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SCIENTOMETRIC REVIEW OF SMART WATER MANAGEMENT LITERATURE FROM THE SUSTAINABLE DEVELOPMENT GOAL PERSPECTIVE

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Abstract. Water is essential to human survival; however, many people, particularly those in poorer countries, lack access to reliable sources of clean and safe water. Despite decades of effort to address this issue, water sustainability remains elusive even today. Smart technologies have been widely adopted for water management, rendering smart water management a promising path to achieving water sustainability. Nevertheless, the efficacy of such smart water management in attaining sustainability remains unclear. This study aims to investigate the progress made in pursuing water sustainability with smart water management through a scientometric literature review. The Scopus database was employed to extract a pool of 460 candidate publications, which were then analyzed for content using bibliometric analysis and VOSviewer software. Nine clustered research themes were classified, corresponding to the nine targets of sustainable development goals (SDGs) for water. The findings show that engagement across these topics is highly unequal, providing substantial guidance on where emerging research efforts should be concentrated. The novelty of this study mainly lies in the SDG perspective that provides a significant but overlooked angle for observing progress in smart water management domain. The findings can enlighten the international water industry to create a more favorable environment for regions lagging in using smart technologies to facilitate overall water sustainability.

Keywords: water resources, water sustainability, smart water management, UN sustainable development goals, SDG 6.

Introduction

Water is a crucial resource for human well-being, but years of human misconduct have resulted in a global scarcity of this once-abundant resource (Waage et al., 2015). The United Nations (UN) has launched a worldwide campaign to "Ensure the availability and sustainable management of water and sanitation for all," which is articulated in "Sustainable Development Goal (SDG) 6," one of 17 SDGs agreed by all UN member states in 2015 (United Nations, 2015). The SDG 6 initiative recognizes that better water management is fundamental to achieving sustainable global development.

Emerging information and communication technologies (ICTs) offer the water industry a smart, novel, and efficient means to prevent the deterioration of water sustainability (Antzoulatos et al., 2020). Advocates have introduced various state-of-the-art technologies into this industry, such as the Internet of Things (IoTs), big data, artificial intelligence (AI), machine learning, blockchain, Geographic Information Systems (GIS), and wireless sensor networks (e.g. Carminati et al., 2020; Fernández Moniz et al., 2020; Ismail et al., 2022; Nie et al., 2020; Thakur et al., 2021). Seemingly, the smart-sustainability concept has been widely accepted as the way forward in achieving sustainable development in the water sector. However, many academics have noticed that technology alone does not necessarily guarantee sustainable development (Martin et al., 2019). In fact, a considerable body of literature emphasizes technology inventions, often neglecting their application status in practice (Cowie et al., 2020). Therefore, experts have urged for an in-depth analysis of existing smart water literature to understand better the linkage between emerging smart technologies and the goal of sustainable water

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development. Such an understanding will provide valuable guidance to the scientific community and water industry on catalyzing the efficacy of smart technologies in expediting practical, positive outcomes. To date, no such literature analysis has explored this connection.

This study aims to systematically review the literature pertinent to smart solutions to global water management issues. The UN's SDG 6 aspirations, definitions, and targets regarding water services are universally accepted. Therefore, the SDG 6 project is adopted as the benchmark theme in this systematic literature analysis. This study aims to answer two research questions:

1. How much progress has been made in using smart solutions to achieve various water sustainability targets?
2. What priorities should future researchers and policymakers focus on to better use smart solutions for achieving water sustainability?

Elsevier's Scopus was selected as the search engine to identify relevant publications due to its comprehensive and authoritative coverage of multidiscipline literature. It has also been widely adopted as a reliable searching tool by many researchers in sustainable development (Blasi et al., 2022). A structured three-stage review process was undertaken. Subsequently, VOSviewer software was used to visualize keyword clusters and linkages among the varied topics. The literature review findings reveal significant imbalances in research attention being paid across the various aspects impacting SDG 6, indicating a need for academics and practitioners to broaden their scope of concern regarding water sustainability. This study provides guidance on where attention should be productively redirected.

The remainder of this study is structured as follows: the next section provides background information on SDG 6, followed by a description of the bibliographic review methodology, discussion of results, recommendations for future research, and a concluding section.

1. Background: targets of SDG 6

Despite some progress made since the establishment of the SDGs (United Nations, 2022a), the world still faces enormous water-related stress levels. The pace of progress is insufficient to meet the SDG requirement, with approximately half of the world's population still lacking access to potable water, sanitation, and hygiene services. This situation persists due to an ongoing lack of necessary and appropriate management methods and facilities (United Nations, 2022a). To address this issue, the UN created SDG 6, which aims to "ensure availability and sustainable management of water and sanitation for all." The United Nations (2015) divided SDG 6 into eight targets to provide clear, measurable, and achievable goals. Figure 1 provides a summary of the definitions of these targets.

Figure 1. Targets of SDG 6 (United Nations, 2015)

The eight targets can be broadly categorized into two categories: "what to do" targets (T1–T6) and "how to do" targets (T7–T8) (Bhaduri et al., 2016). In the context of smart water management, the "what to do" targets specify the specific objectives that ICTs are meant to engage with, and the "how to do" targets indicate how ICTs can be applied more effectively. Although these targets are globally accepted, they can be improved to reflect the interlinkages of SDG 6 with other UN water-related goals (Bhaduri et al., 2016). Essex et al. (2020) proposed a more inclusive performance measurement framework containing 24 indicators aligned with SDG 6 and other water-related SDGs by considering the circular economics of water. To conduct a comprehensive review of smart water management literature, this study integrates the above findings by defining T9, which focuses on the synergies of multiple SDGs. It extracts keywords from indicators and categorizes them into nine targets to serve as the basis for literature classification and analysis. Figure 2 presents the details of this integration.

