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Smart water grid: the future water management platform

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ABSTRACT

This study introduces a schematic methodology for smart water grids (SWGs) for use in water management platforms, which integrates information and communication technology (ICT) into a single water management scheme. SWG technology is seen as a promising solution for resolving recent critical global water problems. To ensure the security of water quantity, safety of water quality, and ICT-based water management solutions, SWG technology should integrate five prime research areas: (1) platform configuration in both water and ICT networks, (2) guarantee water resources including both natural and manufactured water, (3) intelligent control of water flow using bi-directional communication in water infrastructure, (4) better management scheme dealing with risk-minimization for assets in the water infrastructure, and (5) energy efficiency in operating and maintaining water infrastructure. Two platforms (i.e. water and ICT platforms) are introduced as examples of well-designed platforms for the management of bi-directional water and data flows in accordance with both the consumer's water demands and supplier's water distribution schemes, in both centralized and decentralized water distribution grids. To guarantee water resources, harvesting both natural sources (e.g. river, lake, groundwater, etc.) and manufactured sources (e.g. desalination, reused waters, etc.) is proposed as a top priority. Using the platforms and multiple water resources, the intelligent water grid control plays a key role in satisfying the consumer's as well as the supplier's water needs, using self-diagnosing sensors and ICT-based cooperative networks. Improved management in risk-minimization for water infrastructure assets requires the GIS-based information of assets, their historical changes, and their renewal plans according to monitoring/forecasting data, etc. To improve water infrastructure energy efficiency, low energy processes combined with alternative energy sources and smart power grid management are suggested as key cost-saving methods for water production and/or distribution. Thus, integrating the five prime research areas in SWG technology can provide water managers insight into planning water infrastructure and shed light on the roles of the SWGs in future smart cities.

Keywords: Smart water grid; Intelligent water management; Water infrastructure; Bi-directional water flow; Centralized and decentralized water network; Water-energy nexus

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1. Introduction

Current water network structures are based on large and centralized systems in which the management options are limited. The major limitations of these systems are: low operating efficiency due to the imbalance between the supply of and demand for fresh water, loss and/or contamination of the supply water, high energy requirements for production and transportation of the supply water, high treatment cost and/or low treatment efficiency of both supply water and waste water due to the fixed treatment processes, and lack of integration of alternative water sources. In order to overcome these limitations, a new water management scheme that can make real-time management possible is required.

Conventional centralized water networks are typically based on one-directional flow [1]. These systems generally use dams as water sources and after treatment the product water is directly distributed to all customers in the area. However, the construction of distribution elements and the transportation of water from a single source to the entire urban area are not only economically infeasible but are also prone to leakages and pipe bursts along the transportation lines [2,3]. Leakages and pipe bursts are common failures in urban water distribution networks; when there is a major burst in the main pipeline, a complete shutdown of the water distribution process becomes imminent [4,5]. Decentralized systems are widely accepted as being more economically feasible, less prone to accidents, and one of the most promising approaches for improving the water management in urban areas [6]. Decentralized systems are also suitable for using alternative water sources, such as reclaimed wastewater, rain, and sea water [7]. However, even though decentralized systems have major advantages over conventional centralized systems, they also have management limitations when water quality and quantity are considered.

The imbalance between the supply of and demand for fresh water is another important urban water management problem. Even though water consumption is higher during daylight hours than during the nighttime [8], the supply of water is produced at a relatively constant rate throughout the day, which sometimes creates oversupply and/or water shortage problems. A similar problem also occurs in waste water treatment systems. When the inlet waste water flow rate is higher than the plant capacity, the system becomes insufficient; the treatment systems become infeasible when there is a low inlet waste water flow rate, as a result of fixed treatment processes.

By considering these limitations in water infrastructure, a smart water grid (SWG) is proposed as a next generation water management scheme, one that integrates information and communication technology (ICT) into the water network structure in order to increase the efficiencies of all elements in the water network.

2. Methodology

2.1. Platforms

Platforms are essential building blocks and the skeletons of the new SWG-based water infrastructure, as the entire system will be formed on these platforms. There are two main platforms established in the new water management infrastructure: the water grid platform and the ICT platform.

