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Modern Technologies for Innovative Urban Water Management in Smart Cities

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Abstract: The efficient usage of resources is essential to the development and operation of smart cities, with recent technologies playing a pivotal role. In particular, advanced electronics and digital innovations are transforming energy and water management, integrating clean technologies and promoting sustainability. Smart sensors, IoT networks, and automated systems enable real-time data collection and analysis, allowing for predictive maintenance, timely interventions, and optimized resource allocation. Leading-edge technologies such as AI-powered analytics and machine learning models enhance decision-making processes by providing actionable insights for urban management. Additionally, blockchain technology can ensure secure data exchange, while 5G connectivity facilitates faster communication between devices, improving the overall productivity of urban systems. These advancements are increasingly integrated into the infrastructure of newly developed smart cities built with technology at their fundamental. At the same time, in many cities of Europe the existing infrastructure is retrofitted with smart solutions to improve their operations. This study will examine these achievements and point out two possibilities of their potential application in cities of Serbia, as well as Bosnia and Herzegovina. The goal is to systematize the ways in which modern electronic technologies are involved for sustainable water management, intelligent urban infrastructure, and resilient urban development.

Keywords: Smart cities, sensors and systems, water management.

1 INTRODUCTION

The aspiration to a better quality of life in urban areas, combined with the population growth, have led to the emergence of new concepts in the development and management of the city, as well as the application of novel technology and new solutions. Further, climate change significantly influences both the quantity and quality of water resources, with these effects being mainly pronounced in urban areas. Given that more than half of the global population currently resides in cities, with this number expected to increase, the optimization of resource utilization is becoming increasingly important, particularly in terms of the efficient consumption of energy and water [1]. As a result, there is an increasing focus on adopting innovative solutions and modern technologies associated with smart city development.

The development of the smart city concept, through the implementation of integrated systems, optimizes water management efficiency with the aim of reducing consumption. Beyond individual solutions in various areas of conventional water management (WM), these innovative systems enhance comprehensive WM within the urban water cycle, ultimately leading to intelligent WM [2-7]. Moreover, in a smart city, intelligent technologies complement and improve existing infrastructure and technologies for water management across the entire urban system. This is achieved through the use of real-time integrated information and electronic components and systems, such as sensors, monitors, Geographic Information Systems (GIS), remote sensing, and other contactless intelligent tools in urban area [7].

Existing water management practices in smart cities align with at least five Sustainable Development Goals (SDGs) of the 2030 Agenda: ensuring healthy lives and promoting well-being (Goal 3); providing access to sustainable water and sanitation management (Goal 6); improving inclusive, safe, and resilient cities (Goal 11); ensuring sustainable consumption and production patterns (Goal 12); and combating the impacts of climate change (Goal 13) [8]. Numerous programs and projects funded by global, regional and national institutions promote progress in improving the water conservation and control [8-12], often through the development of digital service tools to improve specific segments (e.g., water supply or stormwater management) while simultaneously fostering technologies for public engagement in water management.

The aim of this study is to investigate the applied modern technologies in water management and required devices necessary for their application. The research of functional practices in selected smart cities of Europe can be useful for highlighting strategies potentially applicable in the cities of Serbia, as well as Bosnia and Herzegovina.

2 TECHNOLOGIES FOR INOVATIVE URBAN WATER MANAGEMENT

Smart cities from the list of global smart cities, more than a third of which are in Europe, were chosen for the analysis [14]. In addition to already existing cities where new technologies are applied to improve citizens' quality of life, a city initially established as a smart city was also selected. Additionally, the study also considers emerging smart cities that are rapidly integrating digital solutions to address urban challenges, such as sustainability, mobility, and public services, aiming to transform their infrastructures into fully interconnected ecosystems.

2.1 Milton Keynes, United Kingdom

Milton Keyneswas founded almost 65 years ago as a smart city. Thanks to advanced thinking and technological integrations, a synergy has been created between water supply, waste water treatment and storm water management, optimizing the use of resources and increasing the overall efficiency of the system.