2. Research methodology

The review comprises three stages (Figure 3). In stage 1, relevant publications were collected for further analysis. Collected publications were classified and preliminarily analyzed from a sustainable development perspective. In stage 3, a detailed literature analysis was conducted. This study adopted the structured three-stage research process because its reliability has been frequently verified by many previous review studies focusing on various research domains (Bao et al., 2018; Kasznar et al., 2021; Yi & Chan, 2014).

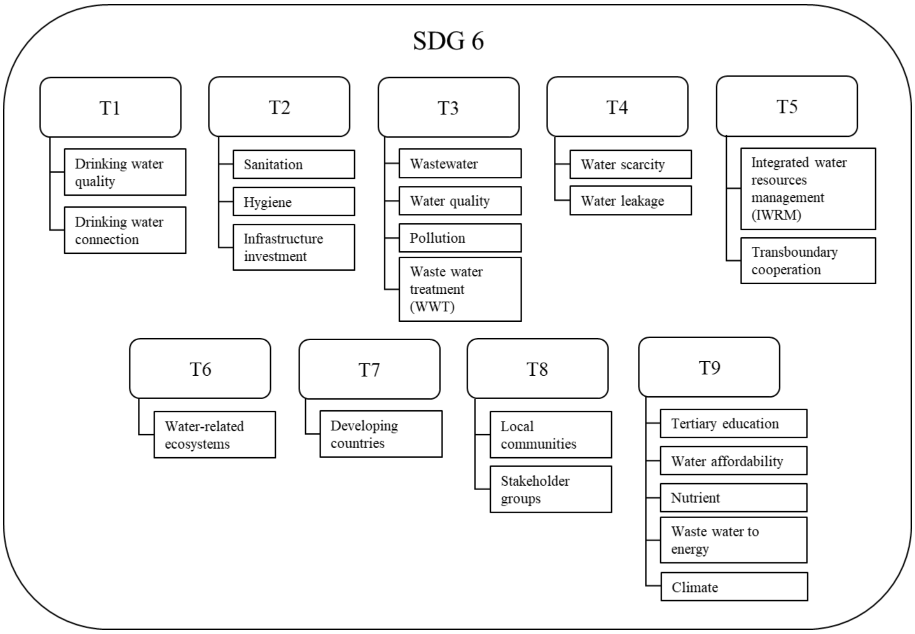

Figure 2. Adapted targets and indicators of SDG 6 (United Nations, 2015; Essex et al., 2020)

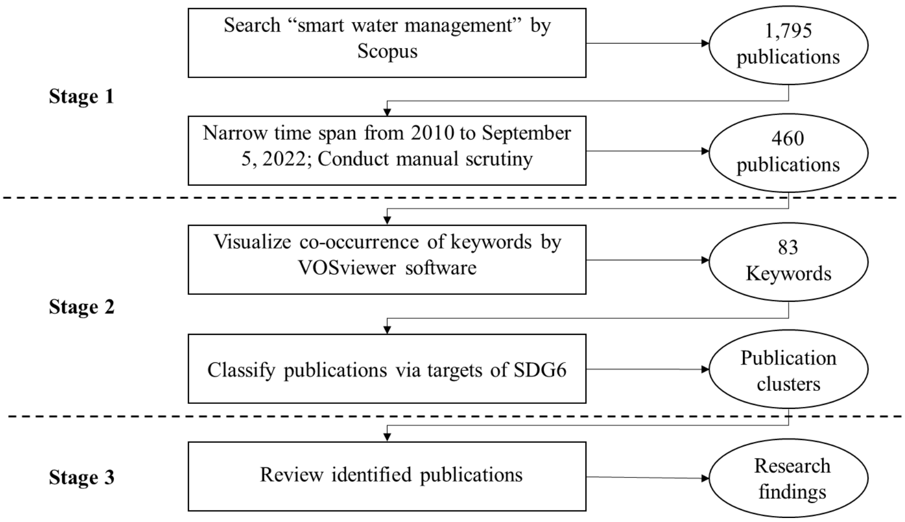

Figure 3. Research process

2.1. Collection of relevant publications

The first step in similar review studies was to determine the keywords for the publication search. However, previous studies in the smart-related literature used either extremely broad or extremely narrow keyword scopes, resulting in extremely large or small document collections. For example, Kasznar et al. (2021) used the term "smart city" to review smart city infrastructure literature, resulting in over 5,200 documents from Scopus. Li et al. (2020) combined the terms "Structure," "Layer," "Framework," and "Smart Water," collecting merely 32 documents on smart water framework research. This study selected "smart water management" as the search keyword to avoid the two extremes. On the one hand, "smart water" is inclusive enough to cover all potential publications on various ICTs in the water sector; on the other hand, "management" sets a proper boundary filtering out technology-centric studies (Cowie et al., 2020).

Although many bibliographic databases offer wide, multidisciplinary coverage of literature, Elsevier's Scopus emerged as the more suitable tool for this review due to several advantages. First, Scopus provides wider overall content coverage than other leading bibliographic databases, such as Web of Science (Pranckutė, 2021), which is beneficial for a systematic literature review. Second, Scopus extensively covers top-tier research publications (Blasi et al., 2022) and has been frequently utilized in literature review studies across various disciplines (Bao et al., 2018; Kasznar et al., 2021; Yi & Chan, 2014). Third, in the specific smart-related research domain, many existing studies have adopted Scopus as the search engine

(Jayasena et al., 2021; Kasznar et al., 2021; Li et al., 2020). Even for review studies using multiple bibliographic databases, Scopus typically produces the best search results (Jayasena et al., 2021). Therefore, this study used Scopus to search for relevant publications, limiting the search to the last 12 years (2010–2022), during which the concept of "smart" had entered the mainstream, and to peer-reviewed articles written in English. The term "smart water management" was searched under "title," "abstract," and "keyword" within Scopus.

