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SMART WATER APPLICATIONS VS. INFORMATION AND COMMUNICATION TECHNOLOGIES – AN INTEGRATIVE SELECTION FRAMEWORK

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Abstract

In urban water infrastructure, information and communication technology are presently concentrated on central facilities (e.g., treatment plant) or are installed at main points in the urban drainage or water distribution network, e.g., inlet points of district meter areas or combined sewer overflow structures. In this regard, the Internet of Things concept as part of smart city development enables a large-scale implementation of measuring equipment and allows the integration of decentralised elements into an overall controlled system. Consequently, reliable and suitable information and communication technology is a key element for the exchange of measurement and control data as well as for the success of these systems. From a water engineering perspective, it is often difficult to choose the right information and communication technology for the intended urban water infrastructure application. Likewise, from an Internet of Things perspective, it is often unclear what kind of urban water infrastructure applications are feasible, making them difficult to efficiently implement.

Aim of this work is to develop a first-decision making tool, which can be used by network operators, researcher, and stakeholders to support supervisory control and data acquisition development and to realise an efficient information and communication technology system in the field of network-based urban water infrastructure. In contrast to existing recommendations, our approach is based on a comprehensive review of required spatial and temporal resolution of measurement and control data for a wide range of different network-based urban water infrastructure applications. Subsequently, this enables a targeted coordination with the properties of communication technologies (e.g., data rate, range, and quality of service) and leads to a significantly improved and integrative decision-making tool.

Subsequently, we tested the functionality of the framework on two exemplary applications in urban water infrastructure, namely (1) determining suitable communication technologies for an early warning system for leakage detection and localisation in water distribution networks (e.g., (Wireless)Meter-Bus for water meters, long range wide area network for water pressure sensors, and global system for mobile communications at inlet points of district meter areas, and (2) identifying feasible applications for an existing long range wide area network (e.g., monitoring micro-climate and automatic irrigation at nature-based solutions). Results from the framework application have been evaluated through a literature review on used communication technologies, and are found to be consistent with real-word applications. As conclusion, different communication technologies are necessary to satisfy different requirements associated with an integrative management of urban water infrastructure.

Keywords
Decision making tool, ICT, integrative management, SCADA system, urban water infrastructure

1 INTRODUCTION

In urban water infrastructure (UWI), information and communication technology (ICT) are widely found in central facilities [1], e.g., treatment plants, while the implementation in the networks is mainly concentrated at the main points, e.g., combined sewer overflow (CSO) structures [2] or inlet points of district metering areas (DMAs) [3]. In this regard, the Internet of Things (IoT) concept as part of smart city development enables a large-scale implementation of measuring equipment even at remote and underground structure [4], thereby increasing the data availability significantly. Additionally, the IoT concept supports the integration of decentralised network elements like nature-based solutions (NBS) into an overall controlled system.

Consequently, reliable and suitable ICT is a key element for the exchange of measurement and control data as well as for the success of these systems. Thereby, the following two challenges can be identified: (1) from a water engineering perspective, the limitations and benefits of different IoT concepts are usually unclear and thus it is difficult to choose suitable communication technologies and (2) from an IoT technology perspective, it is often unclear what kind of UWI applications are feasible, making them difficult to efficiently implement. To tackle these challenges, there are several frameworks outlined in literature, e.g., [5-7], in which suitable communication technologies are suggested based on the area of interest (e.g., smart metering). However, as concluded in the review of [8], it requires a coordination of the usable communication technology and the required temporal and spatial resolution of the measurement and control data to implement an efficient monitoring and controlling network.

To overcome this limitation, we present a first decision making tool in this work. In contrast to the existing recommendations, our approach is based on a comprehensive review of required spatial and temporal resolution of measurement and control data as well as used communication technologies for a wide range of different network-based UWI applications. The decision-making tool can be used by network operators, researcher, and stakeholders to support supervisory control and data acquisition (SCADA) development and to realise an efficient ICT system in the field of network-based UWI.