2.1.1. Water grid platform

The water grid platform divides the urban macro water grid into smaller meso-grids in order to establish a stable decentralization plan, while installing a central management and a storage structure. Each meso-grid is comprised of a fresh water source, a treatment structure, a fresh water reservoir, and a residential or industrial/irrigational area. In addition to the overall meso-grid water network scheme, alternative water sources can also be integrated to the system based on their availability in each meso-grid. Bi-directional water flow between the freshwater reservoirs and central reservoir allows the management scheme to allocate water from one water grid to the other one without disturbing the urban water cycle and causing public annoyance. Centralized storage is a unique solution to the urban water supply and demand problems, which can collect excess water produced during the night, and supply it as needed to areas in an urban area during the day, even in a spiked-demand situation. A detailed schematic of the water grid platform is given in Fig. 1.

The urban water cycle is categorized into two components: the fresh water cycle and the reclaimed water cycle. Multiple water sources are assigned to the fresh water cycle for mainly domestic consumption; all water reclaimed from domestic consumption is designated for agricultural and industrial consumption. Therefore, the new water grid platform configuration uses as little fresh water as possible for industrial and agricultural consumption, which fulfills the zero water discharge goal.

The domestic water network is divided into several meso-grids with respect to available fresh water

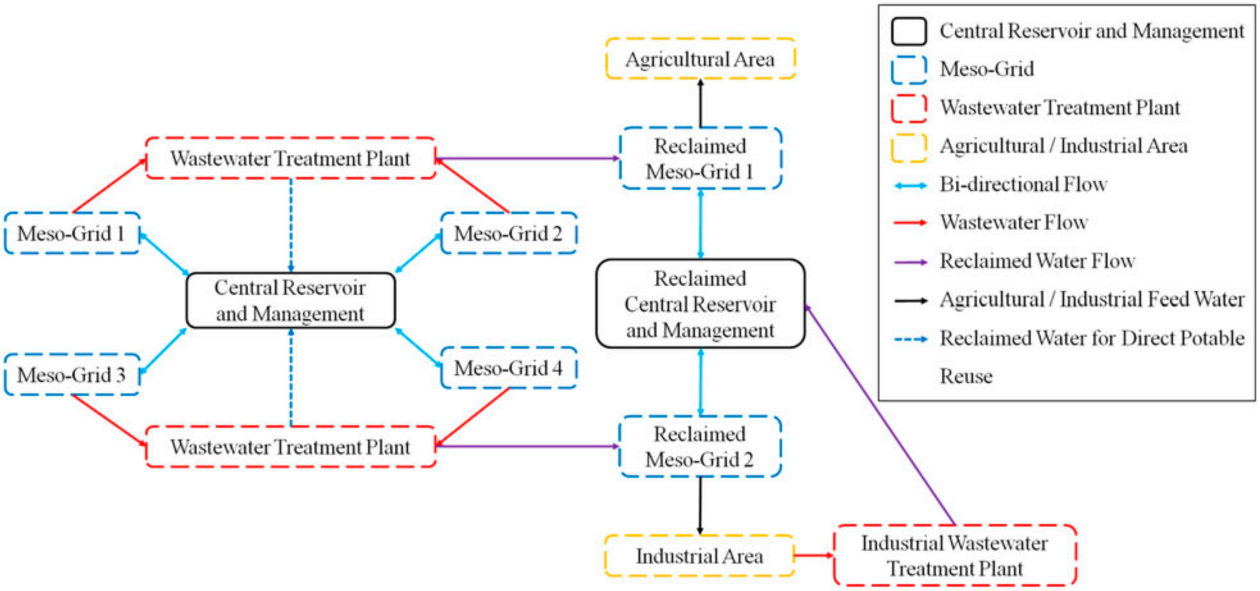

Fig. 1. Water grid platform: fresh and reclaimed water cycles with zero water discharge.