Initially, 1,795 publications were retrieved, but many focused on tangential subjects, such as chemistry, oil, and molecular biology. Therefore, the search was further restricted within the "water management" scope. However, some papers focusing on unrelated domain still appeared (e.g., chemistry, oil, and molecular biology). Therefore, the authors manually scanned all the publications by reading the titles, abstracts, and main parts to filter out irrelevant publications. Finally, 460 publications were identified as pertinent for subsequent analysis.

2.2. Classification of identified publications

For the classification of the 460 identified publications, a preliminary analysis was conducted following a three-step pattern:

1. The bibliographic data of the publications was input into VOSviewer software to identify keywords with the highest co-occurrence frequency. VOSviewer is a reliable and widely used bibliometric analysis tool (Blasi et al., 2022).
2. The identified keywords were compared with the target indicators of SDG 6 (Figure 2) to determine their affiliation and to classify related publications into themed groups.
3. The above two steps were repeated until no changes were found.

For instance, the keyword "water quality" was found with 46 co-occurrences, indicating that 46 out of the 460 publications had this keyword. Simultaneously, T3 of SDG 6 refers to improving water quality. Therefore, the identified 46 publications were classified into the T3 group based on the rules established by this study. Publications were allowed to belong to multiple groups because they can include diverse keywords. Additionally, only keywords with explicit connections to certain SDG 6 targets were used for publication classification. The subjectivity and uncertainty of the classification were further minimized because the research was conducted by the same group of researchers (Y. Hong et al., 2012).

2.3. Analysis of publications' countries, institutions, subject categorizes and sources

As shown in Table 1, the United States (U.S.), China, Italy, Australia, and India have the highest number of publications in smart water management domain for the past decade. In the U.S., only 17 researchers were involved in at least two publications, whereas the vast majority of researchers participated in a single study. Among the total 78 publications, 61 were published after 2017. In China, only two researchers were included in two studies, and each of the others had only one paper published. Thirty-three of the 66 publications belonging to China were published in the last two years of the research period (i.e., 2021 and 2022). A similar trend can also be observed in the other three countries in the top five. This result indicates that the smart water management domain gained universal attention mainly in recent years, and as a multidisciplinary research domain that is still developing, it presents a decentralized pattern in which no particular researchers stood out as leading ones. However, taking all identified countries into consideration, the developed economies were observed to have made the major contribution to this particular domain, in spite of the rapid progress made by China and India.

As for the institutions with publications, Griffin University in Australia had the most with 18 publications, followed by four European universities, including three from Italy with 14, 8, and 8 publications, respectively, and one from Greece with 7 publications (Table 1). This result can partially show Europe's constant activity in exploring smart solutions to promote water sustainability. In fact, Europe has been the most active player in pursuing smart and sustainable development for the past decade, and has acquired much progress in smart-related research and practice covering both cities and rural villages (Atkočiūnienė & Vaznonienė, 2019). Therefore, Europe taking a leading role in smart water management domain is not surprising. However, the absolute numbers of publications for institutions in Table 1 were relatively small compared with the total of 460, which suggests that researchers in the smart water management domain are dispersed.

Among the five subject categories in Table 1, Environmental Science ranks first, covering 332 of the 460 publications, greatly outnumbering the second largest category, Engineering, with 137 publications. Social Science and Agricultural and Biological Sciences take up the third and fourth places, with 128 and 100 publications, respectively, and Computer Science ranks last in the top 5, with 84 publications identified. The majority of publications being related to Environmental Science is understandable because most water-related issues are either caused by or the cause of worsening environmental degradation (United Nations, 2022a). However, the current research seems more focused on the "Science" aspect of smart water management (note that four of the top five subjects belong to "Science" category), suggesting that academia should enhance research on "Engineering" topics to facilitate better transfer of scientific knowledge into engineering practice. Furthermore, although the present study intentionally emphasizes "water management" in the research design, research on "Management" is still scarce. This can also be a reminder for smart water management researchers to broaden their research interests in more subject categories in need.

Table 1. Top five publications' countries, affiliations, subject categorizes and sources

Countries		Institutions		Subject categorizes		Sources	
United States	78	Griffith University	18	Environmental Science	332	Water	41
China	66	Universitat Politècnica de València	14	Engineering	137	Sustainability	21
Italy	50	Università degli Studi di Napoli Federico II	8	Social Science	128	Journal of Water Resources Planning and Management	18
Australia	49	Politecnico di Milano	8	Agricultural and Biological Sciences	100	Agricultural Water Management	17
India	48	National Technical University of Athens	7	Computer Science	84	Water Resources Management	14

In terms of publication sources, publisher MDPI (Multidisciplinary Digital Publishing Institute) emerges as the most popular platform for publishing smart water management research. Two MDPI journals, namely, Water and Sustainability, occupy the top two places, with 62 publications in total. The third is ASCE (American Society of Civil Engineers)'s Journal of Water Resources Planning and Management, which published 18 papers during the research period. Then follows Elsevier's Agricultural Water Management with 18 papers, and Springer's Water Resources Management with 14. Compared with the other four journals with an evident relation to the water sector ("water" appears in all four journals' names), Sustainability journal seems not so advantageous in attracting researchers in the smart water management domain. However, its popularity in reality can be viewed as proper proof of the tight correlation between smart water management and water sustainability goals.

2.4. Overview of smart water management literature

A total of 83 keywords were identified by VOSviewer, with a minimum occurrence of a keyword set at 15. These keywords constitute a network showing complicated interlinkages across distinct research interests concerning smart water management (Figure 4). Figure 4 also displays how the research trend has developed chronologically. In the early stage of the research period, research mainly referred to classic water management topics, such as water demand management and water pollution (purple dots in Figure 4), and emerging ICTs, such as IoTs, AI, and machine learning (yellow dots in Figure 4) only appeared in recent years.