2 METHODS

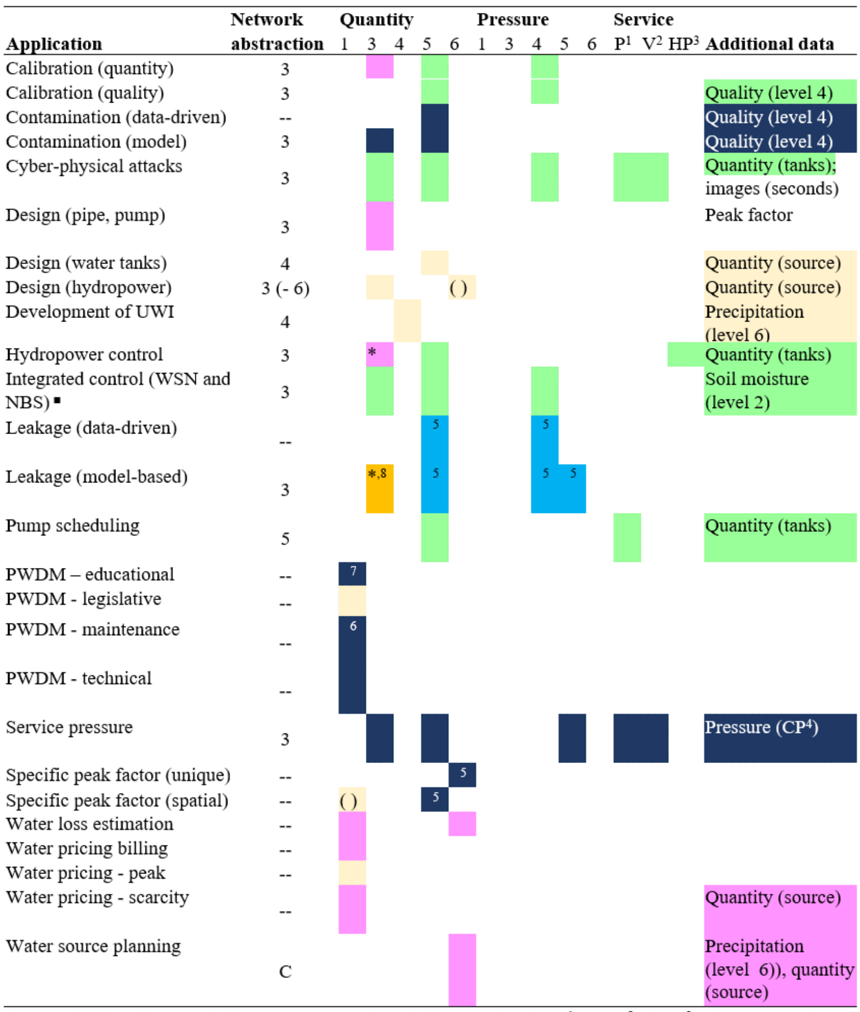
The development of the decision making tool is based on the results of the comprehensive review of [8] as mentioned above. Therefore, the main outcomes are shortly summarised in this chapter.

2.1 Data requirements of application

Figure 1- 3 gives an overview over the temporal and spatial resolution of different applications in water distribution and urban drainage networks including nature-based solutions identified from literature. For the abbreviations used, refer to Table 1. As can be seen, each application is characterised by different requirements regarding data resolution, which also differ between the applications.

Table 1. Abbreviation for used spatial and temporal resolution

Colour	Temporal resolution	System level	Spatial resolution
■	1 s – 5 min	1	Household scale
■	5 min – 10 min	2	Nature-based solution
■	10 min – 1 h	3	Network nodes
■	1 h – 1 d	4	Grid with 100 – 500 m
■	1 d – 1 m	5	Examination area (e.g., DMA, CSO)
■	1 m – 1 y	6	Total area (e.g., city)



( ) = possibility, *downscaled to same temporal resolution as other data; [1]pump, [2]valve, [3]hydropower unit, [4]critical point (e.g., area with low pressure); [5]also used with 5 min – 10 min in literature, [6]also used with 10 min – 1 h in literature, [7]also used with 1 d – 1 m in literature, [8]also used with 1 m – 1 y in literature

Figure 1. Spatial and temporal resolution for applications related to water distribution networks (This figure is reproduced with small alterations (deletion of the reference column) from [8] under an Attribution 4.0 International license (CC BY 4.0)).