The innovative solutions applied in Milton Keynes include: smart water meters, data collection, analysis, and predictive modelling, advanced leak detection technologies, smart irrigation systems, grey water recycling, flood risk management systems, public engagement and education, UV system planning for water supply [15]. These solutions and applied devices are presented in Fig. 1.

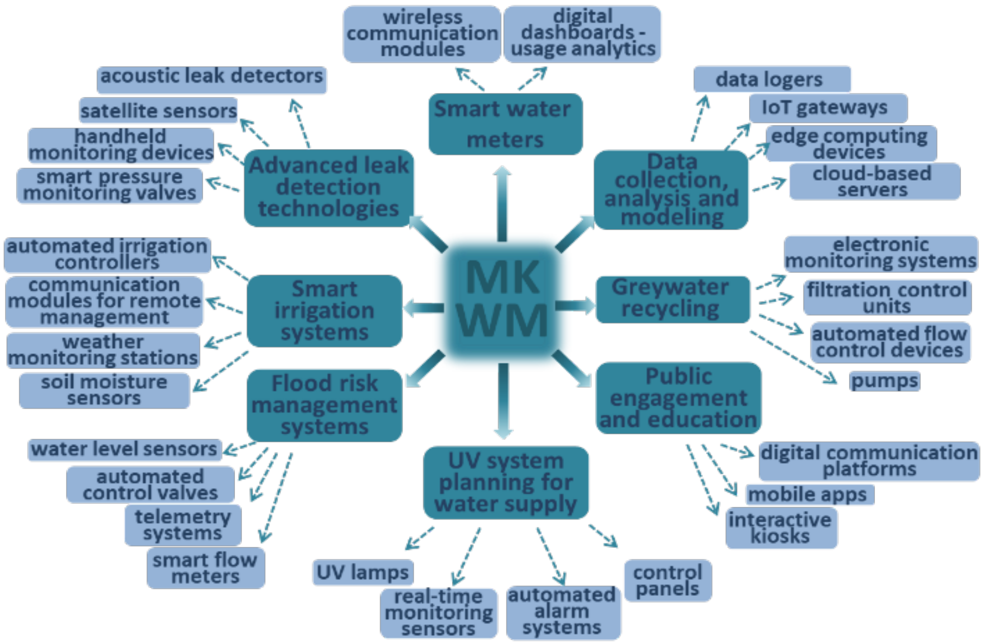

Figure 1 Innovative solution elements for water management in Milton Keynes and applied devices

Smart water meters enable real-time monitoring of water consumption. These devices provide valuable data to both consumers and water management authorities, fostering efficient water usage and early detection of abnormal consumption patterns. These meters are typically equipped with wireless communication modules for data transmission and are integrated with digital dashboards that provide usage analytics.

Data collection, analysis and predictive modelling are allowed by sophisticated data analytics platforms. Predictive modelling helps in efficient forecasting and management of water demand, allowing the city to proactively address potential supply issues. Devices such as data loggers, IoT (Internet of Things) gateways, edge computing devices, and cloud-based servers are integral to this system.

Advanced leak detection technologies are used to minimize water losses. This is achieved through the application and integration of acoustic sensors and satellite images. These technologies enable rapid identification and repair of leaks within the water distribution network, enhancing overall efficiency. Key electronic devices include acoustic leak detectors, satellite sensors, handheld monitoring devices, and smart pressure monitoring valves.

Smart irrigation systems are used for precise irrigation scheduling. This is achieved through the utilization of sensor-driven smart irrigation systems combined with weather forecasts. Such approach reduces water waste and optimizes water use for green spaces and agricultural purposes. The systems rely on soil moisture sensors, weather monitoring stations, automated irrigation controllers, and communication modules for remote management.

Grey water recycling was achieved through the establishment of nine dedicated grey water recycling centres. These centres collect and treat wastewater from sinks, showers, and various appliances, repurposing it for landscape irrigation and toilet flushing. The recycling process is supported by electronic monitoring systems, pumps, filtration control units, and automated flow control devices.