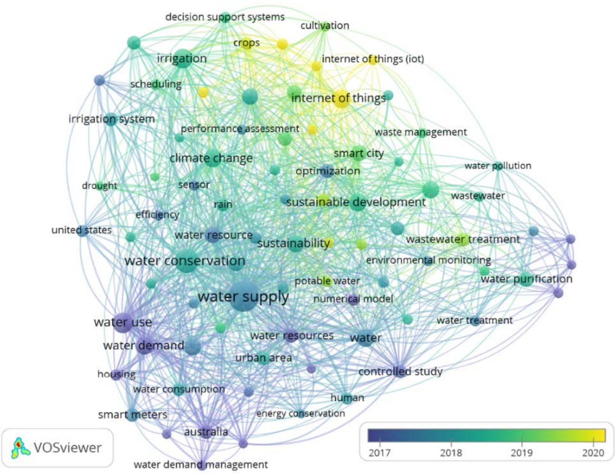

Figure 4. Keyword network of smart water management literature

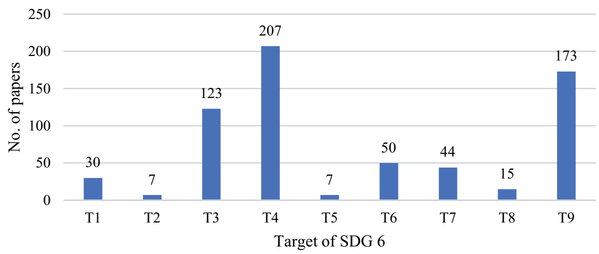

Figure 5. Classification of smart water management literature

Following the three-step classification method, collected publications were classified into nine groups based on the correlations of their keywords with the nine targets of the adapted SDG 6, for instance, "potable water" and "drinking water" with T1 and "climate change" and "agriculture" with T9. Figure 5 shows the classification results.

The number of publications varies for different groups. T4 (referring to water-use efficiency) contains the most publications at 207, higher than that of T9 (synergies of multiple sustainable development goals), in second place, with 173 publications. T3 (referring to the water quality of treated wastewater) sits in third place with 123 publications. T6 (protection of water-related ecosystems) and T7 (support to developing countries), come in with 50 and 44 publications, respectively. For T1 (pertinent to drinking water), 30 publications were found. Subsequently, the number plummets to 15 for group T8 (about the participation of local communities and stakeholder groups), T2 (sanitation and hygiene), and T5 (IWRM), both of which have only seven publications. As the number of research publications can be considered to reflect the extent to which a topic has been studied (Bao et al., 2018), the progress of smart water management research evidently varies across the nine targets of SDG 6. The following section reports the analysis results of the literature in further detail.

3. Discussion from the perspective of UN's SDG 6

3.1. Drinking water quality and drinking water connection (T1)

As mentioned, global communities, especially in poor countries, still lack safely managed drinking water services (United Nations, 2022a). Efforts should be made to understand and resolve the issue; however, this seems far from being undertaken adequately.

Of the 30 studies in T1, eight address improving drinking water quality. Hadley and Newell (2012) provided a new approach to remediate contaminated groundwater to potable standards. J. Hong et al. (2016) and Alshehri et al. (2021) attempted to optimize the water desalination process through new technologies. Mink et al. (2019) introduced a smartphone-based way to enhance the connection of the public with drinking water supply systems. However, the remaining studies deal with drinking-water-related issues under other contexts, such as smart city systems (Conejos Fuertes et al., 2020; Joseph et al., 2022; Valentin et al., 2016) and smart agricultural systems (Begum et al., 2022; Saad et al., 2020). Table 2 presents the numbers and main topics of studies grouped in T1.

Table 2. Numbers and main topics of studies in group T1

Studies straight on drinking water		Studies on other topics covering drinking water	
No.	Topics	No.	Topics
8	– Groundwater remediation – Desalination water management – Mobile crowd participation in drinking water monitoring – Removal of organic and inorganic pollutants from water – Drinking water quality sensing network	22	– Smart water metering – Smart city systems – Smart agricultural systems – Smart sewage systems – Smart water grids – Water distribution networks – Large landscape urban irrigation – Urban smart rainwater harvesting

Despite technological innovations, the goal of all people having basic access to drinkable water is still far from being realized. This indicates two major deficiencies existing in current smart water management literature. First, places suffering from drinking water problems have not received adequate attention. Until 2020, over 3 billion people lived in conditions of unknown water quality due to an absence of monitoring (United Nations, 2022a). Ironically, this is not due to a lack of necessary technologies (Lawford et al., 2013). Consequently, the second deficiency emerges as the deficit of effective means, especially in terms of institutional systems and socioeconomic environment, to attract global support to facilitate the achievement of T1 in places in need.

3.2. Sanitation, hygiene, and infrastructure investment (T2)

Access to safe sanitation and hygiene is one of the most critical sustainable development goals (Schuster-Wallace et al., 2015). According to World Water Assessment Programme (UNESCO-WWAP, 2021), as of 2020, approximately 3.4 billion people lack such access. The situation is worsened by increasing worldwide challenges brought on by COVID-19 and climate change.

However, this urgent matter appears to have escaped the attention of researchers. Only seven publications were classified into T2 via the keywords "sanitation," "hygiene," "sewage," "drainage," and "infrastructure investment." Despite these seven publications, sanitation and hygiene are subordinate to other research concerns. For example, Turrén-Cruz and López Zavala (2021) introduced an S3 (smart and sustainable societies) framework to achieve sustainable households and communities, considering a smart sanitation and hygiene system.

The mismatch between practical need and academic focus possibly lies in the imbalance of regional developments. Similar to the situation regarding drinking water, an urgent need for sanitation and hygiene facilities mainly exists in the least developed countries or areas that are financially unattractive to investment (UNESCO-WWAP, 2021). However, basic water infrastructure like sanitation and hygiene facilities in developed economies have been established for a long time and are no longer a problem. As sanitation and hygiene remain basic human rights for all (United Nations General Assembly, 2007), global scientific communities should develop effective measures to assist countries with sanitation and hygiene problems in attracting needed investment. This attempt can be initiated by encouraging researchers to focus on topics related to the third keyword of T2 (Figure 2), "infrastructure investment."