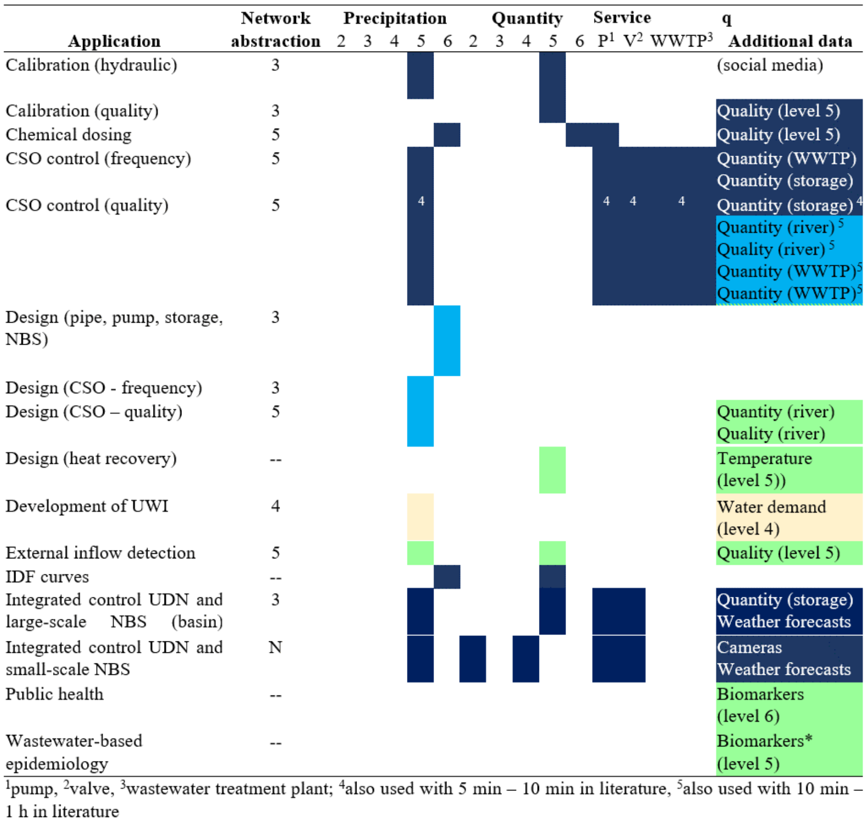


Figure 2. Spatial and temporal resolution for applications related to urban drainage networks (This figure is reproduced with small alterations (deletion of the reference column) from [8] under an Attribution 4.0 International license (CC BY 4.0)).

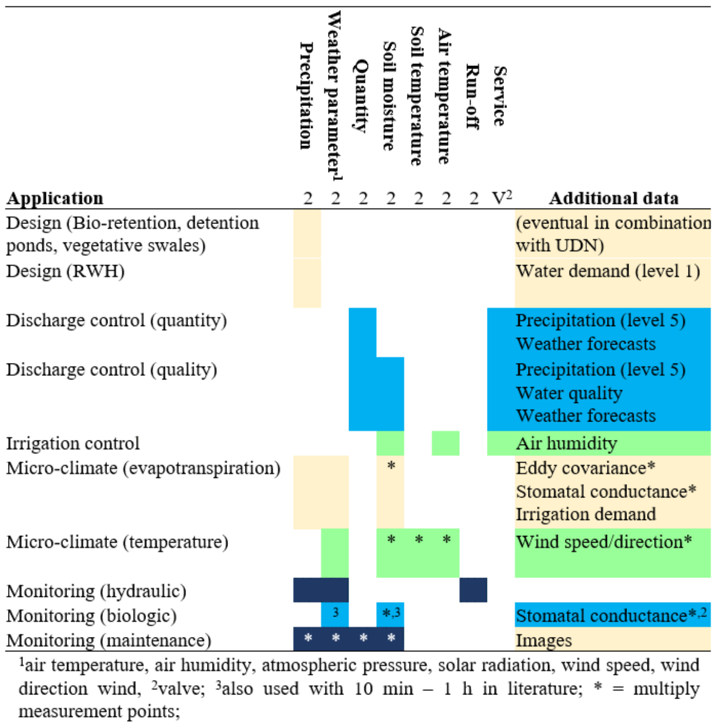


Figure 3. Temporal resolution for applications related to nature-based solutions (This figure is reproduced with small alterations (deletion of the reference column) from [8] under an Attribution 4.0 International license (CC BY 4.0)).