sources, including ground water, water from dams, direct water intake from rivers, and water from seawater desalination. Each fresh water source is then assigned to one meso-grid in the urban area, all of which are able to operate independently from each other. Each grid has its own fresh water reservoir, which is fed by the fresh water source via a suitable treatment system. However, in contrast to conventional design aspects, these fresh water reservoirs are connected bi-directionally to one central reservoir that will be used for back-up, quality control, and the extensive management of the domestic water cycle. In this way, the central reservoir ensures a stable domestic water supply is maintained when scenarios such as high magnitude bursts, contamination, and sudden spikes in the water demand occur. It should be noted, however, that converting all current water distribution structures from one-directional to bi-directional may not be economically feasible because of the elevation differences between the centralized and fresh water reservoirs. Therefore, the appropriate locations of central reservoirs and the number of macro water grids required must be selected with respect to pressure points and the elevation map of the urban area.

In case of a major burst, the central reservoir maintains the water supply to the affected area by relocating fresh water. In a similar way, the central reservoir acts as the main fresh water supply in the urban area when a serious contamination or a malfunction of the water treatment system occurs. In addition, when the water demand spikes as a result of large events such as festivals and expos, or droughts, the central reservoir supplies the required amount of water to the area. Thus, the combination of decentralized water grids and a central reservoir can create a better management scheme for urban water networks by applying a state-of-the-art bi-directional flow design.

Wastewater reclaimed from the domestic water network is the main water source for the industrial water network, in a policy that strives for zero water discharge and minimizes fresh water consumption. Domestic wastewater treatment plant effluent is collected in water reclamation reservoirs and each of these reservoirs is connected to one industrial or agricultural meso-grid. Similar to the domestic water network, a central reservoir will be constructed for back-up and advanced management of the industrial water network. In order to achieve the goal of zero water discharge, the effluent from industrial wastewater treatment plants will be recycled back in to the reservoir.

2.1.2. ICT platform

The ICT platform is constructed on the main water grid platform (Fig. 2). Bi-directional data flow between individual water network elements and between these elements and the central management scheme creates an effective management structure. When no disturbance is present, each grid can act as an individual water network with no central management required. However, when there is a disturbance in one or more of the grids, the central management can take over the

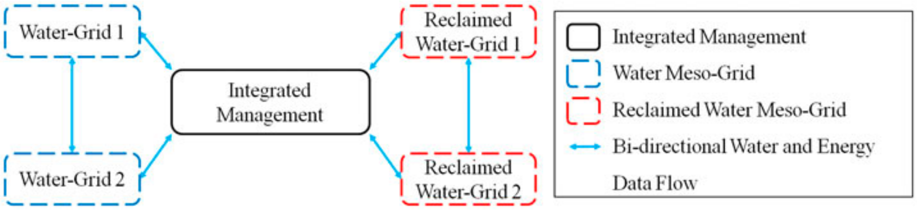

Fig. 2. Bi-directional data flow for water and energy within the water grids and between grids and the central management structure.

control and make adjustments in the whole system. For example, if one water treatment facility is out of order, the central management scheme will receive data from the problematic grid and increase the water production in other grids while supplying fresh water from the central reservoir to the problematic grid. In this system, the ICT platform enables the data flow from numerous sensors to both the individual grids and the central management structure. Pressure sensors for burst (or leak) monitoring and biosensors for water quality monitoring are examples of these sensors. The ICT platform also combines the power and water grid data in order to increase the efficiencies in both grids and to minimize the energy consumption.

2.2. Resources

Securing traditional and alternative water sources is crucial for a sustainable water cycle. Even though there are numerous water sources in and around an urban area, including reclaimed water for the intent of direct potable reuse, only some are available for fresh water production and distribution. In order to make a decision about these water sources, parameters such as quality, feasibility of production, and location are considered and carefully analyzed (Fig. 3).

When a water source is considered as a fresh water source for domestic consumption, characteristics of the water demand and usage in the area (grid) must also be considered. Some water sources may be feasible to harvest in one area whereas they are unavailable in another. Note, however, that in areas with higher water demand and higher socioeconomic characteristics, harvesting a water source at a higher production cost might be a viable option.

