The Role of Resource Efficient Decentralized Wastewater Treatment in Smart Cities

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Abstract—As urbanization continues as a global mega-trend, cities must provide healthy and sustainable living spaces and deliver basic infrastructure services with greater efficiency in environmental and economic resource use. One vital concern is the provision and usage of water. This paper argues that energy-efficient decentralized wastewater treatment facilities can play an integral role as smart cities develop in the coming years. In particular, it focuses on three main points. First, in order to meet growing water demands, the use of wastewater treatment for the recycling and reuse of water streams will increase. Second, the need for recycling and reuse at the point of usage strongly favors a decentralized rather than centralized approach to wastewater infrastructure. Finally, ecological techniques to wastewater treatment will be required to provide such a service with greater resource efficiency. The paper concludes with a potential wastewater treatment design that may meet these specific needs of smart cities.

Keywords—Smart Cities; water infrastructure, water management; on-site wastewater treatment; energy-water-nexus

I. INTRODUCTION: SMART CITIES HAVE DEMANDING REQUIREMENTS

In the emerging vision for the smart city of tomorrow, the most important objective of smart cities is to meet its citizens’ requirements economically and efficiently [1]. To fulfill this goal, several hard and soft domains need to be considered diligently [2] as the total number of citizens and consequently city sizes grows at breathtaking speed [3].

Many works on smart cities have been devoted to smart (electric power) grids [4], [5], intelligent buildings [6], [7] and transportation systems [8]. This paper draws attention to smart water systems and the need to develop more efficient approaches to wastewater as a resource. In particular, it argues that energy-efficient decentralized wastewater treatment facilities can play an integral role as smart cities develop in the coming years.

The paper is organized as follows: Section 2 discusses the need for reusing water in a smart city. Section 3 then introduces the need for decentralized treatment systems and is followed by Section 4 which systematically compares these systems to their centralized counterparts. Section 5 addresses the need for resource efficiency in the wastewater treatment process. Section 6 then mentions several promising technologies for wastewater treatment in a smart city context. The paper is brought to a conclusion in Section 7.

II. THE NEED FOR WATER RECYCLING & REUSE IN A SMART CITY

The mega-trend of urbanization creates a highly concentrated demand on the local environment’s water resources. While water supply systems can be built to convey water over long distances, the growth in water demand can often outstrip the ability to build such an infrastructure [9], [10]. Furthermore, before this water can reach its actual site of consumption, 20% to 50% of the water input is lost due to leakage [11]. Consequently, water recycling and reuse allow the potential to maximize the usage of local water resources and minimize water import & loss; thus improving the city’s resilience as a whole [12], [13].

Going beyond water balance alone, water and energy are inextricably linked. Extracting, delivering and disposing water requires energy [14]. Additionally, most processes for extracting and refining various fuel sources and producing electricity use water [14]. This interconnection between these most vital resources is known as energy-water nexus [15], [16], [17]. As a consequence, both the water and energy challenge must be addressed simultaneously.

Water recycling and reuse is located at a central point in this energy-water nexus due to its potential to short-circuit fresh water and wastewater infrastructure. Freshwater supply can be particularly energy-intensive. For instance, the states of the Arabian Gulf are spending up to 12% of their total energy consumption on desalination alone [14]. Consequently, leakages in the water supply system also represent a lost embedded energy [18]. Water recycling, therefore, offers a promising alternative by substituting freshwater and thus reducing water losses [19]. Rather than producing and
distributing 1.2-1.5m³ of water, 1m³ of recycled water may be used instead at considerably lower energy intensity.

The sustainable use of wastewater is also connected to nutrient management, material usage, and waste generation [20], [21]. Nutrients, for example, which are essential for fertilizers are highly concentrated in wastewater [20]. Among those, mineral phosphate, in particular, is a non-renewable resource that will become scarce or even exhausted during the next 50 to 100 years [22], making it a logical resource for recycling efforts.