3.3. Wastewater, water quality, and pollution (T3)

Progression toward economic growth, which is closely correlated with increased production and consumption, poses significant trade-offs in achieving SDG 6 (Pradhan et al., 2017). During production and consumption, wastewater loads are produced and discharged without proper treatment, causing severe pollution (United Nations, 2022a). The wastewater issue impacts every country, whether developing or developed. Noting the prevalence of wastewater issues, the second largest number of studies (123) belonging to this group is not surprising.

Studies in T3 mainly center on the following facets: water purification, water quality monitoring, and wastewater reuse. Table 3 presents the numbers and main topics of studies relating to the three facets.

Water purification technology is a prominent aspect. Various technologies, ranging from hydrophilic polyvinylpyrrolidone-coated iron oxide nanoparticles (Palchoudhury & Lead, 2014), UV-responsive nanosponge

Table 3. Numbers and main topics of studies centering on water purification, water quality monitoring, and wastewater reuse

Water purification		Water quality monitoring		Wastewater reuse	
No.	Topics	No.	Topics	No.	Topics
45	Smart technologies for water purification Integrated water treatment systems	25	ICT advancements for water quality monitoring, such as IoT, big data, wireless sensor networks, and machine learning, etc.	20	Usages of treated wastewater, such as agriculture irrigation and bioproducts Integrated wastewater and reuse systems

(D. H. Kim et al., 2015), amphiphilic antifouling membranes by polydopamine mediated molecular grafting (Nayak et al., 2021), to specific technologies for efficient saltwater purification (Chang et al., 2019; Silambarasan et al., 2020), have been reported.

Water quality monitoring of both sewage wastewater and raw water has improved, owing to technological advances, especially following the ICT achievements of recent years (Antzoulatos et al., 2020). These state-of-the-art ICTs include the IoT, big data, wireless sensor networks, machine learning, smart mobile communication, and cloud (Chen & Han, 2018; Junior et al., 2021; Kumar & Hong, 2022; Mink et al., 2019).

From a circular economy perspective, repeatedly reusing wastewater makes water itself part of the infrastructure besides a consumable resource. Agricultural irrigation is the most common end-use for reclaimed water (Ramasamy et al., 2021). Wastewater can also produce biogas through microalgae-based treatment systems (Uggetti et al., 2018).

Literature analysis shows that wastewater treatment is increasingly considered under integrated management frameworks to realize synergistic effects (Radini et al., 2021). However, many underdeveloped regions remain excluded due to technological and economic disadvantages considering that integrated frameworks require adequate technological and economic capacities. This handicap requires attention from the scientific community to allow all countries to adopt the latest research outcomes equally in practice.

3.4. Water scarcity and water leakage (T4)

Increased water stress and scarcity are key drivers of water-related risk (Carbon Disclosure Project, 2020). The issue of water scarcity features prominently in the smart water management literature as the topic of 207 publications (Figure 5). Two aspects of water scarcity risk stand out. These are the withdrawal and supply of freshwater and water-use efficiency (Figure 1).

Figure 6 shows the keywords with the highest frequency in the 207 publications. From Figure 6, the top five keywords are water conservation, water demand, water distribution systems, water meter, and water consumption, all of which are related to promoting water-use efficiency. Water conservation is a common goal of water management, and the other keywords represent potential ways to achieve that goal. Emerging ICTs are deemed necessary tools to support goal outcomes. Tian and Chen (2022) suggested the use of smart water sensors to monitor the water consumption of citizens. Giudicianni et al. (2020) proposed an adaptive management framework for water distribution systems. Brentan et al. (2018) presented a hybrid technique based on self-organizing maps coupled with k-means algorithms to promote the data processing ability of water distribution systems. Many researchers have found smart water metering to be effective for improving water-use efficiency (Cardell-Oliver et al., 2016; Giurco et al., 2010; Hsia et al., 2012; Li & Chong, 2019; Msamadya et al., 2022). Other emerging technologies, such as digital twins (Ramos et al., 2022) and deep learning (J. Kim et al., 2022), have also been employed for efficient water distribution.

However, water scarcity crises have not been fully resolved despite technological progress. For example, ICT-based smart water distribution systems may be useful for developed urban household water use but may not be a priority for people living in relatively underdeveloped areas that lack basic institutional and managerial capacities to water management (Chitakira & Nyikadzino, 2020). Unfortunately, much less attention is given to the latter scenario than the former (Maroli et al., 2021). Compared with water use efficiency, research outcomes related to sustainable freshwater withdrawal, the other keywords of T4, are limited. The sustainability of freshwater withdrawal requires high interdependence of states with transboundary cooperation on water resource management, which can often lead to a political impasse between actor states (UNESCO-WWAP, 2021). Therefore, efforts to generate actual cooperation in the field are still needed.

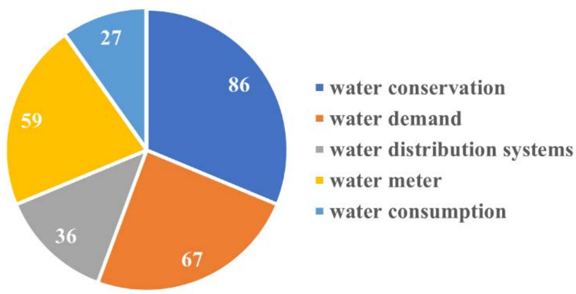

Figure 6. Top five keywords with the most occurrence in T4

3.5. IWRM and transboundary cooperation (T5)

The philosophy of IWRM, as formulated and specified in a series of international conferences on sustainable water management in the 1990s, has long been deemed a necessary process for the sustainable development of water resources (Vieira et al., 2020). Despite its universally accepted benefits and increasing conceptual popularity, implementation and effectiveness are still at a fledgling stage, requiring transboundary cooperation among countries with conflicts of interest that are not easily mediated (Jønch-Clausen, 2004). According to the United Nations (2022b), of the 153 countries that share transboundary water resources (i.e., rivers, lakes, and aquifers), only 32 countries, most (24) in Europe and North America, have reached operational arrangements on transboundary water resource management.