2.2 Communication technologies

Figure 4 gives an overview over the communication technologies with transmission ranges and data rates as characteristic properties. The communication technologies can be subdivided into wired and wireless communication, using a cable and electromagnetic waves for the exchange of data, respectively. For more information about communication technologies, refer to relevant literature [6,9-11].

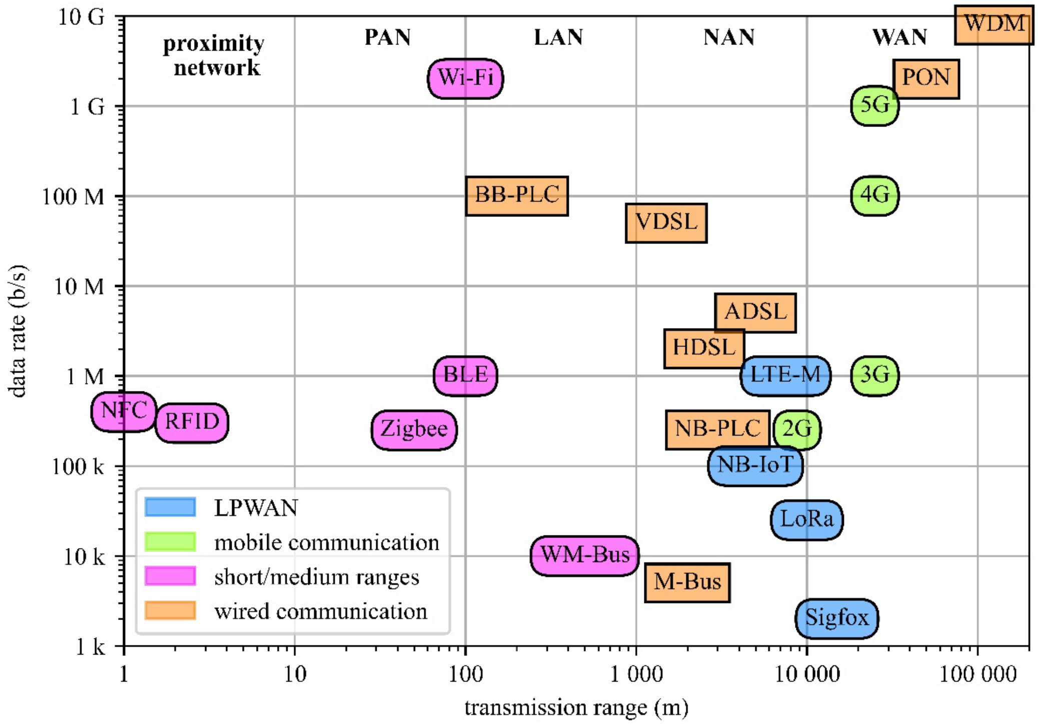


Figure 4. Overview of different communication technologies based on transmission range and data rate (This figure is reproduced from [8] under an Attribution 4.0 International license (CC BY 4.0)).

For UWI, the wired communication technologies fibre optic as the backbone of the internet and Meter-Bus (M-Wus) for the remote-readout of water meters are of importance. Wired communication technologies provide a high quality of service as packet losses are low and allow nearly almost any transmission interval. In contrast to wireless communication technologies, the installation of wires requires considerable efforts and is less flexible.

Short and medium ranges include a wide range of technologies with a transmission range up to 500 m. For interests are ZigBee (smart home applications), Wireless-Fidelity (Wi-Fi) (public hot spots) and WM-Bus (alternative for water meters). These communication technologies are primarily applied in the surroundings of buildings, as the transmission range is limited.

Mobile communication uses radio waves for the transmission of data, and cellular communication networks cover a large area. For UWI, GSM/GPRS (2G) are widely applied for monitoring and controlling approaches in UWI. Furthermore, cellular communication operates in licenced frequency bandwidths, thereby providing a high quality of service with low packet losses. However, the energy consumption is high, requiring additional approaches for a long-maintenance operation, e.g., to decrease transmission interval or to include additional energy sources.