2.3. Intelligent network

The intelligent network structure consists of two parts: self-diagnosing sensors and ICT based cooperation network. The integration of standardized sensor systems for water quality, quantity, and pressure then can be used to create a sustainable data flow structure in the water network infrastructure. In this system, auto-diagnosis enabled digital smart telemeters, which have low power consumption and can work both online and offline, enhance the management abilities in both the water grid and ICT platform.

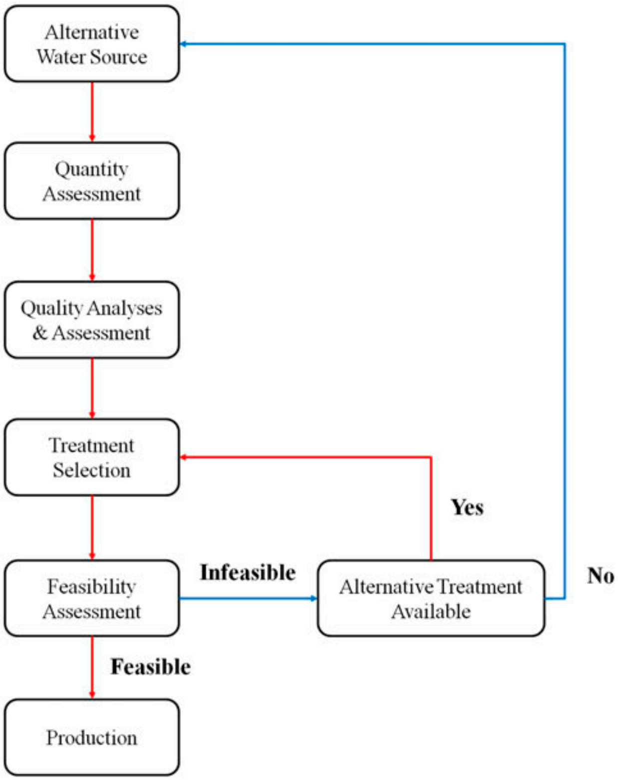

Fig. 3. Production decision scheme for alternative water sources in a designated meso-grid [13].

In order to establish an ICT network, sensor interface technologies and smart node networks are required that have open code software, protocols, etc. The ICT network can then establish a smarter water management scheme based on proactive asset management, rapid real-time decision-making, and system-level decision-making.

2.4. Management

Water supply asset and resource risk management are considered the core management structures in the SWG-integrated water infrastructure. Water supply assets can be divided into two groups: pipeline and non-pipeline assets. The structural conditions of pipes and the performance data of the pipelines require continuous monitoring by integrated ICT structures, and the data collected can then be evaluated by the management scheme. Non-pipeline assets such as pumping stations, reservoirs, and Wastewater Treatment Plants (WTPs) will also be managed both in the individual grids and by the central management structure.

Resource risk management estimates the water demand with respect to the hourly, seasonal, and yearly forecasting models and then re-establishes the projected need according to these inputs. Climate and land changes are also important parameters for water demand and shortage forecasting; therefore, the resource risk management scheme will take these parameters under consideration when creating strategies.

Another important aspect of the SWG technology is to forecast the water demand using several prediction models. Water demand predictions for urban areas obtained using support vector regression models (SVR) have been relatively accurate [9]. The basic idea of SVR is to map the data (x) into a high dimensional space (F) through non-linear mapping (ϕ), and then to obtain a linear regression of the data in this higher dimensional space.

$$f(x) = (\omega \cdot \phi(x)) + b \tag{1}$$

with ϕ: Rn $\rightarrow F$, $\omega \in F$, where b is a threshold [9]. Artificial neural networks, projection pursuit regression, and multivariate adaptive regression splines models can also be used for water demand forecasting, with respect to specific independent variables of the selected area. For example, Xu et al. [10] showed that combined forecasting models can be used to predict urban water demand in a changing environment (climate changes, etc.). This method could even be extended to seasonal and yearly forecasts with respect to climate and actual changes.

