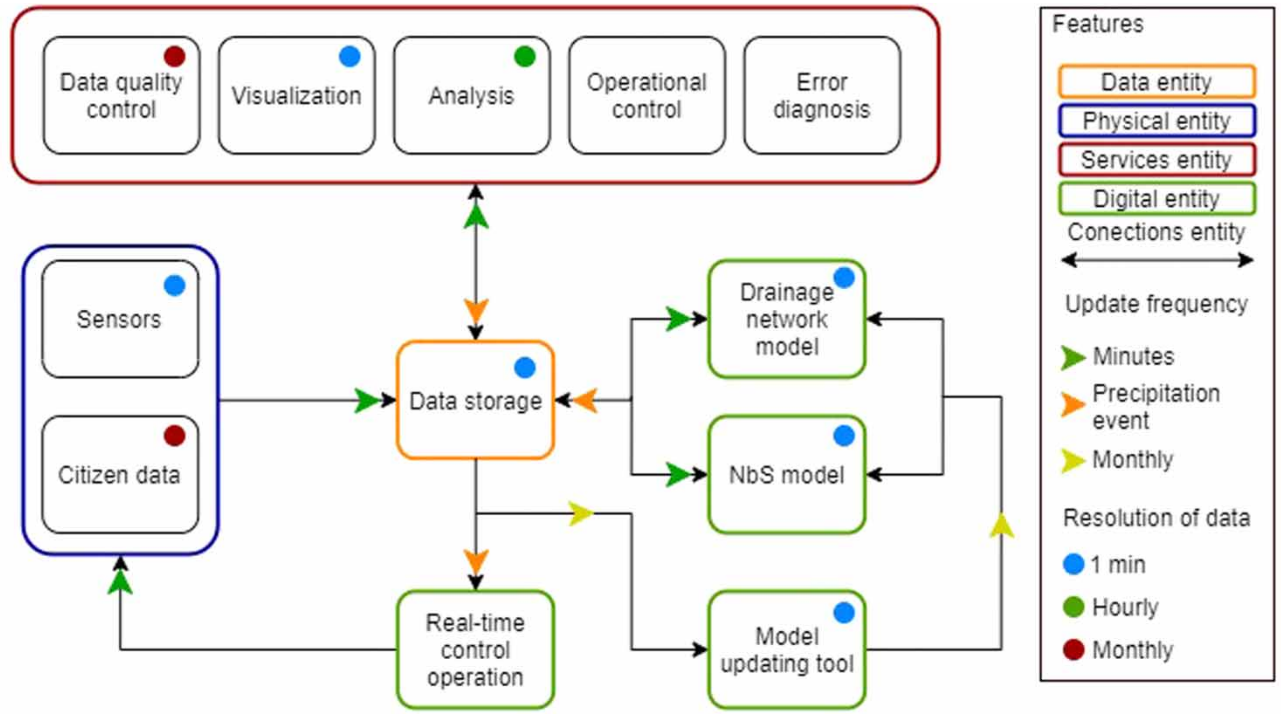

Figure 3 | Flowchart of data flow. The data resolution and update frequency can be adapted for different NbS or different modeling techniques. *Source*: Adapted from Pedersen *et al.* (2021).

The main connection needed for the development of the DT is regarding the Data Acquisition System (DAC), where the sensors of the physical entity send the data and status of the connected devices to the data entity, allowing the application of IoT with different communication technologies (Mashaly 2021). However, depending on the amount of data, which is directly related to the temporal resolution, the number of sensors and monitored variables, techniques such as edge computing can be used. In this way, the transmission and storage processes are more efficient; however, there is a difficulty in expanding the monitoring network.

Regarding the type of network, connections can be one-way or two-way. One-way connections are unidirectional, connecting at least two nodes in the system, where one node necessarily sends information and the other receives it, while in two-way connections, both nodes send and receive information. Depending on the functioning of the DT applied to NbS, some connections can be developed to only receive or send data. Observing the star structure, the entities communicate with the database, so the monitoring structures of the physical entity send data to the data entity, which, in turn, sends the stored data to perform the necessary simulations in the digital entity. The digital entity, then, sends the data to the services for the decision-maker to visualize it. Therefore, these connections can be one-way. However, the digital entity and the services, in addition to receiving the data, must send the operating commands in real time to open or close valves to optimize the performance of the physical entity, thus requiring two-way connections.

Another determining factor for communication between entities is the communication technology that will be applied. The decision process of these technologies must consider whether there is a constant source of electrical energy, the distance that the data must be sent, the amount of data that must be sent and the maximum latency desired to send data and control commands. From the knowledge of the system, you can then decide whether to use a cable connection or a wireless connection.