Low power wide area networks (LPWANs) support the large-scale implementation of multiple devices through long transmission ranges and ultra-low-power operation. Leading technologies are LoRa and Sigfox in the unlicensed frequency bands and NB-IoT in the licensed frequency bands. Devices using LPWANs for data transmission are most of the time unreachable, as the transceivers are turned off to save energy. Therefore, these communication technologies are usable for delay-tolerant applications. Additionally, as Sigfox and LoRa are operating in the unlicensed bands, they are subject to fair-use policy (max. number of packets and limitation of packet length) including packet losses, which are depending on number of connected devices and connection quality.

Summarised, each communication technology has different properties and limitations, influencing the spatial and temporal resolution of transmittable measurement and control data. Therefore, it requires a coordination between intended applications and communication technologies to implement an efficient monitoring and controlling network.

3 RESULTS AND DISCUSSION

The information about required spatial and temporal resolution of measurement data and communication technologies was used to develop a first-decision making tool to support network operators, researcher, and stakeholders with the implementation of ICT. This work is primarily based on real-world implementation, of course, different approaches are also feasible. Additionally, field test should be carried out before implementation to assess the functionality under local conditions. The framework is organised into two categories: (1) (near) real-time transmission of data and (2) transmission of aggregated and historical data.

3.1 Real-time Transmission

Figure 5 gives an overview about recommended communication technology for real-time transmissions. The first decision criterion is the intended purpose. Real-time monitoring describes the exchange of monitoring data from the sensor nodes to the central system and therefor a unidirectional connection is sufficient. In contrast, real-time operation requires a bidirectional connection for the exchange of status notifications (from the control organ to the central system) and control commands (from the central system to the control organ). Nearly all communication technologies support a bidirectional communication, but the number of downlinks can be limited as with LPWANs.

Second, the desired properties influence the choice of the communication technology. Real-time monitoring can be distinguished between text packet (e.g., an identification number, a time point, and a measurement value) and images, having a packet size in bytes and mega-bytes, respectively. Therefore, the data rate and the maximum packet length influences the choice of suitable communication technologies. Real-time operation differs between delay-sensitive applications (control process should take place immediately) and delay-tolerant applications (delays have only a limited influence on system performance). Following, the reachability is the decisive factor for the selection of suitable communication technologies.

Finally, it requires a trade-off between maintenance and installation efforts and the reliability. Cellular and wired communication provide a high reliability and allow nearly every transmission interval but require either a wire for data communication or power supply due to high energy consumption. Therefore, these communication technologies are suitable for only few installation places. In contrast, LPWANs enable an easy large-scale implementation of sensor nodes with relative low investment costs. However, they are not suitable for high transmission intervals due to an increased energy demand. Additionally, Sigfox and LoRa operates in the public frequency band widths which include also packet losses. In this regard, short and medium range technologies can be used for both high spatial and temporal resolution, but the limited range will require the inclusion of the public to cope with the high installation and maintenance efforts.

Application purpose		**Maintenance and installation efforts**		**Communication technology**									
				Wired communication		Mobile communication		Short and medium ranges			Low power wide area networks		
Purpose	Properties	Transmission interval	Scale of implementation	M-Bus	Fibre optic	GSM/GPRS	LTE / 5G	Wi-Fi	WM-Bus	Zigbee	LoRa	NB-IoT	Sigfox
Real-time monitoring	Text	1s - 5min	1 - 4	✓[1,2]				✓[1]	✓[1,2]	✓[1]	✓[3]		
			5 - 6		✓	✓[4]						✓[3]	
		5min - 10min	1 - 4	✓[1,2]				✓[1]	✓[1,2]	✓[1]	✓		
			5 - 6		✓	✓[4]						✓	
		10min - 1d	1 - 4	✓[1,2]				✓[1]	✓[1,2]	✓[1]	✓[5]	✓[6]	✓[5]
			5 - 6		✓	✓[4]						✓	
	Images	1s - 5min	1 - 4		✓			✓[1]					
			5 - 6		✓		✓[4]						
		5min - 10min	1 - 4		✓			✓[1]					
			5 - 6		✓		✓[4]						
		10min - 1d	1 - 4		✓			✓[1]					
			5 - 6		✓		✓[4]						
Real-time operation	Delay-sensitive	1s - 5min	1 - 4					✓[1]		✓[1]			
			5 - 6		✓	✓[4]							
		5min - 10min	1 - 4					✓[1]		✓[1]			
			5 - 6		✓	✓[4]						✓[3]	
		10min - 1d	1 - 4					✓[1]		✓[1]		✓	
			5 - 6		✓	✓[4]						✓	
	Delay-tolerante	1s - 5min	1 - 4					✓[1]		✓[1]			
			5 - 6		✓	✓[4]							
		5min - 10min	1 - 4					✓[1]		✓[1]			
			5 - 6		✓	✓[4]						✓[3]	
		10min - 1d	1 - 4								✓		✓[3]
			5 - 6									✓	