However, this study merely identifies seven publications regarding IWRM and transboundary cooperation. Only some pilot studies discuss IWRM issues from the perspective of smart solutions, such as IT-based collaboration platforms enabling multiorganizational water resource management (Hidaka et al., 2011). Researchers observe that transferring IWRM-related smart management systems across countries remains difficult, given that doing so requires significant multilevel changes in the countries' institutional capacity (Zevenbergen et al., 2018). These changes are closely interlinked with a country's socioeconomic, cultural, geographical, and historical context, making it impossible for "one-size-fits-all" solutions (Jønch-Clausen, 2004).

To support the development and application of IWRM, the Global Water Partnership (2017) suggests tools applicable to three areas of the initiative: (1) enabling environment, (2) institutional roles, and (3) management instruments. The first two require tools that can address social facets of certain jurisdictions, and smart technologies, such as GIS and decision support systems, apply to the third. Thus, the prerequisite for better utilization of smart technologies in developing IWRM is establishing more supportive environmental and institutional systems.

3.6. Water-related ecosystems (T6)

T6 emphasizes several water-related ecosystems, including mountains, forests, wetlands, rivers, lakes, and aquifers. The most biologically diverse ecosystems, wetlands, have experienced an 85% of loss in extent over the past 300 years, leading to massive devastating repercussions, such as species extinction, the spread of disease, and climate change (United Nations, 2022a). Other water-related ecosystems also face rapid degradation, requiring urgent efforts to protect and restore these biological habitats (United Nations, 2022b).

50 publications were identified related to water ecosystems. Aquifer, or groundwater, is the most popular keyword, being included in 35 out of the 50 studies (Table 4). Groundwater comprises more than 98% of liquid freshwater (FAO, 2012). Smart water management literature focuses on two groundwater-related issues: contamination and water level drop (Barati et al., 2019; Hadley & Newell, 2012). Advanced technologies make it possible to consider the two issues simultaneously. For example, a so-called sequential managed aquifer recharge technology (SMART) has been designed to recharge aquifers with treated wastewater (Karakurt-Fischer et al., 2020). Most studies tried to improve groundwater use efficiency using smart solutions (Fornarelli et al., 2022). The remaining 15 studies considered other ecosystems, such as wetlands (Mahdianpari et al., 2021), lakes (Maleki et al., 2022), mountains (Gilliom et al., 2019), and rivers (Kartakis et al., 2017).

Table 4. Numbers of studies on water-related ecosystems

Aquifer	Wetlands	Lakes	Mountains	Rivers	Others
35	3	3	2	2	5

Existing literature on water-related ecosystems has two obvious limitations. First, most of the research is centered on the aquifer ecosystems due to their critical role in supporting sustainable human well-being. However, urgent intervention is needed for the other ecosystems beyond aquifers to be sustainable. Second, most literature focuses on ecosystems in developed economies and urban areas. Again, a much broader scope that encompasses needier regions of the world should be considered.

3.7. Developing countries, local communities, and stakeholder groups (T7 & T8)

T7 refers to government-coordinated activities and programs supported by international assistance in developing countries. Similarly, T8 is concerned with local administrative units that prompt communities and stakeholder groups to participate in water management. As both themes emphasize the role of stakeholders and how competency may be raised in leading water management projects, these are discussed jointly here.

A total of 44 publications covering water-related topics in developing countries were identified. However, studies that shed light on governments' actions and plans for promoting smart water management are scarce; with only six studies identified (Figure 7). For example, Van Dijk and Liang (2012) analyzed the hierarchical governance structure of the water sector in Beijing, China, in the context of future ecocities, and Sharma et al. (2021) constructed a hybrid framework for sustainable urban water

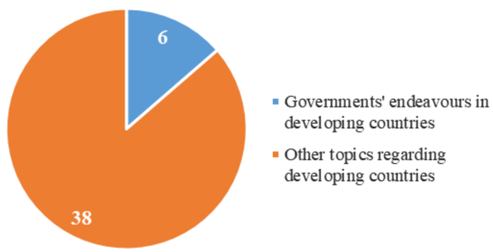

Figure 7. Numbers of studies relating to developing countries

management that considered governance, in addition to infrastructure and technology.

Regarding the involvement of local communities and stakeholder groups, 14 publications show that water customers attract the most research attention. Digital technologies (e.g., smart meters) were applied to improve water consumers' awareness of water value and accessibility of knowledge to encourage community participation in water-saving purposes (Fornarelli et al., 2022). Communication technologies (e.g., smartphones and applications) were also introduced into the water management systems to enhance local engagement and empowerment in efficient household water usage (Mink et al., 2019). However, few studies considered, as required by T8, what the governments per se should do to develop a friendlier environment for the successful execution of those smart solutions. The literature analysis shows that smart water management remains a hypothetical aspiration if solid policies and government political support are absent (Msamadya et al., 2022).

3.8. Synergies of multiple sustainable development goals (T9)

Achievement of SDG 6 targets can be facilitated by improving the education level of people and by mitigating climate change; conversely, failure of those targets may compromise goals of food security, human health, resilient cities, and ecosystem and biodiversity protection (Bhaduri et al., 2016). This observed phenomenon indicates trade-offs and synergies of SDG 6 with other SDGs.

Linkages between SDG 6 and several other SDGs have been considered in the literature (Table 5). Climate action (SDG 13) is the most topical in 90 publications of 173. The impact of climate change on water management in the agriculture sector attracted the most attention. Some researchers designed smart irrigation decision support systems that estimate weekly irrigation needs (Navarro-Hellín et al., 2016). Others used dynamic system models to analyze irrigation management processes that improve the efficacy of water resource allocation in times of drought (Wu et al., 2017). The agriculture sector also proposed an integrated approach to water harvesting, microirrigation, and resource conservation farming (Patle et al., 2020).

