Smart Technologies for Sustainable Water Management

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As projections highlight that half of the global population will be living in regions facing severe water scarcity by 2050, sustainable water management policies and practices are more imperative than ever. Following the Sustainable Development Goals for equitable water access and prudent use of natural resources, emerging digital technologies may foster efficient monitoring, control, optimization, and forecasting of freshwater consumption and pollution. Indicatively, the use of sensors, Internet of Things, machine learning, and big data analytics has been catalyzing smart water management.

smart water management | digitalization | urban sustainability

1. Introduction

Freshwater resources have been depleting at an alarming rate due to the growing world population, climate change, and increasing industrialization [1][2]. Notably, researchers predict that 52% of the world's population in 2050 (9.7 billion people forecasted) will be living in water-stressed or scarce regions [3]. In this light, health, environmental, and social concerns necessitate the design and implementation of sustainable water management policies [4][5][6]. To that end, the United Nations' Sustainable Development Goals (SDGs) have set specific targets for universal and equitable clean water access (SDG#6) [7] and responsible use of natural resources, including freshwater (SDG#12) [8], by 2030. At the same time, projections highlight that 68% of the global population will be living in urban areas by 2050 [9]. Growing urbanization has been accelerating water scarcity in urban areas, leading to severe water imbalance and shortages [10][11][12]. Therefore, sustainable actions, policies, and technologies towards urban water stewardship, at municipal and/or residential/industrial levels, have been emerging as imperative [13][14][15].

Following the 4th industrial revolution, urban water management has also been transformed into "smart" [16][17] as the only viable way to achieve water sustainability in the cities of the future [18]. According to the International Water Resources Association [19], "smart water management" utilizes information and communication technology (ICT) and real-time data to tackle water management challenges by integrating digital solutions into urban, regional, and/or national strategies, indicatively referring to water quality and quantity, efficient irrigation, leakages, pressure and flow, floods, and droughts. On this basis, smart technologies have been considered to improve water resource management and, in turn, limit water scarcity globally [20]. Thus, the European Union has been already funding several research projects in this direction (e.g., [21][22]), while the water market has been shifting to digitalized business models [23]. It should be highlighted that automation in complex urban water systems is principally based on receiving feedback from sensors and then using computer algorithms to analyze signals and propose specific actions [24]. In a broader context, several digital technologies, such as sensors and Internet of Things (IoT) networks, cloud-based technologies, algorithms (e.g., machine learning), as well as big data analytics [25][26][27] have been used for achieving water security in urban landscapes [15] and industrial facilities [28]. Not only does the adoption of digitalization improve efficiency and flexibility in urban water systems but also provides sophisticated novel services to the society with reduced costs [29]. In particular, these disruptive interventions have facilitated the real-time monitoring, optimization, and forecasting of freshwater consumption and pollution [30], either at a municipal level (e.g., [31]) or a residential/industrial one (e.g., [32], further serving as decision support tools [33]. It should be underlined that special emphasis has been placed on smart leakage detection as a part of sustainable water supply networks [34].

2. Smart Technologies for Sustainable Water Management

In this section, the analysis of the extant literature, divided by the level of analysis (i.e., municipal, or residential/industrial), is performed. Information about the scientific approach, the digital technologies used in urban water supply and distribution, and the major scope of each research article are provided in brief. **Table 1** summarizes the basic distillation of the literature review analysis in a systematic approach according to the three main categories (i.e., level, technology, focus). **Table 2** provides a matrix of groups of papers belonging to the same categories. More specifically, the matrix summarizes the categorization of the papers under consideration in terms of the level of analysis along with the adopted technology and focus. It can be easily derived that most of the studies were utilizing sensors and IoT networks, data analytics, as well as algorithms, while the use of cloud-based technologies and GIS systems can be characterized as rather obsolete. Furthermore, except for monitoring, the majority of the papers focus on leakage detection, as it is one of the most important parameters for vulnerability assessment and risk management of infrastructure and critical facilities.