[1]requires involvement of public; [2]alternative for water meters; [3]possible to a limited extent - requires feasibility study on site (not recommended); [4]requires additional energy sources; [5]peak -hour pricing – not recommended; [6]peak -hour pricing – alternative;

Figure 5. Recommended communication technologies for real-time applications.

3.2 Historical and aggregated data

Figure 6 gives an overview about the recommended communication technologies for applications based on historical data. In contrast to real-time applications, multiple measurement values can be aggregated and transmitted periodically. As stated before, the maximum packet length is limited for LPWANs. Therefore, the first decision criterion is the number of measurement values per transmitted data packet. For example, the maximum number of measurement values is 6, 120, and 800 for Sigfox, LoRa, and NB-IoT, respectively, by assuming a storage size of 2 bytes.

Another decision criterion is the reliability of data transmission. Using technologies operating in the public frequency band widths, data gaps must be expected. In contrast, if a continuous time series without data gap is needed, wired and cellular communication technologies are recommended. Additionally, short and medium range technologies represent an alternative for high spatial resolution.

Data size		Communication technology									
		Wired		Mobile		Short and medium			Low power wide area		
Transmission interval	Measurement interval	M-Bus	Fibre optic	GSM/GPRS	LTE / 5G	Wi-Fi	WM-Bus	Zigbee	LoRa	NB-IoT	Sigfox
30min	10s		✓	✓	✓	✓				✓	
	1min	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	5min	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	10min	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1h	10s		✓	✓	✓	✓				✓	
	1min	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	5min	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	10min	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	1h	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1d	10s		✓	✓	✓	✓					
	1min		✓	✓	✓	✓					
	5min		✓	✓	✓	✓				✓	
	10min		✓	✓	✓	✓				✓	
	1h	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	1d	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1m	10s		✓	✓	✓	✓					
	1min		✓	✓	✓	✓					
	5min		✓	✓	✓	✓					
	10min		✓	✓	✓	✓					
	1h		✓	✓	✓	✓				✓	
	1d	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	1m	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Figure 6. Recommended communication technologies for historical and aggregated data.

3.3 Usability of the developed first decision making tool

The developed first decision making tool can be used for following aims: (1) to determine suitable communication technologies for a selected application in the field of UWI and (2) to identify feasible applications in the field of UWI for an existing communication network. Therefore, Figure 7 gives an overview of how the first decision making tool can be applied.