2.5. Energy efficiency

In the next-generation water management structure, the smart power grid (SPG) is integrated into SWG to harvest alternative energy sources and optimize water-related energy consumption. To increase the efficiency of the water-energy nexus, a series of new technologies and applications of existing technologies are adopted into the existing infrastructure. When domestic water consumption is considered, the majority of water-related energy is consumed through residential water usage (around 80%). Therefore, the energy efficiency priority of SWG is to minimize energy consumption in households, by applying low-energy processes. For instance, gray water heat recovery devices, gray water fed toilet flushing, and solar powered water heaters are some of the energy effective technologies that are already being used in developed countries. While promoting and magnifying the usage of existing energy efficient technologies, new technologies will also be developed.

In order to simultaneously optimize energy consumption and water consumption, water and energy demand forecasting will be integrated into one management structure. For example, during office hours the majority of water and energy are consumed by industrial and agricultural processes, and from the end of office hours to midnight this behavior shifts to domestic usage. Thus, minimizing the energy and water flow to residential areas during office hours (according to data obtained and forecast data for each grid) by storing or simply re-routing can then be used to significantly reduce energy consumption.

The integration of water and power grids will also create mutual benefits with respect to reliability and energy savings. Bi-directional data flow between the water and power grids will promote advanced city management by enabling a certain degree of control over the cities' two most important resources.

3. Global trends toward SWG technologies

Over the last decade, a number of natural events such as droughts, earthquakes, and tsunamis have forced governments and water companies to develop preventative measures for water security. Globally, there have been several different approaches used to secure the water quality and quantity required for urban areas. However, to date, only two governments have successfully established new water management infrastructures. One is the South East Queensland (SEQ) Water Grid from Australia, and the other is the Water Supply Network Department (PUB) from Singapore. These two governmental bodies have become the leading authorities on this topic in the world.

There are also numbers of new projects and proposals, some funded by governments, that will be applied to megacities pending their degree of success. One such project is the SWG project funded by Korea Ministry of Land, Infrastructure and Transport. The SWG methodology mentioned above is the core technology of this project.

Another interesting project proposal is the National Smart Water Grid (NSWG) from the USA. Even though there has not been an initiative action for this project, it is still a sophisticated solution to alleviating water scarcity problems in the midwest USA.

3.1. SEQ water grid, Australia

During 2007 and 2008, SEQ faced the worst droughts on record, when the combined water levels in three major dams (Wivenhoe, Somerset, and North Pine) dropped to less than 17% capacity. The SEQ Water Grid was developed and delivered during this time as the largest urban water security response in Australia.

The SEQ water grid is an integrated system that focuses on the security and management of SEQ's water supplies. In brief, the SEQ infrastructure is comprised of treatment facilities and two-way pipelines that make bi-directional water movement possible. One of the major changes that the SEQ water grid introduced was the integration of climate-resilient water sources (desalination and purified recycled water) to the system, in addition to new water sources such as rainwater. They also integrated water demand forecasting into their management structure in order to avoid future water scarcity issues.

The SEQ water grid includes: 12 connected dams, 10 connected drinking water treatment plants, 3 advanced water treatment plants (purified recycled water), 1 desalination plant, 28 water reservoirs, and 22 bulk water pumping stations.

The SEQ water grid can move water to where it is needed most by using bi-directional water pipelines, and purified recycled water can be introduced to the system at several points. Therefore, SEQ's rainfall dependency dropped from 95 to 75% in just four years [11].

3.2. Water Supply Network Department (PUB), Singapore

Singapore does not have enough natural water sources to establish a self-sufficient water network, with more than half of Singapore's water requirements currently being imported from neighboring countries. Therefore, Singapore established PUB in order to resolve their water scarcity problems. PUB is responsible for the collection, production, distribution, and reclamation of water in Singapore. Water sources consist of harvested rain and storm water, desalinated seawater, and reclaimed water.

Rain and storm water is collected through rivers, canals, drains, and streams, and then stored in 17 reservoirs. Pipelines having bi-directional flow capabilities allow excess water to be transported from one reservoir to another, thus optimizing the storage capacity. Raw water is also treated and then integrated into the water network. In order to establish and extend this smart water management system, PUB is also planning to spend USD 7 billion on projects, such as a new 250 km pipeline structure.