Flood risk management systems are used to mitigate these risks. The city employs decentralized stormwater management solutions, also known as Sustainable Urban Drainage Systems. These systems manage rainwater effectively and reduce the burden on conventional drainage networks. Electronic components such as water level sensors, automated control valves, smart flow meters, and telemetry systems are used to monitor and regulate stormwater flow.

Public engagement and education are used to promote sustainable water management practices. Milton Keynes actively engages with residents and businesses through educational programs and public awareness campaigns. These initiatives encourage the adoption of eco-friendly behaviours and community participation in water conservation efforts. Digital communication platforms, mobile apps, and interactive kiosks play a role in these engagement efforts.

UV System Planning for Water Supply is a notable example of innovation. This novelty in water management is the analysis and forecasting of water demand using devices based on the application of ultraviolet waves. The city has developed predictive models based on five different scenarios for population growth and regulatory changes in the construction of new residential buildings. These models assist in optimizing water supply infrastructure and ensuring resilience in the face of urban expansion. Electronic components used in UV systems include ultra violet lamps, control panels, real-time monitoring sensors, and automated alarm systems for maintenance notifications.

The advanced management approach in Milton Keynes and the integration of advanced technological solutions have made it a benchmark for sustainable and intelligent water management in urban environments. By leveraging smart technologies and innovative systems and devices, the city shows how efficient management of water resources can contribute to the creation of a sustainable and resilient urban ecosystem.

2.2 Barcelona, Spain

In Barcelona, the transformation towards smart city started 35 years ago and further developed according to the 2012 model, which ensures efficient services for all citizens across various levels of urban management through information and communication technology. The core concept behind the model is managing the city as a "network of networks" [16]. The model encompasses 12 sectors, including environmental protection, mobility, energy, water, and public open spaces, each defined by specific programs and projects. For most sectors, in Barcelona is employed a three-layer technological structure: (i) Sensors installed throughout the city, connected via the Sentilo platform [17]. (ii) City OS platform: Aggregates and analyses data from various applications. (iii) Open user platform: Facilitates data sharing and analysis results [16].

In the domain of water management, or "smart water," as often emphasized in smart cities, Barcelona introduced remote control technologies in the mid-2010s. These included the management of public green space irrigation, the operation of public fountains, and two networks supplying hot water to 64 buildings. The annual savings attributed to smart water technology during that period were estimated at $58 million [16]. Today, Barcelona is one of the global leaders in smart water management, leveraging various novel technologies across numerous sectors,

Innovative technical systems for water management in Barcelona involve several integrated solutions aimed at optimizing water usage and reducing operational costs. One key initiative is the deployment of a comprehensive sensor network to monitor water levels, flow rates, and leakage detection in real time. These sensors are strategically placed across the water distribution network and connected to the Sentilo platform [17], which allows for centralized data collection and analysis.

Additionally, in Barcelona are utilized smart irrigation systems in its public green spaces. These systems rely on soil moisture sensors (Fig. 2) and weather data to determine the optimal amount of water needed, significantly reducing water wastage. Remote control units enable city managers to adjust irrigation schedules and monitor the system's performance from a central dashboard. The implementation of this technology has led to more efficient water use and healthier urban greenery.

Public fountains in the city are also equipped with smart control systems that monitor water quality, detect malfunctions, and optimize operating hours. These systems are managed remotely, allowing for immediate response to any issues and contributing to significant maintenance cost reductions.

Figure 2 Smart irrigation unit with water level sensor in Barcelona (source: ajuntament.barcelona.cat)

Another notable innovation is the use of advanced metering infrastructure for residential and commercial water consumption. Smart water meters provide real-time data on water usage, helping both utility providers and consumers to identify and address inefficiencies. These meters are connected to the City OS platform, enabling detailed consumption analytics and the development of predictive maintenance strategies.

