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Information Systems for Sustainable Use of Water in Smart Cities: A Review and Call for Future Research

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Abstract

Water is the basis of life—that being said, the rising scarcity triggered by climate change and urbanization is an increasingly important challenge in urban areas. The United Nations present “water” as one of 17 Sustainable Development Goals (SDGs), and experts make impassionate calls for sustainable water management solutions as a seminal part of smart cities. While there are numerous research efforts in the IS community regarding certain SDGs and smart cities, we demonstrate in a structured literature review that urban water scarcity is still a blind spot. In this paper, we present pathways for future research alleys on this topic. We sketch out a vision for a smart city water system that is based on a novel information system. We draw on the energy informatics framework as a theoretical basis for our work and provide a context-specific discussion on its transferability to the resource of water in smart cities. By introducing urban water scarcity to the IS research agenda and showing opportunities as well as boundaries for the transfer of the energy informatics framework, we hope to stimulate IS researchers to be more active in pursuing research efforts in this pressing topic.

Keywords

Sustainability, Sustainable development goals, smart city, water, water scarcity, Green IS.

Introduction

Water scarcity has become a critical challenge, not only in arid areas but also in the western world. The United Nations (UN) have declared “Water” as the 6th of its Sustainable Development Goals (SDGs). Especially cities which at the same time face challenges resulting from increasing urbanization are strongly affected (McDonald et al. 2014). While the urban population is growing, heatwaves and droughts strain water reservoirs and diminish groundwater-levels, so that in many European and American regions, citizens are increasingly urged to reduce their personal water consumption (Heggie 2020; Mallet and Arnold 2020).

With an expected 80% increase in urban water demand by 2050 driven by rapid urbanization and climate change, water challenges are expected to become even more urgent (Flörke et al. 2018). The UN have already acknowledged the pressing issue by declaring “Sustainable Cities and Communities” as another one of 17 SDGs. Literature suggests that the IS discipline, with its interdisciplinarity and canon of methodologies, is particularly equipped for contributing to the SDGs (Thomas et al. 2020). One promising approach to addressing these urban challenges is the concept of smart cities (Brandt et al. 2018). There are various definitions for smart cities with recent literature increasingly stressing the role of digitization to tackle urban issues (Marrone and Hammerle 2018). However, the term still remains fuzzy and is yet to be defined more precisely like according to Alter's (2020) understanding of "smartness" for example. While, in fact, there is a growing body of literature on this matter and various researchers have already focused on the emerging role of smart cities in helping to achieve particular SDGs (Pan and Zhang 2020), we observed that there are only a few research efforts that address urban water scarcity.

To provide a solid ground for future research, we conducted a structured literature review to identify studies addressing water scarcity in cities and present our findings in this paper. In fact, our review in major IS databases such as the Senior Scholars' Basket of Journals and the AIS eLibrary confirmed our observations and revealed a blind spot in the IS literature.

To pave the way for future research on the increasingly pressing topic of urban water scarcity, we suggest research pathways, which we will outline in the following. In particular, we aim to demonstrate the value of information systems leveraging the capabilities of digital technologies to tackle urban water scarcity. We will sketch the vision of smart water systems to foster sustainable use of water in smart cities. Our model is based on the energy informatics framework (Watson et al. 2010) as a fundamental concept of Green IS. We will then proceed to discuss the transferability of this framework to the resource of water and discuss different use cases of applications with a special focus on use cases in natural ecosystems such as water use for irrigation of plants and green spaces to outline boundaries of the framework.

The remainder of this paper is structured as follows: First, we report the results of our structured review of IS literature on the issue of water in smart cities. Second, we briefly introduce the energy informatics framework (Watson et al. 2010) as a theoretical background. Third, we introduce theoretical considerations on a water informatics framework and discuss the resulting contributions. Fourth, we describe practical considerations on the applicability of the framework to the issue of water scarcity in the city of Frankfurt am Main and provide an outlook on future pathways research. Fifth, we conclude with a summary of our contributions and a call for contributions to the IS community.