Wastewater is collected via an extensive sewage system and treated at water reclamation plants. A portion of the treated water is further purified for use as drinkable water (NEWater) and added to the water network for potable reuse, while the remaining portion is discharged into the sea. Desalination is also used extensively in the PUB infrastructure, with the entire system being referred to as The Water Loop.

PUB started its own SWG research in 2011 using a road map that consists of three stages: asset management, process applications, and customer engagement. Data mining, database integration, and risk management framework development are the major focuses in asset management. In contrast, real-time monitoring and predictive measures such as event and demand predictions are the core applications in the second stage. PUB has already deployed 25 pressure nodes in city, which are being used to detect leaks and predict water demand [12].

3.3. National smart water grid (NSWG), USA

The midwest states in the USA experience devastating floods almost annually, while the western states are trying to resolve drought problems. The Lawrence Livermore National Laboratory proposed a project that consists of pumping fresh water from the Mississippi, Arkansas, and Missouri Rivers into the Colorado River and western states. In brief, the project proposed the pumping of fresh water via pipelines from areas of overabundance/flood to areas of drought or high demand. It is predicted that $1.23 \times 1{,}010$–$7.4 \times 1{,}010$ m^3 of fresh water can be captured per flood event. This captured water can be introduced into the upstream of Lake Powell, Utah, to be distributed to destinations near Denver, Colorado, and then be used in areas along the pipelines. For example, the fresh water introduced into the Colorado River can be used by cities in southern Nevada, southern California, northern Arizona, Colorado, Utah, the Indian

Tribes, and Mexico. It was estimated that the construction of over 5,000 km of new pipelines and collector structures will cost USD 82 billion. However, it is also predicted that the NSWG will pay for itself from the water captured from a single flood event [13].

3.4. SWG research, Korea

Korea has been taking the water scarcity issue seriously as it has faced severe droughts over the last couple of decades due to climate change and the exponential growth in city populations. For example, the Gol-ji River in Taebaek almost dried out in 2009, and the government was forced to limit water consumption during day times. Based on the need for a stable water supply, Korea is planning to spend more than USD 10 billion by 2025 in order to expand water facilities, repair decrepit facilities, stabilize the facilities, and increase the research and development (R&D) outcomes. Around USD 800 million will be spent on R&D, and the outcomes from these studies will be applied to cities and watersheds. To perform SWG research in Korea, three main steps are required to extend the core technology from pure research to applications in industry [14]:

(1) Smart water grid
   (a) Component technology development.
   (b) Optimized parts and materials development.
   (c) Development of ICT-based integrated management system for SWG.

(2) Construction of water grid test bed
   (a) Test bed demonstration.
   (b) Optimized combination of each component.
   (c) Public relations supporting test bed.
   (d) Scaling up for cities and megacities.

(3) Promotion of world’s first water grid industry
   (a) Export of components for water grid.
   (b) Preoccupancy of world water market through expert of SWG.

4. Conclusion

SWG technology is based on the creation of ICT-integrated water management solutions to guarantee the security of water quantity and the safety of water quality. SWG also focuses on water-related energy consumption, as water and energy consumption cannot be separated because of their direct dependencies on each other.

SWG technology integrates five PRIME research areas for the construction of next-generation water infrastructure in order to overcome management limitations and to create a sustainable water cycle in urban areas:

- *Platform*: integrated combination of a remodeled water grid platform and a new ICT platform is the skeleton of the SWG technology, i.e. the other water infrastructure elements are formed on this skeleton.
- *Resources*: securing both alternative water and conventional water sources in the water grid platform creates and enables a partially decentralized management scheme.
- *Intelligent network*: intelligent control of the water flow and infrastructure elements in both the water and ICT platforms allows for bi-directional communication between the elements. Intelligent control also enables each of these elements to operate both as standalone and combined processes.
- *Management*: SWG technology contains risk-assessment and forecasting technologies and methodologies for assets in the water infrastructure in order to create a better management scheme.
- *Energy efficiency*: integration of SWG and SPG and the application of energy efficient applications increases the energy efficiency in operating and maintaining the water infrastructure.

Therefore, it is expected that SWG technology can give water managers new insights into planning future water infrastructures as it provides new roles for SWGs in future smart cities.

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