2.1. Municipal Level

In the work of Devasena et al. [35], an IoT-based water distribution system to monitor water flow was proposed, quantity, and leakage in an urban distribution system. Although the sensors were implemented at individual households, the analysis was performed and controlled centrally by the local municipality. Similarly, Slaný et al. [17] developed a smart metering network to monitor water usage and detect leakages. The network was firstly simulated in laboratory conditions to optimize its functionality and then put into real-world operation in a Czech municipality. From a more comprehensive perspective, Howell et al. [33] described the integration of a Semantic Web of Things with an IoT platform for smart water networks. The ontology and rule-based system allowed for seamless integration of sensors and comprehensive interpretation of lower- and higher-order knowledge. The proposed knowledge-based information system extended its functionality, is more scalable, and increased its interoperability capacity.

Notably, several authors have been particularly focused on leakage detection. A novel methodology was developed by Levinas et al. [32], using sensors and algorithms for predicting any leaking pipes in urban water distribution systems. The authors further performed computational data analytics to simulate the networks' performance. On top of this, Gong et al. [36] utilized smart water technologies, including accelerometers and algorithms, to monitor and detect cracks and leaks in urban distribution systems in a timely manner. Furthermore, Stephens et al. [37] implemented an acoustic sensors network for the early detection of leakages in an urban distribution network in Australia. The aim of the proposed IoT solution was to localize and repair cracks timely before the uncontrolled failure of the system.

Except for the technological perspective of digital leakage detection, several authors further targeted the sustainable benefits. Ramos et al. [38] developed smart water grids, modelled using GIS, to monitor and control water losses through identifying the urban network's leakages and cracks. The proposed IoT solution supported process optimization and decision-making for continuous improvement in terms of economic and sustainable (e.g., CO_2 emissions reduction) efficiency. Moreover, Geng et al. [39] created an algorithmic method for leakage detections based on sensor-monitoring data in complex water distribution networks. Compared with the other traditional methods, the proposed one is more effective in locating the leaky pipe and promoting sustainable water utilization.

Farah et al. [40] introduced a smart water network, capable of monitoring water usage, as well as identifying leakages. This is accomplished by the use of sensors and algorithmic analysis supports computing additional indices (e.g., minimum night flow), as well as analyzing operating hours flow rate. In addition, Farah and Shahrour [41] presented an innovative approach to leakage detection that is based on the traditional water balance and an enhanced minimum night flow implementation. The introduction of thresholds to the minimum night flow method exhibited highly positive results in the demonstration on the campus of Lille University, representing a small town. Farah and Shahrour [42] developed a smart metering system for timely leakage detection, implemented again in the same university. The review analysis presented herein highlighted that early identification of leaks can significantly reduce water losses and related costs.

Dealing mainly with algorithmic applications, Cristodoulou et al. [43] introduced a heuristic algorithm for sensor placement that performs a longitudinal optimization on entropy properties. By maximizing entropy in the system, sensor locations were determined, and, as the use case highlighted, nearly optimal solutions were reached, while water loss incidents were detected. The work of Comboul and Ghanem [44] contributed by developing and testing an algorithm dealing with the uncertainty of demand and sensor accuracy in water distribution networks monitored for quality. Intrusions, accidents, and contaminations were modeled by the algorithm to optimize sensor layout in the network. Results revealed that sensor layout was highly dependent on the demand hypothesis. Although imperfect sensor grids seemed more robust, they required a higher number of sensors to operate efficiently.

Additional smart water management solutions, mainly referring to water use and quality control, were identified at a municipal level. In the recent study of Oberascher et al. [45], a system that implemented smart rain barrels, as an IoT-based solution for rainwater harvesting, is introduced. The barrels included a network of sensors and controllers attached to open-source software to allow for efficient monitoring and generate simulation scenarios for water management. Although implemented at the household level, all digital rain barrels were centrally controlled by an Austrian municipality, acting as alternative storage units of the main urban water infrastructure. Amini et al. [46] attempted to create a smart framework to monitor, control, and manage groundwater wells and pumps using a combination of machine learning algorithms and statistical analysis. The authors finally proposed a forecast model to predict the water flow rate in Mashhad City wells in Iran. Finally, Llausàs et al. [47] utilized aerial imagery and remote sensing-based technologies to map residential swimming pools in the area of Barcelona to estimate the related water use. The authors further compared their results with cadastral data to support spatial planning.