Methodology: An IS Literature Review on Water in Smart Cities

To understand prior efforts of the IS community regarding water scarcity in cities, we conducted a structured review of IS literature. The review methodology is based on the recommendations of Webster and Watson (2002). We conducted the literature search in January 2021, covering the Senior Scholars' Basket of Journals (basket of 8) and the AIS library as the two most important collections of high-quality IS research articles. An abstract search with the search terms "water" AND "city" OR "cities" OR "urban" in the AIS library resulted in an initial set of 10 articles. With an additional query in the journal databases of all basket of 8 journals with the same search string, one additional article was retrieved. Overall, this search resulted in an initial set of 11 documents. From this initial set we excluded one article which was not written in English. The refined set of articles was analyzed for relevance based on a detailed screening of keywords, title, abstract, and full text. We excluded four articles that did not contain any content regarding the investigated issue of water in cities. After this screening, a final sample of 6 documents remained for detailed analysis and review. A forward and backward search revealed some additional papers in other, non-IS-centered domains like environmental sciences or sensor technologies. But as our focus is reviewing the topic from an IS perspective, we refrain from summarizing these articles in this paper.

The six articles in the final sample were published between 2000 and 2020. Five articles were presented at conferences (HICSS, ISD, PACIS, ICEB, and AMCIS), while only one article was published in a journal (Information Systems Journal).

The articles address the topic of water in cities in different ways (see Table 1). First, three papers present prototypes for smart solutions regarding water in different use cases, such as smart farming for intelligent crop irrigation (Sari et al. 2017), intelligent water management using water meters to manage assets of water utility (Li et al. 2017), and Advanced Metering Infrastructure in smart cities including water meter as one of the multiple devices (Di Leo et al. 2019). Second, two papers mention water as either a problem or solution domain for sustainable infrastructure decision-making (Courtney et al. 2000) or green IS solutions. In a literature analysis on Green IS solutions in smart cities, Brauer et al. (2015) identify only one article regarding water.[1] Third, one article elaborates on a conceptual solution framework, covering the issue of water. Corbett and Mellouli (2017) develop a conceptual model to explain the role of IS to build smart and sustainable cities and present a framework of action for researchers in their article published in the Information Systems Journal. Regarding SDG 6 Water, they give water quality management as an example area of green IS to increase drinking water quality.

	Solution prototype	**Problem/Solution domain**	**Solution framework**
Sari et al. (2017)	x		
Li et al. (2017)	x		
Di Leo et al. (2019)	x		
Courtney et al. (2000)		x	
Brauer et al. (2015)		x	
Corbett and Mellouli (2017)			x
This paper	x	x	x

Table 1: Literature Review on Water in Smart Cities

In summary, we recognize that only a limited number of articles were published addressing the use of water in cities (either providing a solution prototype, discussing a problem or solution domain, or deriving a solution framework). Except for only one article published in a reputable journal, a vast majority of articles in our sample is published in conference proceedings, indicating the novelty of the field to the IS community. Overall, we identified a research gap with regards to comprehensive considerations of more sustainable use of water in urban areas that integrate not only the problem domain with a (theoretical) solution framework but also suggest approaches for developing solution prototypes or even products. Therefore, we call for IS researchers to explore this pressing issue. Especially we encourage researchers to contribute to a more sustainable use of water in cities.

As a starting point, we introduce and motivate the problem domain “Sustainable Use of Water in Smart Cities” in this paper and present a theoretical solution framework lying out some impulses for IS researchers on how to address this topic. Thereby we build on the work of Watson et al. (2010), who advocate a research agenda to establish energy informatics to increase energy efficiency. We conclude with the discussion and motivation of a solution prototype for smart irrigation in the city of Frankfurt am Main, based on our theoretical solution framework. In the following section, we introduce the energy informatics framework as the theoretical background of our work.

Theoretical Background: The Energy Informatics Framework

With the introduction of energy informatics in IS research, Watson et al. (2010) set the cornerstone for Green IS research advancements by calling on the “transformative power of IS to create an environmentally sustainable society” (Watson et al. 2010, p. 24). The authors introduced the energy informatics framework (see Figure 1), which builds on the potential of IS to reduce overall energy consumption and, thus, CO2 emissions. During the last decade, the framework was referred to in various contexts such as motivating energy-efficient behavior (Loock et al. 2013), the economics of multi-hop ride-sharing (Teubner and Flath 2015), or sensemaking support systems in environmental sustainability transformations (Seidel et al. 2018).

[1] This article was published by Chamberlain et al. (2014) in IEEE Transactions on Computers and describes a decision support system prototype to help community planners identify, design and evaluate sustainable solutions for wastewater management.