For NbS systems applied to urban drainage, in most cases, using cable communication so that the network of sensors and servers work in an integrated way is usually unfeasible in relation to the costs necessary for installation. Cable communication technologies can be seen in Frenzel (2018). Nevertheless, it is important to consider that systems that use cable technology require less maintenance and have a high lifespan, high transmission rate and low data loss, in addition to allowing two-way communications (Mitsugi 1994).

Regarding wireless communication, several solutions can be applied. For DT use, Mashaly (2021) recommends the use of technologies that allow the connection of several devices, with a high transmission rate due to the high amount of data. Thus, 5G is a technology indicated for the implementation of DT because, despite the high power consumption, it has a high transmission rate (up to 1 GB/s), with low latency and high data security (Nguyen *et al.* 2021).

However, 5G is a technology that is still in the early stages of implementation in most countries and coverage is still low compared to other mobile communication technologies (Oughton *et al.* 2019). Therefore, other technologies already available with a greater coverage and that work two-way can be used, such as wireless fidelity (Wi-Fi), other generations of mobile communication (e.g., 3G and 4G), ZigBee or LoRa. The use of wireless technologies is usually a trade-off between communication rate, power consumption and transmission distance. While Wi-Fi can transmit large amounts of data, its power consumption is high, and it has a short transmission distance. ZigBee has a low power consumption; however, distance and transmission rate are equally low. Regarding the transmission distance, mobile protocols achieve a wider application range, despite the high energy consumption, while technologies such as LoRa have a high transmission range with a low energy consumption, but with a low transmission rate.

CHALLENGES, FUTURE PERSPECTIVES AND POTENTIAL BENEFITS

Literature on DT applied to water resource structures is still recent. However, there is a tendency to use these techniques since they solve problems often found in traditional approaches, such those related to real-time monitoring, compatibility between collected data and improvement in simulation processes, and the creation of interface with the decision-maker and security systems. As DT techniques are studied and tested for water resource structures, specific modeling and monitoring technologies for these applications are leveraged and can be used in complex problems involving demand, export of water from different locations, operation of interconnected reservoirs to urban drainage, as well as for water supply. In this way, the development of DT for each stage can contribute, so that systems usually modeled in isolation are understood as integrated systems.

From the point of view of demand, the water security of urban catchments is complex mainly due to the need to compete for different external sources with other catchments, which leads to their co-dependence from the point of view of water production and consumption (Thompson *et al.* 2011). This codependency is aggravated as cities develop into large urban centers, such as megacities, where the need for consumption is high in a concentrated region. For these cases, the transboundary nature of water security projects elevates either the codependency or the complexity of attributes for selecting variables, parameters and causal loops with strong feedbacks. In the example of the relationship of Brazilian megacities, Rio de Janeiro and São Paulo with flow transfer are examples of complex systems with mutual dependence. Figure 4 illustrates the dependence system of three hydrographic basins such as Paraíba do Sul, Alto-Tietê and Piracicaba-Capivari-Jundiaí Rivers. The last two are represented by the reservoirs that comprise the Cantareira System and its consumer population, which is mostly located in the metropolitan region of São Paulo. The Paraíba do Sul River Basin has its head located in the states of Minas Gerais and São Paulo, with its mouth located in the state of Rio de Janeiro. Extremely important for the region, this basin serves important cities in São Paulo and has part of its flow transferred to the Guandu River, which supplies the Metropolitan Region of Rio de Janeiro (Formiga-Johnsson & Britto 2020).

When considering a complex system of urban basins that use competing sources, the development of DT for each stage can not only optimize the monitoring, transmission and operation characteristics of these reservoirs, but also integrate them with DT in other related areas. The DTs developed specifically for NbS applied to urban drainage can be included, helping in part in the treatment of water sent to the treatment plant, in addition to reducing flood peaks and storing water during periods of drought. Thus, the development of different DT approaches for different structures can be integrated to assist in the process of simulating and modeling high complexity systems into simpler and more connected systems through multicriteria analysis approaches and different scenarios.

The need to operate as close as possible to the real time required by DTs also means that more investment is produced in monitoring solutions. Sensors adapted to work in real time with adequate reliability for application in the physical entity, as well as the transmission network of these data, can bring benefits not only to the areas of water resources, but also to related areas. The development of technologies such as 5G can facilitate the use of smart devices, allowing IoT applications to become popular in the collection and use of data in favor of urban resilience facing extreme events. With the development and application of specific frameworks, DT structures can work in an integrated way, so that the entire system is continuously monitored, simulated and optimized.