The electronic devices essential for these solutions, include IoT-enabled sensors (such as flow meters and soil moisture sensors), communication modules (for real-time data transmission), and smart controllers for automated irrigation and fountain management. The data from these devices is aggregated and analysed through cloud-based platforms, allowing for actionable insights and informed decision-making.

The holistic approach of Barcelona to smart water management demonstrates the potential of combining advanced technology with data-driven strategies to create a more sustainable and efficient urban environment [18]. The city's on-going commitment to innovation in this sector has positioned it as a model for other cities seeking to adopt similar solutions.

2.3 Berlin, Germany

The improvement of water management in the City of Berlin happened as a part of the political agenda on digitalization, adopting the term "digital water" similarly to other smart cities [19]. Key pressures on the urban water cycle have been identified, including: 1) drinking water production, 2) discharges of stormwater and treated wastewater, 3) combined sewer overflows, and 4) recreational purposes. Based on these challenges, the following objectives have been formulated: enhancing the performance of wastewater and drinking water infrastructure; and encouraging public engagement in urban water management. In Fig. 3 wastewater pump station at the plant in Berlin is presented [20].

Experts are focused on digital water, which illustrates a commitment to integrating technological advances to optimize urban water systems and promote participatory management approaches. Activities related to digital water in Berlin involve the several important solutions which will be explained [19].

Figure 3 Wastewater pump station at the plant in Berlin [20]

Innovative technical systems for water management in Berlin include a number of leading solutions designed to improve efficiency, sustainability, and transparency in water-related processes. One such system involves the deployment of IoT-enabled sensors in water distribution and wastewater infrastructure. These sensors monitor water flow, pressure levels, and detect leaks in real-time, enabling quick intervention and maintenance, which reduces water losses. Another innovative solution is the use of digital monitoring systems for tracking unauthorized water connections. This involves advanced surveillance and data analysis technologies that help utility companies detect illegal connections, ensuring the integrity of the water supply network.

In Berlin are also applied next-generation sensors for real-time bacterial measurement in the Spree River and combined sewer overflow systems. These sensors provide immediate data on water quality, allowing authorities to take prompt action to prevent public health risks and maintain safe water conditions for recreational activities. In addition, augmented reality (AR) technology is applied to support water infrastructure projects and promote tap water consumption. AR visualizations are used to educate the public about water system upgrades and investments, thereby fostering community engagement and acceptance of necessary infrastructure developments.

To further optimize water usage, smart irrigation systems have been installed in public parks and green spaces. These systems rely on soil moisture sensors and weather data to determine the optimal watering schedule, thereby conserving water resources. The electronic devices crucial for these innovative solutions include IoT sensors for water quality and flow monitoring, AR headsets for visualization in public engagement initiatives, smart meters for accurate consumption tracking, and cloud-based platforms for data aggregation and analysis.

An emphasis on data-driven water management has also led to the development of a centralized digital platform for visualizing operations at drinking water wells. This platform integrates data from multiple sources and provides decision-makers with valuable insights for optimizing water production and distribution.

By integrating these advanced technologies, Berlin is positioned as a leader in digital water management. This demonstrated the potential for smart solutions to solve complex urban water challenges, while simultaneously promoting sustainability and citizen participation.

2.4 Paris, France

The broader Paris region, home to 7.2 million residents, has implemented integrated smart water management within its sewer system. The establishment of this system dates back forty years, when the primary goal was to improve the deteriorating water quality of the Seine and Marne rivers. The construction of numerous wastewater treatment plants and transport sewer networks, along with the installation of real-time monitoring sensors, has brought the region close to meeting the stringent requirements of the EU Water Framework Directive. Since 2008, the MAGES real-time control system [21] has been in operation, integrating data from 2000 sensors into a hydraulic model that simulates flow under various scenarios. This enables optimized management of multiple treatment plants under different weather conditions. The smart system allows the rerouting of sewage from one facility to another, enhancing system reliability during planned maintenance or unexpected incidents, such as system component failures. In Fig. 4 schematic of data and MAGES output processing operations is shown.