The core idea behind the framework can be summarized as follows: *Energy + Information < Energy*. The framework integrates central elements of an energy supply and demand system with an IS at the center of the framework, which enables the management of supply and demand to reduce the total demand and energy consumption. The IS integrates three major technological components: sensor networks and flow networks on the supply side, as well as sensitized objects on the demand side. A flow network is *"a set of connected transport components that supports the movement of continuous matter (e.g., electricity, oil, air, and water) or discrete objects (e.g., cars, packages, containers, and people)"* (Watson et al. 2010, p.26). A sensor network is a "*set of spatially distributed devices that reports the status of a physical item or environmental condition*" (Watson et al. 2010, p.26). And a sensitized object describes "*a physical good that a consumer owns or manages and has the capability to sense and report data about its use*" (Watson et al. 2010, p.26). Further, external factors are presented influencing the deployment of the system, which are key stakeholders, such as consumers, suppliers, and governments, as well as three eco-goals, efficiency, effectiveness, and equity, that shape the organization's and individual's thinking and behavior. Despite its main focus on energy, the energy informatics framework can well be applied "*to other increasingly scarce resources, such as water*" (Watson et al. 2010, p.24). We will thus proceed to discuss the framework in our context of urban water use and sketch out opportunities and boundaries for applying this framework to the context of water.

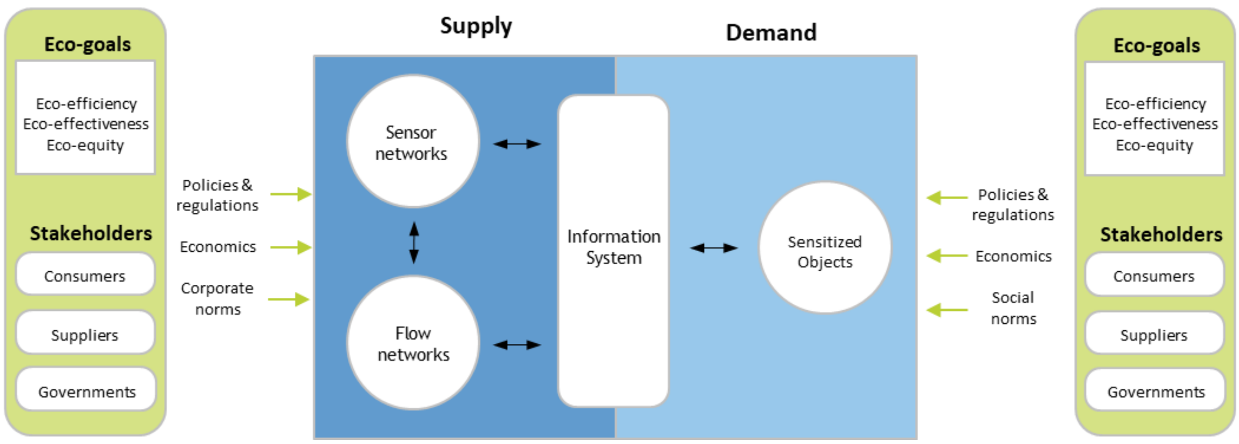

Figure 1: Watson et al.'s (2010) Energy Informatics Framework

Theoretical Considerations: The Water Informatics Framework

We suggest applying the energy informatics framework of Watson et al. (2010) as a basis for developing a conceptual framework of water informatics in a smart city. We thus present a framework on a conceptual level regarding the use of water in cities and explain various thoughts regarding the different elements and their transfer to the context of water. Similar to the energy informatics framework, our *water informatics framework* aims at reducing total water demand by integrating supply and demand with an IS at the heart of the system with the analog core idea in mind: *water + information < water*.

As is also the case in the framework of Watson et al. (2010), the central elements on the supply side are "sensor networks" and "flow networks." In the water context, "sensor networks" refer to devices that report the status of the water supply. We lay out various sources of water supply available in a smart city that could be captured by sensor networks. These include—but are not limited to—tap (drinking) water as well as natural sources such as rain or fog, and the collection of rainwater in smart cities. Importantly, water significantly differs from other types of scarce resources such as electricity by being (naturally) available in various aggregate states and purity levels. One suggestion on the supply side to make water use more sustainable, for example, may be the increased use of naturally available rainwater (as well as process water) for water consumption and thereby reducing the use of tap water to decrease water scarcity in cities. The other central element, "flow networks," describing connected transport components for the movement of the resource water, may include various ways in which water can be transported. For example, pipes enable a continuous flow, while transport vehicles (e.g., in the context of irrigation) facilitate the distribution of discrete units. In addition, natural ways of water distribution, e.g., through air, surface, or soil, need to be taken into account.