With the implementation of a DT, some direct and indirect improvements are achieved. The quantity and quality of data generated regarding the monitoring necessary to the development of a DT contributes to a general understanding of the

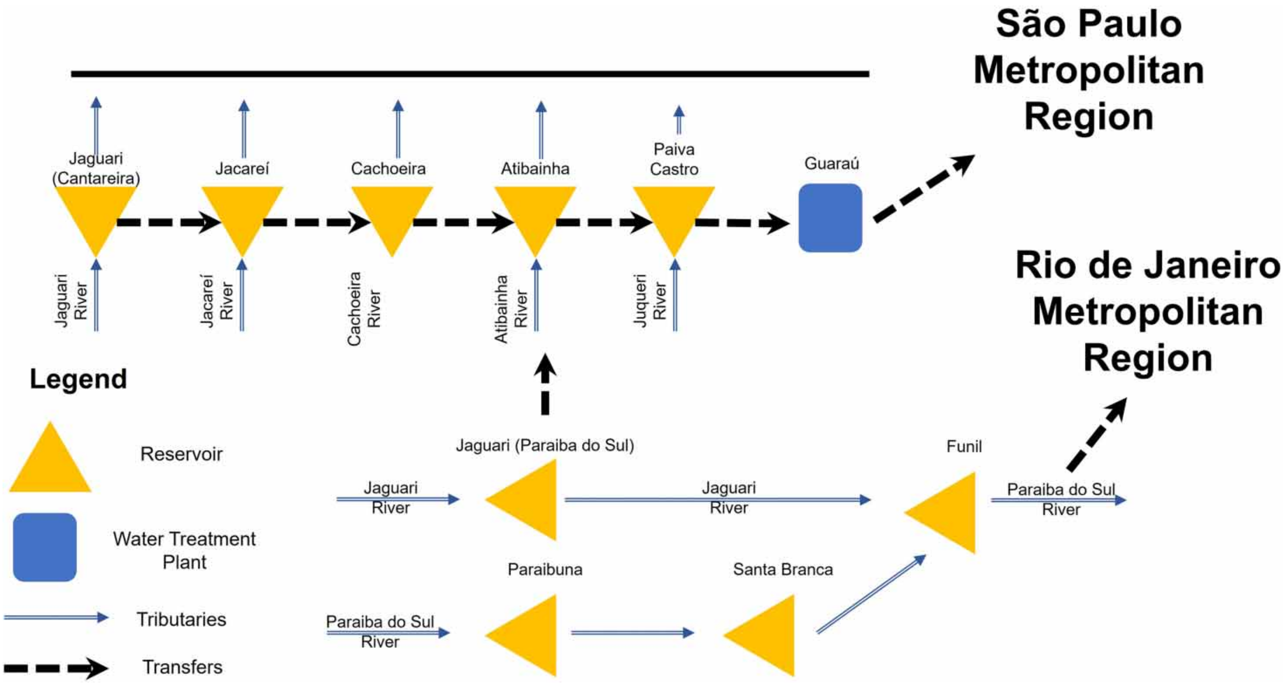

Figure 4 | Water transfer through megacities example. *Source*: Adapted from Souza *et al.* (2021).

system. Additionally, the DT can contribute to optimize the maintenance of vegetated structures (such as bioretention and green roof), as well as the preventive maintenance related to the loss of soil infiltration capacity. Furthermore, after sufficient time has elapsed and data were acquired from the observation of events of different magnitudes, the system models can be improved with data-driven models (Rasheed *et al.* 2020).

Other improvement related to NbS is that, by developing DT integrated to urban drainage, it is possible to implement real-time control structures for both traditional drainage and NbS devices. The application of real-time control optimizes quali-quantitative NbS processes, in addition to providing system connectivity (Brasil *et al.* 2021). With the monitoring of the entire system, it is possible to adapt the system configurations (e.g., opening of inlet valves in detention basins and closing of outlet valves to create anaerobic zones) for situations of extreme floods and droughts, or to improve water treatment (Persaud *et al.* 2019; Shishegar *et al.* 2019; Shen *et al.* 2020).

The use of two DT instances, such as one focused on sizing and design and the other focused on event simulations, also enhances the creation of different future scenarios to improve the functioning of the system. In addition, the services linked to the DT, such as the real-time visualization of the system, allow to improve decision-making regarding a certain area. Thus, incorporating DT to NbS is promising and can leverage the positive results already obtained by these techniques, in addition to reducing the need for emergency maintenance and developing a large database for analysis of the urban drainage system.