In terms of water pollution detection, Chen and Han [48] implemented a wireless sensor network to monitor the water quality in the city of Bristol to enhance the efficiency of the city's water management system. At the same time, Castrillo and García [49] utilize variables that are commonly measured in-situ as surrogates to estimate the concentrations of nutrients in an urban catchment in England, making use of machine learning models, specifically random forests. Legin et al. [50] applied multisensory arrays to assess the urban water environmental safety, under diverse climatic and anthropogenic conditions, receiving samples from two different wastewater treatment plants in St. Petersburg. Focusing on smart sewage systems, Abbas et al. [51] utilized the campus of Lille University as a demonstrator of a smart city to monitor water used for drinking, sewage, electrical, and district heating networks. The analysis supported the numerical modelling and detection of eventual connections between the sewage and stormwater systems.

2.2. Residential/Industrial Level

At a residential level, Antzoulatos et al. [16] proposed an IoT network for monitoring and controlling water usage, as well as providing data analytics and management solutions to provide innovative solutions to consumers and water utility companies. The complete platform aimed to support decision-making in the field of urban water management. Similarly, Nie et al. [52] implemented smart water meters to monitor water quantity and quality to detect leakages or potential contamination. By retrieving data from sensors, they further use algorithms to perform data analysis. The proposed IoT network could allow both customers and companies to control water use in a proactive manner, take the correct decisions, and promote sustainable water supply. In a more integrated manner, Howell et al. [53] introduced semantic web technologies that provide connectivity between demand and supply of water for buildings and providers. The effective instantiation of domain ontology to the system, adding improved visualization and processing capacity, constituted the main innovation of this work.

Moreover, Gautam et al. [54] developed an IoT system to monitor water consumption (i.e., the water level in tanks) in an Indian urban housing complex. Ultrasonic sensors retrieved the related data, while machine learning algorithms forecasted daily water requirements and leaking pipes. Rout et al. [55] developed an IoT protocol architecture including sensors and algorithms to monitor, analyze, and forecast water consumption and loss at a household level. The adopted methodology took into consideration weather data to provide a seasonal analysis. Further considering potential water pollution, Kalimuthu et al. [56] proposed a smart water management system to monitor and analyze both water quality and quantity in buildings, using sensors and algorithms. All data were gathered in the cloud-based systems to be utilized for data analytics. It should be underlined that this system could be expanded for each house at a municipal level. Emphasizing data analytics, Kofinas et al. [57] developed an algorithm capable of producing realistic and reliable synthetic household water usage data, serving the need to preserve the continuity of data for post-processing. The algorithm was tested on two highly differentiated use cases in two European countries with meaningful results.

Table 1. Systematic literature taxonomy of smart urban water management.

Article	Level		Technology						Focus						
	MU	RI	SE	IoT	GIS	CT	AL	DA	MO	CO	LD	OP	SI	FO	DS
Abbas et al. [51]	✓		✓		✓			✓	✓						
Amini et al. [46]	✓		✓				✓	✓	✓	✓				✓	✓
Antzoulatos et al. [16]		✓	✓	✓		✓		✓	✓	✓					✓
Castrillo and García [49]	✓		✓				✓	✓	✓					✓	
Chen and Han [48]	✓		✓	✓					✓						
Christodoulou et al. [43]	✓		✓		✓		✓		✓		✓	✓			
Comboul and Ghanem [44]	✓		✓				✓		✓			✓	✓		
Devasena et al. [35]	✓		✓	✓					✓	✓	✓				
Farah et al. [40]	✓		✓		✓		✓		✓	✓	✓				
Farah and Shahrour [41]	✓		✓	✓					✓		✓				
Farah and Shahrour [42]	✓		✓	✓					✓	✓	✓				
Gautam et al. [54]		✓	✓	✓			✓	✓	✓		✓			✓	
Geng et al. [39]	✓		✓				✓		✓		✓				
Gong et al. [36]	✓		✓	✓			✓		✓		✓				
Howell et al. [53]		✓	✓	✓	✓		✓	✓	✓	✓		✓			
Howell et al. [33]	✓		✓	✓			✓	✓	✓		✓	✓			✓
Kalimuthu et al. [56]		✓	✓	✓		✓	✓	✓	✓	✓					
Kofinas et al. [57]		✓	✓				✓	✓	✓					✓	
Legin et al. [50]	✓		✓						✓						
Levinas et al. [32]	✓		✓				✓	✓	✓		✓		✓		