III. DECENTRALIZED WASTEWATER TREATMENT

The current approach in water management has basically been the same since the 19th century. Freshwater and wastewater are handled in a centralized way. Freshwater is supplied via a distribution network from groundwater, surface water or desalination sources. The water is normally used only once and further discharged into the sewer system that collects all the water from the city, often mixing municipal wastewater, rainwater, and wastewater with high concentrations of contaminants (e.g. from industry and hospitals) [23]. This mixed wastewater is then transported to large treatment plants, which usually discharge their effluent into rivers or seas. Based on the “pipe it away first, then think about what comes next” philosophy, centralized management is the structure of choice in most cities and countries [24].

Centralized systems, initially designed to protect public health and provide fire safety, have been extremely successful in these respects [20]. The resulting improvements in hygiene, security of property and availability of water supply have allowed the historic growth of modern cities. Despite this historic role, the conventional centralized approaches to urban water are resource inefficient and increasingly expensive. This is because only a minor fraction of the high quality freshwater distributed in urban areas is used for human consumption. The major fraction is used for cleaning purposes, toilet flushing and for irrigation of plants and lawns. A significant amount of the drinking water is required as a means to transport the pollutants to the wastewater treatment plant [24]. In contrast, decentralized systems that use the appropriate quality of water for the specific water use are considered less resource intensive and a more ecologically benign form of sanitation [20], [25], [26].

Driven by the growing awareness that sustainable development is a necessity, the development of small-scale wastewater treatment systems has therefore gathered pace in recent years. Technological capacity has progressed with some small-scale wastewater treatment technologies being capable of consistently producing high quality effluents. However, for various reasons, the historical and institutional bias towards centralized infrastructures tends to continue. This reflects a lack of awareness of the benefits of decentralized systems and the assumption of low levels of reliability and poor performance of small-scale wastewater treatment [20], [27].

IV. COMPARISON OF CENTRALIZED AND DECENTRALIZED WASTEWATER MANAGEMENT SYSTEMS

This section more closely compares centralized and decentralized wastewater management systems from both technical as well as economic perspectives.

A. Investment and costs

The cost of implementing a centralized system are particularly large. While a centralized wastewater treatment facility itself offers economies of scale, it also requires the building of a sewer collection system that typically accounts for 80–90% of the total capital cost and more than 65% of the total annual operating costs [28]. Therefore, the costs of sewer systems are almost an order of magnitude greater than the treatment facilities [24]. As diseconomies of scale are inherent to pipe networks, the effect of economies of scale in treatment is often annihilated [20]. Furthermore, because centralized facilities must last several decades, they are dimensioned and built today for a predicted utilization that may not be reached until well into the future. Such low utilization leads to sub-optimal efficiency and operating costs [25]. Additionally, the associated investment cost - much for underutilized capacity - must be made either in a relatively short period of time or financed, potentially burdening the local economy [25], [28].

Decentralized systems offer great potential for cost reduction [28], mainly due to the fact that transport sewers including lifting stations and storage facilities to handle combined sewage flow are not needed [25]. Small-scale distributed systems can be built incrementally, meeting increased demand as it occurs. This means that a sequence of decentralized units can be installed at a lower present value cost than a large centralized system with the equivalent life cycle cost per amount of wastewater treated [20].

B. Flexibility towards Uncertain & Growing Water Demand

The cost challenges of centralized systems are even more exacerbated in a smart cities context. Quickly growing urban centers comes with a commensurate growth in water demand. While centralized systems are often initially oversized and eventually become undersized, they offer limited options for their expansion [29]. Furthermore, as their capacity must be predicted several decades into the future, even small errors in annual water demand growth rates can lead to large errors in the appropriate capacity of water treatment facilities.

In contrast, the small unit size of decentralized systems allows for precise matching of growing wastewater capacity requirements. Less money is tied up in overbuilt capacity. Additionally, project construction periods are considerably shorter allowing greater certainty in tracking water demand [28], [30].

C. Water heterogeneity and treatment efficiency

Another challenge with centralized water treatment facilities is that they mix heterogeneous water streams. Wastewater streams may originate from households, industry, and stormwater. Each of these, taken alone, requires different treatment technologies. When these streams are combined into one stream, it produces a highly complex mixture whose composition of pollutants and nutrients fluctuates. The
effective removal of the pollutants becomes very difficult [24] and the treatment cost increase as compared to a scenario in which each of the individual wastewater streams is treated prior to mixing [31], [32].