In addition to MAGES, there are several other innovative technical systems that improve water management. One such solution is the deployment of IoT-enabled water quality sensors across the Seine and Marne rivers. These sensors provide real-time data on parameters such as turbidity, pH, and pollutant levels, helping authorities promptly identify and mitigate water quality issues.

Smart stormwater management is another critical innovation. Automated detention basins equipped with flow regulation devices control the release of stormwater into the sewer network, preventing flooding and reducing the load on wastewater treatment plants during heavy rainfall. Advanced data analytics and AI-based predictive models are integrated into the MAGES system to forecast potential hydraulic issues and optimize operational decisions. This technology allows operators to anticipate system bottlenecks and pre-emptively reroute sewage flows to maintain the system stability. Smart meters have been introduced for accurate monitoring of water consumption in residential, commercial, and industrial sectors. These meters provide consumers and water utilities with detailed insights into usage patterns, enabling more efficient water resource management. Electronic devices crucial for these solutions include flow sensors, water quality probes, communication modules for real-time data transmission, and programmable logic controllers (PLCs) for automated system operation. Data from these devices is aggregated and visualized through cloud-based platforms, enabling centralized monitoring and control. Also, drone technology is utilized for the inspection of large sewer tunnels, reducing the need for hazardous manual entry and enhancing maintenance efficiency. Thermal imaging cameras on these drones help detect structural weaknesses or leaks within the infrastructure.

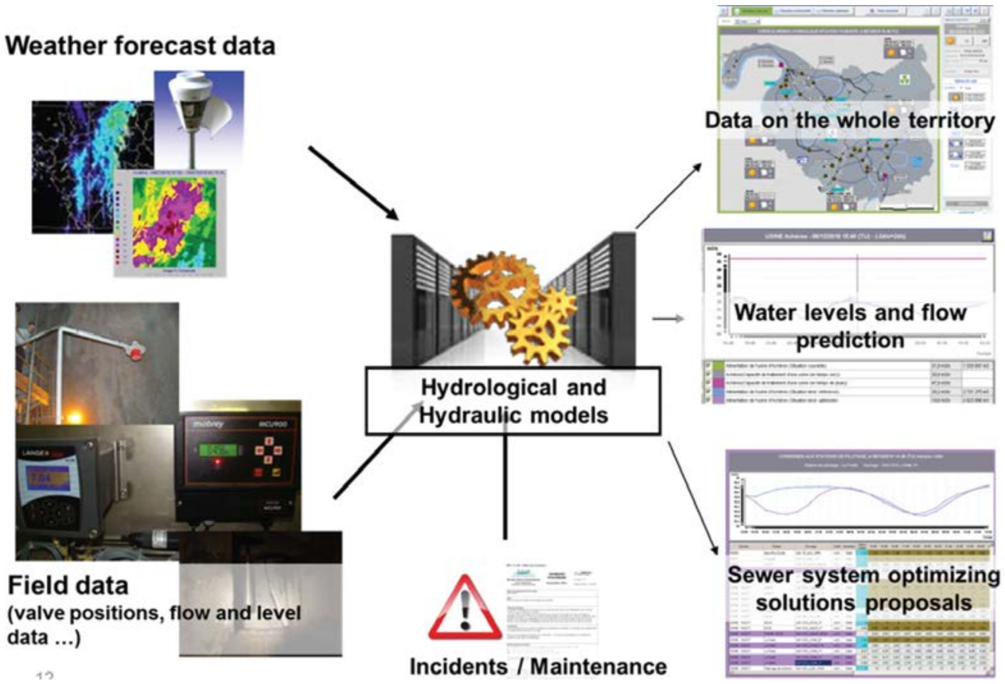

Figure 4 Schematic of data and MAGES output processing operations for Paris [21]

Through these technological advances, Paris is at the forefront of smart water management, demonstrating a commitment to sustainability, innovation and compliance with strict environmental regulations.