Article	Level		Technology						Focus						
	MU	RI	SE	IoT	GIS	CT	AL	DA	MO	CO	LD	OP	SI	FO	DS
Llausàs et al. [47]	✓		✓		✓				✓						
Nie et al. [52]		✓	✓	✓		✓	✓	✓	✓	✓	✓				✓
Oberascher et al. [45]	✓		✓	✓			✓		✓	✓			✓		
Ramos et al. [38]	✓		✓	✓	✓				✓	✓	✓	✓			✓
Rout et al. [55]		✓	✓	✓			✓	✓	✓					✓	
Slaný et al. [17]	✓		✓	✓					✓		✓	✓	✓		

Level	Municipal	Residential/industrial
Technology		
Sensors	All articles	
Extended IoT network	Abbas et al. [51]; Chen and Han [48]; Devasena et al. [35]; Farah and Shahrour [41]; Farah and Shahrour [42]; Gong et al. [36]; Howell et al. [33]; Oberascher et al. [45]; Ramos et al. [38]; Slaný et al. [17]; Stephens et al. [37]	Antzoulatos et al. [16]; Gautam et al. [54]; Howell et al. [53]; Kalimuthu et al. [56]; Nie et al. [52]; Rout et al. [55]
GIS	Christodoulou et al. [43]; Farah et al. [40]; Llausàs et al. [47]; Ramos et al. [38]	Howell et al. [53]
Cloud-based technology	No article	Antzoulatos et al. [16]; Kalimuthu et al. [56]; Nie et al. [52]
Algorithms	Christodoulou et al. [43]; Comboul and Ghanem [44]; Farah et al. [40]; Geng et al. [39]; Gong et al. [36]; Howell et al. [33]; Levinas et al. [32]; Oberascher et al. [45]	Gautam et al. [54]; Howell et al. [53]; Kalimuthu et al. [56]; Kofinas et al. [57]; Nie et al. [52]; Rout et al. [55]
Data analytics	Abbas et al. [51]; Amini et al. [46]; Castrillo and García [49]; Howell et al. [33]; Levinas et al. [32]	Antzoulatos et al. [16]; Gautam et al. [54]; Howell et al. [53]; Kalimuthu et al. [56]; Kofinas et al. [57]; Nie et al. [52]; Rout et al. [55]
Focus		
Monitoring	All articles	
Control	Amini et al. [46]; Devasena et al. [35]; Farah et al. [40]; Farah and Shahrour [42]; Oberascher et al. [45]; Ramos et al. [38]	Antzoulatos et al. [16]; Howell et al. [53]; Kalimuthu et al. [56]; Nie et al. [52]
Leakage detection	Christodoulou et al. [43]; Devasena et al. [35]; Farah et al. [40]; Farah and Shahrour [41]; Farah and	Gautam et al. [54]; Nie et al. [52]

Level	Municipal	Residential/industrial
	Technology	
	Shahrour [42]; Geng et al. [39]; Gong et al. [36]; Howell et al. [33]; Levinas et al. [32]; Ramos et al. [38]; Slaný et al. [17]; Stephens et al. [37]	
Optimization	Christodoulou et al. [43]; Comboul and Ghanem [44]; Howell et al. [33]; Ramos et al. [38]; Slaný et al. [17]	Howell et al. [53]
Simulation	Comboul and Ghanem [44]; Levinas et al. [32]; Oberascher et al. [45]; Slaný et al. [17]	No article
Forecasting	Amini et al. [46]; Castrillo and García [49]	Gautam et al. [54]; Kofinas et al. [57]; Rout et al. [55]
Decision support	Amini et al. [46]; Howell et al. [33]; Ramos et al. [38]	Antzoulatos et al. [16]; Nie et al. [52]

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