Decentralized wastewater treatment, however, can take advantage of the relative homogeneity of wastewater streams at their point of origin. Common household wastewater is less heterogeneous and can be treated with lower effort. At the same time, the discharge from special industries and hospitals contains highly problematic contaminants, also known as “emerging pollutants”, that require specialized treatment processes. In the case of hospitals, for example, residues of medical products and other chemicals are challenging the wastewater treatment processes. In classical centralized wastewater management systems, such specialized treatment processes would be far too expensive, as they would need to be applied in large treatment plants with heavily diluted contaminants concentrations. Decentralized water treatment plants are capable of dealing with such special contaminants in a more specific way by using appropriate treatment technology and producing higher treatment results in terms of stability and overall quality. They are able to achieve these high treatment results with lower effort because they only need to apply the appropriate treatment processes for the respective type of wastewater. In this way, the overall water treatment strategy becomes more cost effective while reuse opportunities increase [28], [30]. That said, decentralized treatment plants, due to the small number of homes and facilities to which they are connected, must be able to deal with fluctuations in water inflow.

D. Reuse possibilities

As decentralized systems do not need large sewer systems, they also do not require extensive networks for the distribution of treated water. The water can be treated and reused close to where it is first used, requiring less energy for water transportation [28] and offering a local opportunity for reuse or groundwater recharge [25], [28], [30]. Because the wastewater streams are separate, household wastewater is less contaminated by problematic substances. Therefore, the water as well as its constituent byproducts (e.g. nutrients, sludge, phosphorous) can be more easily treated and reused [24], [30]. Consequently, decentralized systems can support water recycling using small grids of different water qualities, customized to the respective demand (e.g. irrigation, domestic use, etc.). Such a strategy reduces both fresh water demand and water loss by leakage. Thus, water resource efficiency is increased and energy is conserved [33].

E. Controllability

Centralized systems pose mixed benefits with regard to their controllability. A single centralized wastewater treatment facility is fairly easy to control and maintain. In contrast, monitoring, control and maintenance requirements of a large sewer system are significant. Inadequate operation and maintenance may lead to sewer clogging, local flooding and leakages. These effects can cause pollution of the soil and groundwater and lead to an increase in the hydraulic loading of the treatment plant due to increased inflow and infiltration [24].

In contrast, decentralized systems have many separate treatment facilities each of which require professional maintenance in order to work reliably. Nevertheless, supervision of many small plants can be supported within a smart cities context by advanced remote monitoring and sensing systems [25]. This allows a distribution of health and environmental risks. With many small treatment centers, the probability of simultaneous failure is significantly lower than that of failure of one system serving the entire community [25], [28].

In summary, the classical, centralized wastewater management approach can be characterized by:

- a vast expansion of freshwater networks that regularly permit leakages and require extensive monitoring and maintenance.
- a one-time use of freshwater. Reuse or recycling requires high treatment efforts due to the heterogeneous composition of the collected wastewater.
- a relatively large distance between water treatment facilities and the city center. Because centralized facilities require a lot of land and produce unpleasant odors, they need to be placed relatively far from the city. This increases the distance between the source of wastewater and the point of treatment; further increasing cost and energy demand.
- a high volatility in treatment performance. This is due to the highly mixed influent and the large peaks of flow rate during high precipitation events that regularly result in overflowing treatment facilities.

Decentralized approaches on the other hand can be characterized by:

- their ability to recycle wastewater at the point of wastewater generation. Thus, no big sewers and centralized treatment plants are required and freshwater can be saved.
- a variable approach towards treatment capability. The treatment facilities can be customized to a specific type of wastewater. This enables safe and stable treatment results.
- a variable approach towards treatment capacity. It can grow according to the actual needs, thus reducing sunk cost and ensuring planning certainty.
- a greater need for well-developed operational control and maintenance strategies. As advanced information technologies take root within smart cities initiatives, decentralized approaches for water management are now suited to large scale applications for the first time. These may be implemented within traditional SCADA based systems or more advanced approaches based upon the “Internet of Things”.
V. RESOURCE EFFICIENCY IN DECENTRALIZED WASTEWATER TREATMENT

“Decentralized wastewater treatment has the potential to provide sanitation that meets criteria for sustainable urban water management in a manner that is less resource intensive and more cost effective than centralized approaches. It can facilitate water reuse and nutrient recovery and can potentially reduce the ecological risks of wastewater system failure and the community health risk in a wastewater reuse scheme.” [20]

But to unlock the benefits, which are inherent in the decentralized recycling approaches, new plant designs need to be developed, which are both effective and efficient [25], [28], [34]:

A. Effective plant design

Decentralized wastewater treatment systems need to supply adequate treatment results with high operational reliability. This is particularly true if reuse is intended.