On the demand side, the system aims to capture demand for water via "sensitized objects." Regarding the use of water, we suggest a distinction between technical objects and biological objects as they are fundamentally different regarding i) the possibility to determine actual demand, ii) their consumption patterns and iii) the possibility to adapt demand. The water demand for biological objects such as plants is majorly determined by natural factors such as climate, weather conditions, and the biological ecosystem of the biological object and therefore provides a low level of usable demand-side flexibility. Technical (human-made) objects that consume water (e.g., washing machines) follow the same demand logic as in the energy informatics framework and therefore present a greater potential to shift or reduce demand. Also, the demand for biological objects is difficult to capture and can only be approximated via sensors, while sensitized technical objects can directly report data about their state and demand or consumption.

We outline these specificities of the water system in our framework. However, the core idea still remains similar to the energy informatics framework: The framework incorporates technical components regarding the use of water, which are integrated by a central IS to build on the IS' capabilities to integrate supply and demand and reduce overall water consumption.

The resulting framework for water informatics in cities is presented in Figure 2. It provides a basis for integrating the water supply and demand by using the information provided by the technical elements (i.e., sensor networks, flow networks, and sensitized objects). With this framework, we hope to stimulate IS research to take a more active role towards tackling water scarcity in cities to research this topic from various perspectives and develop solutions to use the scarce resource water in a more effective, efficient, and sustainable way.

To sketch out our theoretical contribution to the Information Systems Literature, we will briefly discuss some necessary refinements when applying the framework to the issue of water scarcity. While we agree with the general idea that the framework of Watson et al. (2010) also applies to other scarce resources, we would particularly like to stress some of the important differences between energy and water systems technologies.

Regarding urban water distribution, it needs to be mentioned that water cannot be regarded as a purely continuous matter, since in some cases (such as irrigation), it needs to be transported or reallocated via discrete objects. Furthermore, some flow networks need to be considered as "unstructured" since they incorporate natural ways of transportation (e.g., through the air, surface, or soil). With regards to the sensor network, this implies several additional challenges. Since the sensor network should support the use of the flow network, a variety of different natural sources of water would need to be covered, e.g., rain, fog, and flood. Since the quality of water is not homogenous in the "unstructured" or natural flow networks, not only the amount but also the "quality" of water needs to be tracked based on sensor data. This is particularly important since different sensitized objects may have different requirements with regards to the type of water they need to consume. While a public water dispenser obviously requires drinking water quality, many public green spaces could also be irrigated with process or rainwater, for example. Another striking difference can be directly linked to this example. While in energy informatics, most sensitized objects have clear specifications and consumption patterns that can be directly measured, this is not the case for many biological sensitized objects. Especially in the tension field between ecological and digital ecosystems, sensitized biological objects such as plants will always depend on sensor networks (as opposed to the energy informatics framework) also on the demand side, to estimate actual water demand based on the measurement of several indicators. The resulting complexity of comprehensive water system technologies is a key challenge in any water informatics framework application.