Smart cities (SDG 11) also feature in the literature, with 47 publications identified. Considering that the maturity of institutional environments serves as the foundation for the application of smart water management solutions (Msamadya et al., 2022), Feingold et al. (2018) suggested the City Blue Approach to assessing the status of city water management, itemizing three considerations: main challenges, adequacy of existing water management, and capacity shortage of existing water governance. Other researchers have honed in on specific aspects of city water management, such as water governance processes adapting water-sensitive urban design (Madonsela et al., 2019) and the fragility of city water infrastructure systems in uncertain future conditions (Babovic et al., 2018).

The synergy of water and energy goals (SDG 7) has also been studied in more than 40 publications. High energy consumption usually accompanies water production, distribution, and consumption. Water is used as an important resource for energy production. Thus, the literature has frequently debated a sustainable water-energy nexus (Ramos et al., 2019). Recently, integrated water management systems that holistically consider a water-energy-food-climate nexus has been proposed, taking advantage of advanced ICT innovations (Radini et al., 2021). Aside from the above three sustainability goals, SDG 6's other interlinked SDGs, such as quality education (SDG 4), poverty alleviation (SDG 1), and reduced inequality (SDG 10), have received less attention. Thus, future researchers should explore the synergistic links and trade-offs between SDG 6 and other SDGs.

4. Recommendations for future research and policy-making

4.1. Covering all SDG targets for overall water sustainability

The current literature review reveals that among all targets of sustainable water development, T3 and T4 received much more attention from smart water management researchers (Figure 5). As discussed previously, T3 regards wastewater, water quality, and pollution as inevitable by-products of economic development. As water pollution can cause severe economic, human health, and ecological crises, companies normally have legal obligations to treat wastewater before discharge (Carbon Disclosure Project, 2020). Research on T4, water scarcity, and water leakage mainly refers to using smart solutions to improve water use efficiency (e.g., water leakage monitoring), by which water companies' interests can be improved (Ali et al., 2022; A. Muhammetoglu et al., 2020; A. Muhammetoglu

Table 5. Numbers and main topics of studies linking SDG 6 with other SDGs

SDG 13		SDG 11		SDG 7	
No.	Topics	No.	Topics	No.	Topics
90	Water management in agriculture sector to mitigate climate change impact Others (e.g. urban water systems to cope with climate change)	47	Assessing water management performance in smart cities Water governance in water-sensitive urban design Fragility of city infrastructure systems	42	Sustainable water-energy nexus Integrated water management systems considering water-energy-food-climate nexus Smart energy-efficient solutions in various industries

& H. Muhammetoglu, 2022). This denotes that some driving forces, such as legal obligations and financial interests, are needed to urge smart water management researchers to focus on other targets of SDG 6. Therefore, future researchers and policymakers are encouraged to collaborate to identify drivers for the other SDG 6 targets and establish inclusive local institutional and socioeconomic systems to develop those drivers (Di Vaio et al., 2021). With such an inclusive environment, diverse smart solutions that suit those overlooked targets of SDG 6 can emerge and grow, and consequently, the overall sustainability of water development can be attained. Possible questions to be answered by future researchers and policymakers include:

– What are the drivers pushing the smart water industry to focus on those overlooked SDG 6 targets?
– How can these drivers be used to prompt the smart water industry to pursue overall water sustainability?
– How can smart technologies be diversified to handle different SDG 6 targets?

4.2. Adopting place-based approaches

From a sustainable development perspective, geographic diversity is a glaring deficiency of current smart water management research. Considering that the development and application of smart technologies are costly (Cowie et al., 2020), developed countries and cities with better socioeconomic conditions are more prone to attract researchers. However, the obligation remains to investigate rural and poorer socioeconomic settings comprehensively considering that the goals of sustainable development are inclusive of all people and water-management challenges experienced are known to be location specific (Madushanki et al., 2019; Maroli et al., 2021). Place-based approaches, deemed effective in addressing territorial, social, and economic inequalities and development capacities (Bentley & Pugalis, 2014), are suggested for future studies and policy making to achieve overall water-related sustainable development. The place-based approaches are especially needed for developing the smart water industry in rural areas because they are typically varied with specific cultural and geographical characteristics (Zavratnik et al., 2018). In accordance with the place-based approaches, the following questions need to be considered in particular for overall water sustainability:

– What is the status quo of smart water development in rural areas?
– What are the goals for developing smart water industry in rural areas?
– What specific strategies should be adopted to meet the goals of developing the smart water industry in rural areas?
– How should the performance of developing the smart water industry in rural areas be assessed?

4.3. Involving a wider stakeholder representation

Many researchers have highlighted the role of multistakeholder partnerships between governments, companies, civil society, investors, and academics in efficiently and successfully dealing with sustainable issues (Blasi et al., 2022). Water-related sustainable development is an extremely complex issue with multiple stakeholders involved across the full water cycle. For example, water consumers with conflicting interests include those in water supply, sanitation and hygiene, agriculture, energy, industry, and the environment (UNESCO-WWAP, 2021). Thus, future researchers and policymakers are encouraged to consider a wider range of stakeholders beyond just household consumers (Msamadya et al., 2022). Specifically, how governments can improve their capacity to facilitate aid should be considered. Furthermore, the private sector deserves additional attention because water infrastructure requires investment funding and expertise that cannot be met by the public sector alone (UNESCO-WWAP, 2021). Thus, researchers and policymakers should explore the role of vehicles, such as public–private partnerships (PPPs) (Jayasena et al., 2021; Selim et al., 2018) in implementing smart water management systems. Specifically, they should investigate the following questions in depth:

– What roles should different stakeholders play in developing effective smart solutions to achieve water sustainability?
– How should governments improve their capacity to build positive institutional and socioeconomic environments for stakeholder collaboration?
– What innovative ways can be utilized to attract private sector participation?
– How can other stakeholders, such as financial institutions, research institutes, and consultancies, contribute more efficiently to water sustainability?