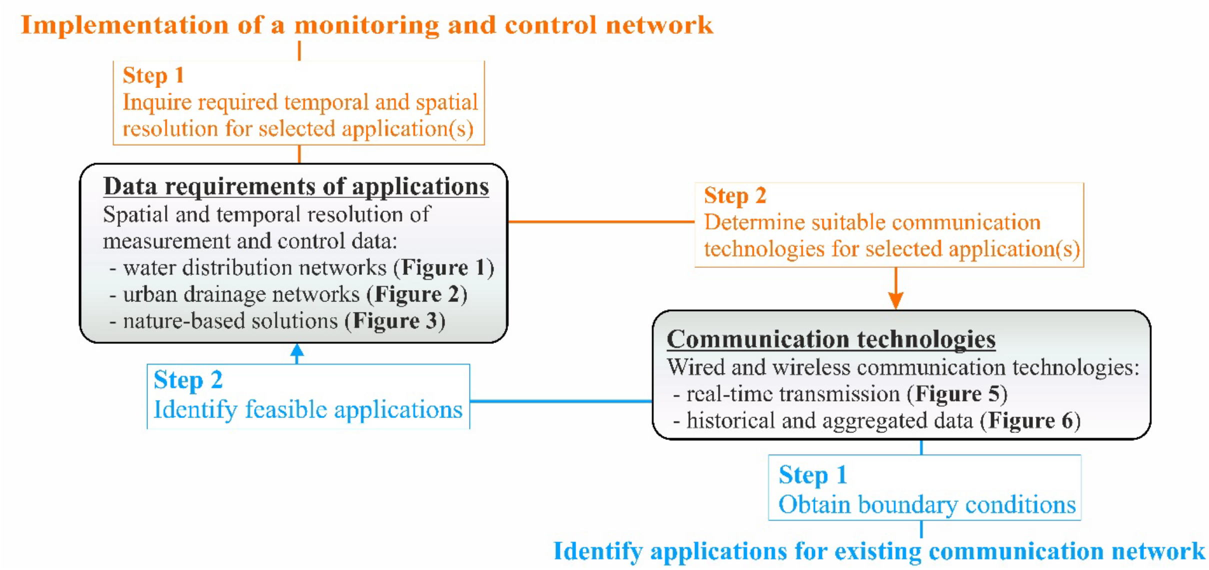


Figure 7. Developed first decision making tool.

In the following two examples for applying the developed decision making tool are outlined:

- A network operator decides to install an early warning system for model-based leakage detection and localisation in the water distribution networks. The workflow is as follows: First, the spatial and temporal resolution of the required measurement data can be obtained in Figure 1, and second, this information is used afterwards in Figure 5 to determine suitable communication technologies. As the temporal resolution of the required measurement data is 5 to 10 min and text-based data packets are transmitted, following communication technologies are selected: (1) (W)M-Bus for water meters installed in households, (2) LoRaWAN for water pressure sensors in a grid arrangement of 100 to 500 m as packet losses are acceptable due to the high number of sensors, and (3) GPRS for water inflow and water pressure at the inlet points of the DMA for a high reliability of data transmission.

- An infrastructure operator deploys an existing LoRa network and searches for real-time applications in the field of UWI. The workflow can be described as follows: First, as shown by Figure 5, LoRa is recommended for text-based data packets with measurement points ranging from household scale to grid arrangement and a temporal resolution of 5 min to 1 day. Subsequently, this information can be used in Figure 1 -3 to identify feasible real-time applications. Exemplary applications are monitoring of micro-climate and an automatic irrigation at nature-based solutions.

The Figures 5 and 6 are based on an extensive literature [8]. As validation, real-world implementations for the two examples are shown: (W)M-Bus is used for read-out of water meters [12,13], LoRa is applied for large-scale monitoring of urban drainage and water distribution networks [13-15] as well as for smart rainwater harvesting [16]; and GPRS is commonly utilised for single measurement points [17,18], which is in concordance with the recommendations of the presented framework.

4 CONCLUSION

Reliable and suitable information and communication technologies (ICT) are a key factor for the implementation of efficient monitoring and controlling systems in the field of urban water infrastructure (UWI). Additionally, the Internet of Things (IoT) concept allows the installation of low-cost sensors even at remote and underground structures, thereby providing new possibilities in the management of UWI. Subsequently, the challenges for both, water engineers (the limitations and benefits of different IoT concepts are usually unclear) and ICT operator (what kind of UWI applications are feasible) are increasing.

To tackle these challenges, we presented a detailed first decision making tool for the realisation of an efficient ICT system in the field of network-based UWI. In contrast to existing recommendations, our approach is based on a comprehensive review of required spatial and temporal resolution of measurement and control data for a wide range of network-based UWI applications. This information was used for a targeted coordination with the properties of different communication technologies, leading to a significantly improved and integrative decision-making tool.

The developed framework can be used by network operators, researchers, and stakeholders for following aims: (1) to determine suitable communication technologies for a selected application in the field of UWI and (2) vice versa to identify feasible applications in the field of UWI for an existing communication network. The functionality of the framework was tested by using two exemplary applications in the field of network-based UWI. The recommended communication technologies are consistent with real-word implementations, thereby demonstrating the applicability of our approach. Additionally, the combination of different communication technologies is necessary to satisfy the requirements for an integrative management of UWI.

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