In this case, effectiveness extends to the terms of water loss and nutrient recycling as well. As for the reduction of water loss, an effective system would minimize evaporative and leakage losses, hence maximizing the amount of recycled water. With regard to nutrient recycling, decentralized treatment systems should be able to conserve or eliminate nutrients, depending on the intended use. Also, conservation of nutrient in mineralized forms would additionally increase efficiency of the systems.

Another aspect of effectiveness is public acceptance by the local communities in which a decentralized water management is to be integrated [28]. This requires design strategies that seamlessly integrate the wastewater treatment systems into the rest of the built environment. Space, functionality, odors and aesthetics are all points for consideration.

B. Efficient plant design

The efficiency of decentralized systems can be most easily assessed from four perspectives: treatment performance, maintenance requirements, land use footprint, and energy efficiency. Each of these can vary significantly based upon the chosen site of installation. Maintenance requirements are a major driver for both costs and safety. This points to a system, which is stable and easily monitored by design. Because decentralized systems are placed close to the point of wastewater generation, in a smart cities context, the land use footprint is of even greater value and requires optimization. Finally, electricity demand of the wastewater treatment plants usually accounts for the largest portion of operating costs (25-40%). Thus, optimization in energy consumption is also critical for the plant’s life-cycle costs.

VI. SUITABLE TYPES OF DECENTRALIZED TREATMENT SYSTEMS

In the past, adoption of decentralized wastewater treatment systems has been impeded by a lack of monitoring technology, high maintenance requirements and unreliable treatment results. Recent advancements in information technology, and most notably the Internet of Things, make it now possible to monitor the performance of distributed treatment systems remotely in an automated manner. This dramatically reduces maintenance efforts as it allows for demand-actuated on-site maintenance only when needed. Accordingly, it ensures reliable and safe effluent quality, thus building trust and enforcing acceptance of water recycling.

Once a decentralized strategy has been adopted, there are several suppliers of wastewater treatment technologies from which to choose. These may be assessed with regards to the requirements already presented above. In many cases, ecological wastewater treatment using constructed wetlands has been identified as the most promising candidate [35]. Because constructed wetland processes are very stable and self-regulatory, they are capable of handling fluctuating wastewater inflow levels. They deliver reliable treatment results and consume very little energy due to their passive aeration processes [35]. Furthermore, experience with constructed wetlands during the last 30 years has proven their very low maintenance requirements [35]. On the other hand, constructed wetland technology has two major drawbacks, which are their huge footprint and their relatively high water loss due to evaporation. Moreover, acceptance in communities can be a challenge because its open design can fuel fears of bad odors and health risks [36], [37].

Therefore, new designs need to be developed to use all the advantages of constructed wetlands while avoiding its drawbacks [28], [35]. Particularly promising are recent designs, which are capable of applying constructed wetland processes in an underground installation applying a multi-level approach. Thus, constructed wetland technology can be integrated even in urban settings, such as under roads, sidewalks, parking spaces or median strips, without using up valuable land. At the same time, the underground installation reduces evaporation water losses significantly, making available more water for reuse. An example of such an underground design is shown in Figure 1.

Such integrated constructed wetland systems make ecological wastewater treatment available for built-up areas with little space availability and thus have the potential to contribute to a more sustainable use of water and nutrients in urban settings.

Fig. 1. Integrated underground constructed wetland system [38].
VII. CONCLUSION AND FUTURE WORK

Relative to centralized approaches, integrated decentralized water and waste management concepts in urban planning processes are capable of bringing several key advantages. The most promising of these are water and nutrient recycling. Recent technological advancements in the field of information technology combined with ecological wastewater treatment have sparked the development of promising new systems that can be integrated into future smart cities. That said, there remains much future work to be done on real use cases and their performance and cost evaluation.

REFERENCES