2.5 Stockholm, Sweden

Digital Demo Stockholm is an innovation partnership between the public sector, academia and private industry that leverages digital solutions to facilitate and improve the quality of life for the citizens of Stockholm. According to this initiative, the management aims to make the city the "smartest city" in the world by 2040 [22]. The water observation network project encompasses a connected real-time water quality monitoring system across the entire city. It was developed to address issues related to water, the environment, and climate through ICT, utilizing an extensive IoT sensor system integrated throughout Stockholm's water supply network. The network monitors key water quality parameters, including conductivity, pH, temperature, and dissolved oxygen. Additionally, big data analytics are combined with the development of water modelling algorithms capable of filtering sensor data to provide a broader understanding of water quality changes. Such changes could alert the city and water utilities to events like algal blooms or the discharge of polluted industrial wastewater while providing detailed information on where and when they occur. This allows the city to take early mitigation measures, allocate resources efficiently, minimize operational costs, and enhance overall process efficiency [22].

In addition to real-time water quality monitoring systems, smart water measurement and leak detection technologies are also used in Stockholm. The smart water meters, equipped with IoT sensors, provide accurate and real-time data on water consumption, allowing for better resource management, reduced waste, and more effective pricing models for consumers. The meters send data directly to a centralized system, which provides detailed consumption insights and allows for the identification of abnormal usage patterns, such as leaks or unauthorized water use.

Furthermore, advanced wastewater treatment systems are integrated, including membrane bioreactors, which significantly improve the efficiency of the water treatment process. These systems use a combination of biological treatment and filtration to produce cleaner, safer water. Data from these systems are constantly monitored and analysed to optimize performance and ensure that treated water meets environmental standards.

Also, predictive analytics, powered by machine learning algorithms, to forecast potential water demand and supply fluctuations are applied. This helps utilities proactively manage water resources, ensuring a consistent supply even during peak demand or periods of drought.

Electronic devices used in these solutions include smart water meters, IoT sensors for monitoring water quality and pressure, communication modules for transmitting data to central platforms, and advanced data processing devices that analyse sensor data in real-time. Additionally, the city employs automated control systems, such as programmable logic controllers, to regulate water flow and optimize wastewater treatment processes based on real-time data inputs.

With the continued integration of digital technologies, it is possible to achieve water management systems that are more efficient, sustainable and resilient to environmental challenges. Fig. 5 illustrates contents of electrical room in facilities for drinking water treatment [23].

