Smart Water Grids

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Smart water grids are urban water infrastructure enhanced through a variety of interconnected devices with the ability to collect and share data with both other devices and data centres. Typically this is done through the use of Internet of Things technology. Some of these devices also have the capacity to make decisions, in a centralised and/or decentralised manner, and to perform physical actions on the water infrastructure that lead to optimal operation and control. Smart water grids can, therefore, be understood as an instance of cyber-physical systems. In the case of water distribution management, in addition to classical objectives such as pressure, quality and leakage control; smart water grids also seek energy efficiency and explore water reuse systems.

Keywords: water supply ; energy recovery ; micro-generation ; pump as turbine ; district metered areas ; digital water ; water–energy nexus ; sustainability ; green infrastructure

1. Introduction

Cities are stressed worldwide predominantly due to significant population growth. Global population has increased by 1500 million people in the last 20 years. The United Nations predicts that this trend will continue and it is expected that up to 6.5 billion people will live in cities by 2050. Cities are a main actor in climate change and the built environment contributes to high levels of global greenhouse gas emissions. However, the challenges for city authorities goes beyond managing growing cities, since as cities develop, their exposure to extreme weather events also increases[1]. Given these current and future scenarios, academics and industry have put in effort over the last two decades towards reducing buildings' energy use[2]. Another solution investigated in depth, and currently in development, is on the benefits of smart power grids[3]. Complimentary to this for the achievement the zero-net target is the efficient management of water distribution systems (WDSs).

The water industry is subject to changes regarding the sustainable management of urban water systems. Many external factors, including the impacts of climate change, drought and population growth in urban centres, had led to an increase in the responsibility to adopt more sustainable management of urban water resources[4]. Other challenges include income and revenue to cover operation and the monitoring and management of water resources as a public service. Additionally, the need for knowledge and understanding of the customers' demand for fair water pricing and use are some of the main challenges to resolve[5].

Over the last few years, the surge of the information and communication technology (ICT) techniques along with the application of new trends on data analytics have been shown to be essential for dealing with the challenges that a urban water infrastructure should face today. The traditional water system, then, is becoming a smart system, or smart water grid, as it can be seen as the combination of critical and digital systems into one converged, smart infrastructure. In return for such a new complexity level, water utilities now have the capability of working in an ideal smart-technology framework that supports efficient operation and management for safer and more secure water supply systems[6]. There are a number of literature reviews that can be considered an antecedent of the current overview. Mala-Jetmarova et al.[7] proposed a systematic literature review of WDS design optimisation, with a special emphasis on methodologies for the expansion and rehabilitation of already existing infrastructure. Anele et al.[8] reported an overview of methods for short-term water demand forecast, highlighting their advantages, disadvantages and future research directions. Digital water metering has been the target of two different literature reviews. Monks et al.'s paper[9] comprehends a literature review along with interviews to industry experts. The aim of such a paper was to report benefits of digital water metering that might be considered for inclusion in business cases. Rahim et al.[10] introduced a review on machine learning and data analysis techniques adapted to digital water metering. The review was complemented by a number of recommendations to improve both management and research further. Makropoulos and Savić[11] worked on a literature review paper about urban hydroinformatics where the benefits of relevant concepts such as ICT and real-time information, data analytics, and the new approach of water cycle and socio-technical system models, among others are revisited.

2. Smart Water Management

Smart water management aims at the sustainable and self-sufficient management of water, at a regional or city level. A smart use of water lies in the use of innovative technologies, such as information and control technologies and monitoring[12]. With this approach, water management contributes to leakage reduction, water quality assurance, improved customer experience and operational optimisation, among other key performance benefits[13]. The concept of "smart city", as related to technological innovations, is relatively recent. A smart city can be defined as the city in which an investment in human and social capital is performed, by encouraging the use of "information and communication technology" as an enabler of sustainable economic growth, providing improvements in the city inhabitants' quality of life, and consequently allowing a better management of water resources and energy. Importantly, a smart city aims to promote socioeconomic development[14] as ultimate objective of any associated technological advancement. Through a socioeconomic model, a city can examine its current state, and in turn, identify the areas that require further development in order to meet the necessary conditions for a smart city.

2.1. Technologies and Improvements

Smart water systems utilise advanced information technologies for system monitoring data for an efficient resource allocation. Some examples are the use of a geographic information system (GIS) providing a clearer representation of the overall system and asset location[15]; or the deployment of SCADA (supervisory control and data acquisition) systems for the collection of historical sensor readings to centrally control spatially distributed assets[16]. In addition, the prevention and the early detection of leaks is key for effective asset management and for efficient control of water losses.

Traditionally, water supply is essentially focused on pumping water at high pressure, enough to reach distant customers. However, a smart system uses near real-time data, variable speed pumps, dynamic control valves, and smart meters to balance the demand, minimise over-pressure in ageing pipelines and save water and energy. Therefore, water sources and systems could operate together with the same objective to maintain sustainability in water management[17]. Smart water systems, or smart water grids, are used to improve the situation of many networks, some of which are characterised by a degraded infrastructure, irregular supply, low levels of customer satisfaction or substantial deviations of the proportional bills to the real consumption. A smart water system can lead to more sustainable water services, reducing financial losses, enabling innovative business models to better serve the urban and rural population. Some of the main advantages of smart water management are an improved understanding of the water system, improved leak detection, enhanced conservation, and a constant monitoring of water quality. The implementation of smart water systems enables public services companies to build a complete database to identify areas where water losses or illegal connections occur. The advantages are economic benefits to water and energy conservation, while the efficiency of the system can improve customer service delivery. In some cases, wireless data transmission can allow clients to analyse their water consumption towards preserving and reducing their water bill[18].