4.4. Encouraging more international cooperation

The UN has pointed out that additional efforts are needed to increase further cooperation among countries to promote further progress of SDG 6 (United Nations, 2022b). The results of this study offer corroborative evidence for this viewpoint. In particular, smart technologies, normally deemed capable of strengthening cooperation, were not as effective as desired. Thus, researchers and practitioners in the smart water industry need to pay attention to two types of international cooperation to facilitate the overall realization of SDG 6. First, transboundary cooperation has only been achieved among a few developed countries, most of which are in Europe or North America (United Nations, 2022b). This situation calls for solutions to effectively employ smart technologies to remove barriers between countries that require transboundary cooperation in water management. Second, international cooperation ought to be strengthened in terms of transferring the abundant resources concentrated in developed economies and urban cities across to those places that are far less developed, to ensure inclusive and equitable access to sustainable development for all (Maja et al., 2020). Specific research questions may include:

– What are the barriers hindering effective transboundary cooperation among countries with IWRM-related issues?

– How should smart solutions be improved to resolve water industry transboundary cooperation issues?
– What measures should be taken to promote cooperation between jurisdictions with abundant resources for smart water development and those without?

4.5. Expanding financing channels for the development of the smart water industry

Funding is a central concern for sustainable development (Georgeson & Maslin, 2018). Even within Europe, financing SDGs is a contested topic (Lagoarde-Segot, 2020). SDG 6, in particular, is a goal saddled with significant financial shortfalls. As estimated by UNESCO-WWAP (2021), achieving universal access to safe drinking water and sanitation (T1 and T2) in 140 low- and middle-income countries will cost approximately US$1.7 trillion from 2016 to 2030. Developing smart water systems that include the necessary infrastructure (e.g., ICT infrastructure) to facilitate the achievement of SDG 6 will increase fiscal stress (Cowie et al., 2020). The existing financial challenge has been extraordinarily highlighted by the COVID-19 pandemic, which has led to a global economic recession, consequently stalling the 2030 target (Benedek et al., 2021).

Under these circumstances, an urgent question for current researchers and policymakers in the field of smart water management area is how to close the expanding financial gap. Apart from traditional funding sources, such as direct government finance, governmental loans, and funding by the private sector (i.e., PPPs) (Selim et al., 2018), researchers and policymakers will need to consider additional applicable financial mechanisms by considering the macroeconomic and institutional characteristics of host countries. Thus, the following research questions are suggested to be addressed:
– What is the status quo of financing conditions for the development of smart water in different economies?
– What are the unique financing features for developing the smart water industry?
– How should traditional financing modes be innovated to meet the unique features of financing the development of the smart water industry?
– For places lacking investment appeal, how can financing channels for developing their smart water industries be expanded?

Conclusions

Access to water, a fundamental necessity of life, has been adversely affected by human activities. Water sustainability has become a mutual goal for all countries. In recent years, smart-sustainability, which means pursuing sustainability with smart solutions, has emerged as a universally accepted philosophy for sustainable development. In the water sector, the pursuit of water sustainability has benefited from the advancement of various smart technologies. However, the extent to which the various water sustainability targets have been facilitated by so-called smart technological progress remains unclear. This study aims to investigate how emergent smart solutions have facilitated water sustainability through a scientometric literature review.

Unlike previous review studies that focused on the technological details of smart solutions, this review emphasizes the degree to which these smart solutions cover different targets of SDG 6, the water-related goal of the 17 SDGs issued by the UN in its 2030 Agenda. A structured three-step research process was used to collect publications for literature analysis. On the basis of the definition of SDG 6, nine targets from T1 to T9 were defined and used as benchmarks for literature classification. A total of 460 publications were identified through Scopus, and 83 keywords with the highest occurrence frequency were visualized in keyword networks generated by VOSviewer.

The literature analysis shows that existing smart water management studies have covered all the nine targets (T1–T9) of SDG 6; however, the distribution of publications differs within these targets. Topics related to water-use efficiency, wastewater, and synergies with other goals have been discussed by considerable studies. However, studies on themes regarding sanitation and hygiene, IWRM, developing countries, local communities, and stakeholder involvement are relatively scarce. This result indicates that progress toward achieving water sustainability has been made, but it has been uneven, and the relatively overlooked SDG 6 targets should be focused to achieve overall water sustainable development. Based on the findings, this study proposes five recommendations for future researchers and policymakers: (1) Covering all SDG targets for overall water sustainability; (2) adopting place-based approaches; (3) involving a wider stakeholder representation; (4) encouraging more international cooperation; and (5) expanding financing channels for the development of smart water industry. The study also presents specific research questions under each recommendation.

The innovation of this study is twofold. The first encompasses the sustainable development approach adopted by the review. This goal-oriented perspective ensures that the research findings genuinely reflect practical needs. The second concerns an emphasis on the application state of the water-related smart solutions, offering a significant supplement to the popularity bias of the technology-centric tendency of current smart water management literature. The findings of this study will assist future researchers by identifying and mapping the status quo of the smart water management literature, providing significant guidance on where further efforts are needed to facilitate the overall achievement of water-related SDGs. The industry can also benefit from the findings by creating more inclusive and adaptive smart solutions with equal access to water services for all.

Although great efforts have been made to collect as much literature as possible, some other relevant publications may still be excluded on the list. However, analysis results show that the identified 460 publications suffice to illustrate the viewpoints of the study. Limited by some objective conditions such as research time and resources, this study merely provides a general depiction of the smart water management literature in serving SDG 6. Therefore, it could of course benefit from a more detailed portrait of the literature in relation to each specific target of the SDG 6. Similarly, in-depth investigation into the performance of individual smart technology in facilitating SDG 6 has yet been carried out in this study. This issue could also be pursued in subsequent research. Additionally, considering that the imbalance of smart water development in different areas has been observed in this study, future researchers are encouraged to go further for more comparative analyses of smart water management studies from countries with varied characteristics.

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