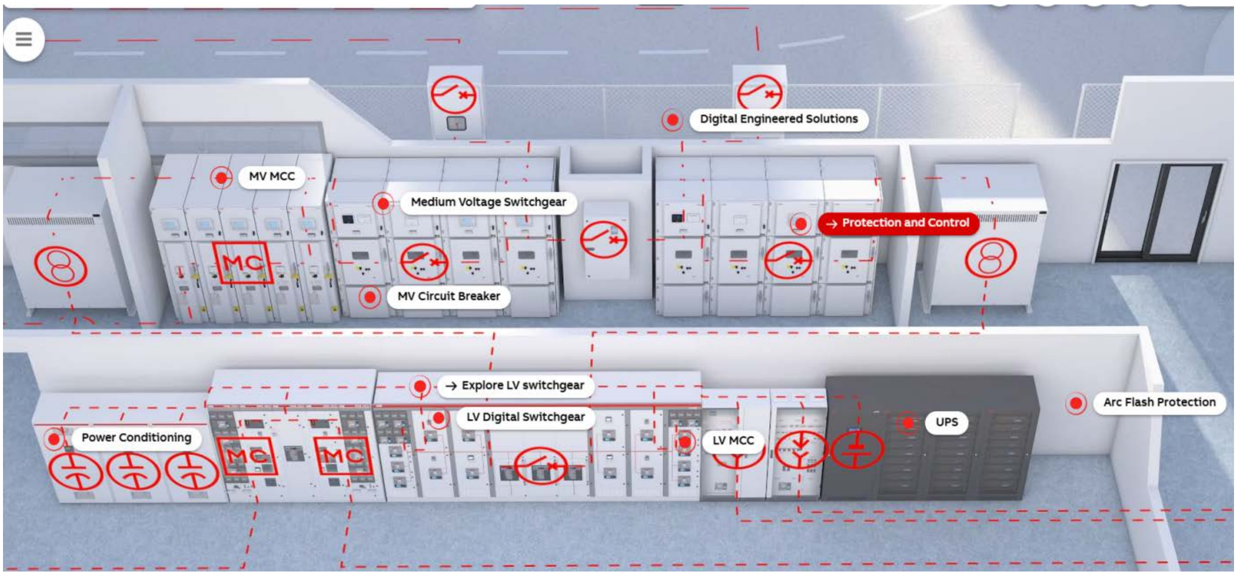

Figure 5 Electrical room in the drinking water treatment facility [23]

2.6 Rome, Italy

In Italy, the fragmented and inefficient management of water resources results in an average of 42% water volume being lost within the network each year [24]. This is additional reason for innovative solutions in many areas, but most promising solutions for water management are applied in Rome. Smart water management strategies have been actively implemented to enhance the efficiency and sustainability of its water resources. A significant initiative is the development of the "Vaidi" application by Ace, the primary water utility from Rome [25].

Remote monitoring is applied by using smart water sensors placed throughout the distribution network in order to monitor water quality and to detect changes in flow and pressure in real-time. IoT-connected devices send continuous data to centralized systems for faster decision-making. Similar to Milton Keynes, smart water meters equipped with wireless communication modules are used in Rome. These devices provide both consumers and water utilities with real-time information on water consumption, helping detect leaks and promoting efficient water use.

Supervisory Control and Data Acquisition (SCADA) systems are widely employed for monitoring and controlling water distribution systems in real time. The SCADA systems gather data from sensors and remote devices across the city and present it through a centralized control interface. Water utility integrates sophisticated acoustic sensors to identify underground water leaks. These sensors help pinpoint leaks without the need for extensive excavation.

Satellite imagery - remote sensing, is used to identify anomalies in soil moisture patterns that may indicate hidden leaks in the water distribution system. Automated flow control valves are the electronically controlled valves which regulate the water flow based on demand patterns and emergency situations. They reduce wastage and maintain system pressure. Also very useful are energy-efficient smart pumps, equipped with sensors and variable speed drives, which optimize water pressure and minimize energy consumption during peak and low demand periods.

In addition, advanced data analytics and AI-driven predictive models to forecast water demand, optimize resource allocation, and improve maintenance schedules are applied. Besides, water supply includes advanced UV disinfection systems that ensure safe drinking water by effectively inactivating harmful microorganisms.

All applied innovative systems and new technologies can additionally contribute to the improvement of water resources management and make this management more efficient.

3 SMART WATER MANAGEMENT IN SELECTED CITIES IN EUROPE

The elements of smart urban water management in the six cities in Europe shown in this paper are summarized in Table 1. These elements correspond to the scheme illustrated in Fig. 1. Areas of analyses water management are presented with followings acronyms: (DC) Data collection, analysis and modelling, (GW) Greywater recycling, (PE) Public engagement and education, (US) UV system planning - water supply, (FR) Flood risk management systems, (IR) Smart irrigation systems, (AD) Advanced leak detection technologies, (SW) Smart water meters.

Table 1 The elements of water management addressed in the analysed cities

Smart city	Urban water smart management element							
	DC	GW	PE	US	FR	IR	AD	SW
MiltonKeynes								
Barcelona								
Berlin								
Paris								
Stockholm								
Rome								

The analysed cities have gone through similar process, well summarized in the evidence-based Roadmap: 6 steps towards Water Smart Cities [26]:

1. Identify challenges and opportunities
2. Define Water Smart City vision
3. Explore co-creation opportunities
4. Co-design solutions
5. Define Business case
6. Implement & evaluate (Continuous).

As water management is a critical aspect of urban sustainability and resilience, innovative technologies in various areas are increasingly adopted in many cities of Europe. In addition to the analysed cities, it should certainly be noted that some aspects of innovative technologies in the field of water management were applied in many other cities as well.