2.1.1. Smart Pipe and Sensors

The prototype of a smart pipe is designed as a module unit with monitoring capacity, expandable for future available sensors[19]. With several smart pipes installed in critical sections of a public water system, a near real-time monitoring automatically detects flow, pressure, leaks (if any) and water quality. All these benefits come without changing the operating conditions of the hydraulic circuit. The individual sensors of smart pipes generally have the following main parts: a data collection and processing unit, transmission unit and the sensor connections. Figure 1 illustrates a general scheme for a smart pipe and a wireless sensor network.

Figure 1. Scheme of a smart pipe and wireless sensor network.

Smart wireless sensor network is a viable solution for monitoring the state of pressure and water losses control in the system. The main advantage compared to other methods of water losses control is the continuous monitoring of the network without local operator intervention and with low energy consumption of the wireless sensor, which allows it to remain operational for long periods[20].

2.1.2. Smart Water Metering

A water meter is a device used to measure the quantity of water consumed, while a smart metering is a measuring device that can store and transmit consumption data using a certain frequency (Figure 2). To develop an efficient water management system is necessary to install sensors and/or actuators to monitor the water network. Therefore, while water meters can be read monthly or twice a month and water bills are generated from this manual reading, the smart metering can provide consumption data over a long distance and with a higher monitoring frequency, thus, providing instantaneously access, and near real-time information from customers and from managing entities. These smart water meters are components of an advanced metering infrastructure (AMI) that water companies should install to improve the hydraulic and energy efficiency of their network, since these devices also enable the control of leakages and non-legal connections in terms of water volumes[21].

Figure 2. Scheme of a smart water metering model.

Therefore, smart water metering provides the opportunity to improve the balance between the provision of access to drinking water, the right of a managing entity to be paid for services, as well as the joint responsibility to preserve water, as a scarce resource. These systems contribute as support tools to make decisions in near real-time based on a registered database, improves network management and can help to better refine the water balance to satisfy demand and to increase the hydraulic and energy efficiency of the WDS.

2.2. Management Models and Decision Support Systems

The implementation of a common framework for measuring the water network performance based on a set of relevant indicators and data applications and interfaces helps to support the decision of the managing entities and allows for the interested parties to evaluate, create trust and confidence and monitor the improvements[22]. There have been important developments in smart water grid management, ranging from models for energy recover for energy generation[23] to models for an optimal dynamic partitioning of the WDS into district metered areas[24]. This section focuses on existing models and systems to support this decision-making process.

2.2.1. Near Real-Time Models

Hydraulic models represent the most effective and viable way to predict the behaviour of the water distribution system under a wide range of conditions of demand anomalies and system failures. The knowledge of reliable short-term demand forecasting patterns is crucial to develop such models and to enable positive decisions, made in near real-time, to be implemented in smart water systems[25]. In addition, optimisation models of operation in near real-time allow us to extend decisions to smart water systems to improve the water network efficiency and to ensure more reliable operations, cost efficiency and environmental and social savings associated with losses.

In near real-time models, the moment the data are collected is the moment the network model is updated. Data include the characteristic parameters of pumps, valves, pressures and flows, as well as hours of operation towards the lowest operating costs. The objective is to make any operational decision almost instantly to meet the requirements for an efficient water supply[26]. Brentan et al.[27] proposed a hybrid methodology to update water demand models. To this end, an off-line procedure is used as a basis for the predictive model which is coupled with an on-line process. The proposal achieves both high accuracy and ability to adapt to new data anomalies and trends. The work also proposed an error control process to timely update the basic, off-line model cyclically, to guarantee a maximum accuracy.

2.2.2. Asset Management

Asset management is a process that water utilities use to make sure that maintenance can be conducted and capital assets (such as pumps, valves, and pipes, among others) can be repaired, replaced, or upgraded on time.

One of the main topics in asset management of a water distribution system is to prioritise the assets in rehabilitation plans. To this end, Cabral et al.[28] approached a solution involving an economic asset performance evaluation using the infrastructure value index as a key performance indicator. Other authors used a multi-criteria decision-making for rehabilitation purposes[29]. Beyond rehabilitation, asset management also deals with proactive maintenance plans driven by risk[30], resilience[31], or by an asset condition assessment[32].

Other central topics in asset management are of main interest for water utilities. This includes the prognosis and asset-health management in which it is key to handle the uncertainty of asset states, since utilities often have imperfect information about their assets. Another related subject to research further is about the optimal level of service (such as what to do in scarcity scenarios), asset criticality, or minimising assets' life-cycle costs.

3. Challenges for Smart Water Grids

The use of machine learning and artificial intelligence is foreseen as a basis for future smart water grid development. In addition, recent advances and future research in complex networks dynamics will be of great importance for near real-time models and big size networks analysis, along with addressing main operational and management issues for sensor placement[33] and contaminant early detection[34], among others. Network dynamics research[35] can be expanded and/or complemented with the investigation of geometric deep learning[36] solutions to undertake even more ambitious challenges such as leakage detection. Agent-based models will also play a key role in the supervision and control of smart water grids[37]. Over all, these and other cutting-edge methodologies will enable disruptive technologies for smart water grids such as blockchain[38] and digital twin[39] models, in addition to the widely use of the advantanges of a WDS management within the context of cyber-physical sytems[40].

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