As with the development of DT in the industry (Tao *et al.* 2019), the developed framework needs to be tested and validated with real data, thus allowing the evolution of concepts and entities, as well as the adaptation to different practices. Although there is no literature of the performance of DT applied to NbS, the literature related to the development of DT on urban drainage and water supply systems shows an improvement in the diagnosis of system errors, model structures, process and decision-making, both for integration of the digital entity with the physical entity and for better planning due to the amount of data collected during the execution of the DT (Pedersen *et al.* 2021, 2022).

However, it is possible to observe that, despite not having the full scope of the DT, some initiatives to apply separate parts of a DT present positive results. The integration of the physical entity with the digital entity, for example, is widely explored in Cyber-Physical systems with the focus on the NbS real-time control. Shishegar *et al.* (2021), for example, developed a system for real-time control of several detention basins spread across urban drainage in Canada, achieving peak discharge mitigation between 59 and 87% in addition to improving water quality in the process. Also related to detention basins, Jacopin *et al.* (2001) tried to experimentally calibrate and develop control strategies, obtaining reductions of 40% from flooding risks while increasing the removal of pollutants.

Related to a smaller spatial scale, bioretention devices also benefit from the integration of mathematical models with the physical system. Persaud *et al.* (2019) used bioretention columns to assess the impact of real-time control on water quality. In this study, it was possible to observe a reduction in parameters such as heavy metals and nutrients such as nitrate and phosphorus. Another example that illustrates the importance of integrating the physical entity with the digital entity can be observed by Shen *et al.* (2020), where, through real-time control, it was possible to improve water quality by 67% for total suspended solids (TSS), 33% for total phosphorus (TP) and 44% for total nitrogen (TN), thus allowing the water stored at the outlet of the device to be within the limits of the guidelines for reuse.

Those examples, despite the lack of the full architecture of a Digital Twin, show that there is potential for improvement when digital and physical entities are integrated. In this way, the developed framework seeks to frame these approaches so that, in addition to the connections between mathematical models and physical systems, the data flow is optimized so that the models developed are improved, in addition to allowing a better spatial–temporal visualization of the system. Finally, the application of DT in NbS, although challenging, can bring qualitative and quantitative benefits to urban drainage, improve water security and assist in decision-making through knowledge of the system through the monitored data.

CONCLUSIONS

Through this literature review on the development of definitions for both industry and urban water systems, it is possible to observe that, despite being recent, studies on DT show promising results for improving the performance of NbS devices applied to urban drainage. Although there are several different architectures for the DT development, the formalization of a framework can help the techniques to be applied in different stages, facilitating their integrated implementation.

Based on recent work related to the development of DT applied specifically to urban water environments and on techniques already applied in industry, it was identified that data collection, distribution and integrity should be the main focus in the implementation stage of a DT. Therefore, the physical entity monitoring structures must be elaborated with enough information, so that the necessary spatial and temporal resolutions can produce a reliable digital entity.

The digital entity is the most documented entity in the literature, as there is a growing interest in representing the physical phenomena of NbS with mathematical equations. However, the development of DT requires specific tools in addition to the representation of physical phenomena, such as real-time operation and control, continuous improvement of models based on collected data, joint modeling of water flow and water quality of traditional urban drainage and systems within NbS. Therefore, the development of tools for this entity depends on the collaboration of researchers from different areas and on a holistic view of the system since different techniques use different processes.

NbS are solutions usually spatially distributed in urban areas, which makes complex the process of data transmission, reception and processing. Therefore, knowledge of the system is necessary, so that digital solutions can be implemented. In addition, the particularities of the different communication protocols must be considered, since the supply of electricity, necessary signal or existing infrastructure may be different, depending on the environment. Therefore, the connection entity is necessary to ensure that the monitored data are distributed to the other entities considering access security and data integrity.

Finally, the application of DT in NbS, although complex, can bring multiple benefits both for the functioning and for the understanding of the system. The proposed integration need for a DT can bring benefits to the amount of data collected in urban drainage systems, which are beneficial in the long term for future expansions and modifications of the system. In addition, the development of mathematical modeling and real-time control of these structures can enhance the functioning of these techniques, as well as the integration with the service entity helps in the real-time visualization process. Although there are still gaps in the literature about DT applied to these structures, applying the development of techniques and technologies is a natural process for the evolution of new generations of these devices.

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The authors declare no conflict of interest

DATA AVAILABILITY STATEMENT

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

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