Therefore, for example, in Amsterdam (Netherlands), advanced solutions for water purification, storage and flood prevention have been developed. Also, phosphate recovery systems ensure efficient recovery of valuable nutrients from wastewater, contributing to the circular economy. The use of smart rainwater storage systems achieves temporary storage of rainwater to mitigate urban flooding. Aquifer Thermal Energy Storage (ATES) that integrates water storage with energy-efficient heating and cooling systems for buildings is applied [27].

It is known that Copenhagen (Denmark) is a leader in climate adaptation strategies and smart water management. Cloudburst tunnels are underground systems designed to channel and store stormwater during heavy rainfall. Smart water meters are real-time monitoring devices that optimize water use and reduce water loss. Green-blue infrastructure enables improvement of water absorption and reduction of runoff. This is achieved by using permeable surfaces and green roofs [28].

Rotterdam (Netherlands) was among the first to start implementing flood prevention and urban water storage solutions. Alternative water storage basins have been implemented to collect and store rainwater in order to prevent flooding. Applied smart urban drainage systems are sensor-based systems that improve drainage efficiency. A famous Water Plaza (Benthemplein water square) is multifunctional public spaces designed for temporary storage of rainwater [29].

Advanced water reuse and smart irrigation technologies are implemented in Lisbon (Portugal). The application of smart irrigation systems optimizes the use of water in parks and agricultural areas by using real-time data. AI-based distribution network management enables leaks to be detected and pressure to be managed to improve efficiency [30].

Water management in Vienna (Austria) is focused on groundwater protection and biofiltration technology. The use of automated groundwater monitoring stations enables the collection of data on water quality and levels in real time. Biofiltration systems naturally purify water for reuse in urban areas.Dual purpose water networks effectively separate potable and non-potable water streams [31].

It should be noted that in Helsinki (Finland) data-based approaches and advanced wastewater treatment technologies are also applied. IoT-based water management systems enable the monitoring and optimization of the efficiency of water networks. Membrane bioreactors (MBRs), which are applied, are advanced systems for the treatment of wastewater. Smart water sensors detect leaks and measure consumption in real time, what is of high importance [32].

Certainly, the experiences of these cities should be analyzed and the possibilities of adaptation and application in the conditions of our region should be considered. An insight and a systematic review of the used devices and new technologies applied to solve water management challenges can be of considerable interest.

4 CONCLUSION

Innovative approaches to water management in cities, characterized by the application of advanced technical and electronic systems to optimize water usage and ensure compliance with water quality standards, are particularly emphasized in the development of smart cities. Solutions presented in selected cities of Europe indicate two possible strategies for achieving smart city objectives in the domain of water management potentially applicable in different areas of Serbia, as well as Bosnia and Herzegovina: a comprehensive or partial approach, based on innovate technology elements and devices.

The comprehensive approach, demonstrated by the examples of Milton Keynes and Barcelona, is facilitated by the systematic collection of thematic data enabled through the widespread deployment of information and communication technologies. The partial approach is exemplified by Berlin, Paris, Stockholm, and Rome highlighting the feasibility of gradual implementation. In addition, there is a possibility of applying innovative approaches in certain elements only, which was initially done in several cities.

Beyond technological advancements and the digitization of water management processes, the transition towards sustainable urban water management in smart cities necessitates the incremental development of services through active collaboration between stakeholders, including local communities, municipalities, enterprises, and civil society actors, alongside developers. This cooperative framework leads to the creation of customized solutions that align with the specific needs and expectations of stakeholders, thereby fostering adaptive and resilient water management systems.

It is imperative to underscore the critical role of institutional support in the development of smart cities. Such support often originates from multiple levels of governance, including national institutions, international organizations, academic institutions, and associations representing relevant industrial sectors. The strategic integration of these participants' efforts in the process and efforts of etengineers in various areas, for applications of novel technologies, ensures the establishment of a robust and adaptive framework for water resource management, enhancing the sustainability and resilience of urban environments.

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