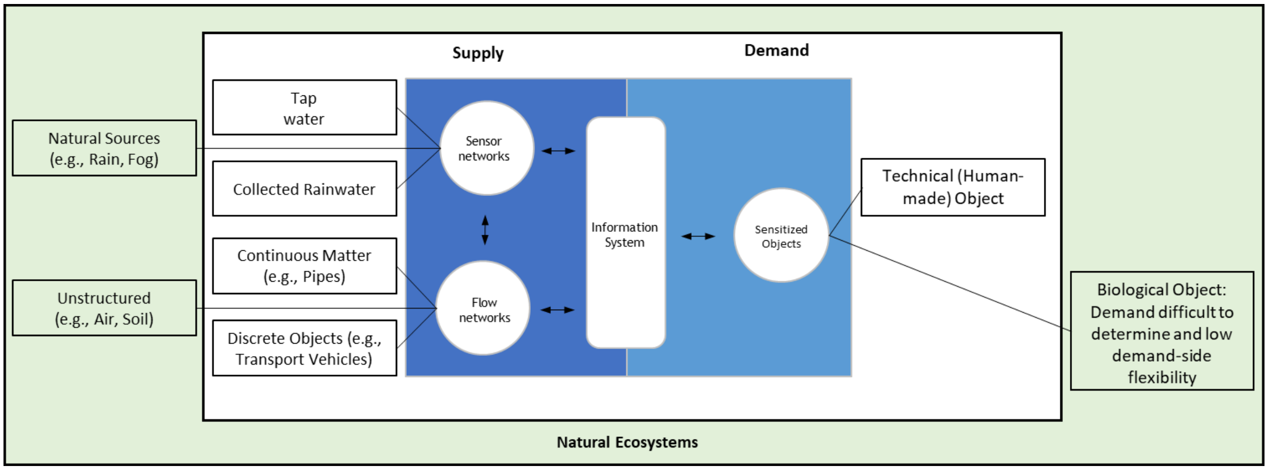

Figure 2: Water Informatics Framework (adopted from Watson et al. 2010)

Practical Considerations: The Case of Frankfurt am Main

For our practical considerations, we particularly focus on one use case in cities regarding the demand side of our framework – that is, the irrigation of public green spaces and urban trees in particular. Urban trees will increasingly suffer from water stress due to rising temperature in cities, while at the same time, they are an essential contributor to urban micro-climate. It is thus of major importance to develop resource-efficient irrigation strategies that protect urban trees and, at the same time, do not unnecessarily exacerbate water scarcity issues. Water scarcity, especially during the summer, is becoming an increasingly important issue for many large cities. Frankfurt am Main, known as one of the hottest places in Germany[2] is no exception from this trend. While saving water with the help of sensitized technical objects (such as dishwashers, washing machines, toilet flushes, showers, etc.) is in many cases already common practice, the frugal use of water in natural ecosystems is not yet well understood. As a prime example, we focus on the irrigation of public green spaces and urban trees. While several initiatives aimed at improving water supply (e.g., through crowdsourcing approaches for urban tree irrigation[3]), there are several open questions related to i) the types of water used for irrigation (in many cases, drinking water is used for irrigation purposes[4]) and ii) the demand-oriented use of water (current irrigation strategies stipulate a regular and fixed amount of 200 liters of water per tree[5]). Regarding the practical contribution of our proposed model, we suggest a prototypical instantiation of the water informatics framework in the smart city of Frankfurt am Main.

In collaboration with local decision-makers for the irrigation of public green spaces and local service providers, we chose a pilot-area in the city of Frankfurt am Main to implement a prototypical instantiation of a smart irrigation system and demonstrate its potential. Since the city of Frankfurt am Main is in an ongoing transition towards becoming a smart city with a potential for data collection and utilization

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[2] https://www.fnp.de/frankfurt/frankfurt-waermste-deutschlands-jahr-2018-10921875.html

[3] https://www.fr.de/frankfurt/stadt-frankfurt-sucht-paten-patinnen-strassenbaeume-13808838.html

[4] https://www.fr.de/frankfurt/aufs-waessern-baeume-frankfurt-zr-13184239.html

[5] https://www.fr.de/frankfurt/waessern-herbst-kommt-zr-12854862.html

(Hawlitschek 2020), it is particularly well-suited as a location for the demonstrator setup. In future research, we will design an IS that supports decision-makers in the city of Frankfurt am Main to better balance supply and demand based on a demand-side sensor network. With the help of the intended decision support system, decision-makers will be able to adjust the commissioning of irrigation service providers in near real-time and thus pave the way for a demand-oriented irrigation strategy.

We hope that the above-mentioned practical considerations stimulate researchers and practitioners, particularly in smart city administrations, to develop and test similar systems. We argue that our proposed model provides a valuable fundament for practical considerations in other smart cities—for example, regarding smart irrigation.

Conclusion

Overall, our research contributes to the investigation of the sustainable use of water in cities. First, we unveil the research gap in IS literature regarding the sustainable use of water in cities. Further, we apply the energy informatics framework (Watson et al. 2010) to propose a framework for smart, sustainable water use in cities, which aims to contribute towards more sustainable and smart use of the scarce resource water. Additionally, we discuss the boundaries of transferring the framework to the context of water. In this notion, we hope to stimulate further research endeavors regarding water scarcity in smart cities. By introducing the topic of water scarcity in smart cities to the IS research community, we encourage future IS research to be more active in this pressing topic of interest and pursue further initiatives to contribute to the SDG 6 Water.

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