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Review

An Overview of Hybrid Water Supply Systems in the Context of Urban Water Management: Challenges and Opportunities

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Abstract: This paper presents a critical review of the physical impacts of decentralized water supply systems on existing centralized water infrastructures. This paper highlights the combination of centralized and decentralized systems, which is referred to as hybrid water supply systems. The system is hypothesized to generate more sustainable and resilient urban water systems. The basic concept is to use decentralized water supply options such as rainwater tanks, storm water harvesting and localized wastewater treatment and reuse in combination with centralized systems. Currently the impact of hybrid water supply technologies on the operational performance of the downstream infrastructure and existing treatment processes is yet to be known. The paper identifies a number of significant research gaps related to interactions between centralized and decentralized urban water services. It indicates that an improved understanding of the interaction between these systems is expected to provide a better integration of hybrid systems by improved sewerage and drainage design, as well as facilitate operation and maintenance planning. The paper also highlights the need for a framework to better understand the interaction between different components of hybrid water supply systems.

Keywords: hybrid water supply systems; wastewater; stormwater; water infrastructures

1. Introduction

Provision of centralized water, wastewater and stormwater services for urban areas has been common practice for over 100 years [1,2]. While such facilities have been in use since the mid-1800s for water and waste water services, it has become increasingly clear in recent years that alternative technical solutions can improve the efficiency and infrastructure functions in urban water management, especially in water scarce areas [3,4]. In the context of changing societal expectations, urban water managers are confronted with increasingly complex and multi-faceted challenges, in particular when the existing and available resources reach the limits of sustainable exploitation [5]. Furthermore, the urban water sector is required to meet increasing demand from growing populations, changing climate, resource availability and at time, some level of community desire for protecting and improving stressed ecosystems [6–8].

Infrastructure investment and replacement is a gradual process and changing the whole infrastructure is neither economically nor environmentally sustainable [9]. With a legacy of centralized infrastructure solutions in combination with growing investment in decentralized infrastructure solutions, the result is a hybridization process where mix of centralized and decentralized systems co-exists. However, there is limited practical or scholarly understanding of how to enable such transition of traditional urban water systems towards hybrid systems [10]. These technologies introduce interactions between the various components of the water cycle such as potable water, wastewater and stormwater [11]. This paper highlights the need for additional research to understand the impacts of hybrid water supply systems in water quality and quantity, in particular, the interaction of these systems with the local environment at a strategic level. Though hybrid technologies may offer benefits in terms of accommodating growing water needs and thus decreasing peak demand from centralized water supply system [4,12], they may have implications on the operational performance of the downstream infrastructure and existing treatment processes. Therefore, combinations of water supply systems should not be decided upon only on the basis of the availability and demand for water [4]. Hence, this review paper discusses the gaps in understanding of the likely impacts of each of these decentralized technologies on wastewater and stormwater quantity and quality when combined with existing centralized systems.

At the beginning, this paper provides challenges of existing centralized and decentralized water supply systems. Then, the paper illustrates the potential impacts of decentralized water supply systems on centralized systems. Later, it introduces hybrid systems as a solution to present water supply problems along with opportunities and challenges of such systems. Finally, it highlights the need of a methodology to assess hybrid systems.

2. Present Water Supply Systems Challenges

2.1. Centralized Water Supply Systems

In general, centralized water services have ensured adequate water supply, sanitation and drainage services to its inhabitants in cities [13,14]. However, demographic changes including the ageing population, socio-economic factors, climate change, biodiversity, energy use, water supply and consumption, as well as ageing water and wastewater infrastructures has put increasing pressure on these urban water systems [1,15]. Marlow *et al.* [16] has also raised similar concerns on centralized urban water systems, which are maladapted to these challenges. In addition, the typical centralized system can limit the potential to adapt water supply systems to local opportunities and needs [1]. As a result, in some circumstances these water infrastructures are considered to be unsuitable to address future challenges [17–19]. In the face of future uncertainties and threats, there is a need for water systems to provide ecologically sustainable services [20]. In many cases, the conventional approach to the water service provision does not comply with the more recent aspirations of ecologically sustainable development [21]. Decentralized water infrastructure is an alternative to the traditional centralized systems for implementing sustainable water infrastructure in urban setting [22]. Sharma *et al*. [23] has defined decentralized system as the system provided for water, wastewater and stormwater services at the property, cluster and development scale that utilizes alternative water resources, including rainwater, wastewater and stormwater, based on a 'fit for purpose' concept. Moreover, the combination of decentralized water supply systems with the centralized system can contribute to the provision of sustainable water supply [22]. The following section provides a detail description of decentralized water system to better understand the scope of a combined water supply system and identify the research gaps in this area.

2.2. Decentralized Water Supply Systems

Many cities are implementing new and alternative approaches to centralized water services including decentralized water systems. These systems are emerging as an important complement to centralized water services [24,25]. This model of water infrastructure involves small to medium scale systems that utilize locally available sources of water for various indoor and outdoor uses, and facilitate use and reuse of generated wastewater and stormwater runoff locally [22]. These systems can operate as standalone systems or as satellite systems (also known as distributed systems) integrated with centralized services [26,27]. The primary drivers for shifting to decentralized water stormwater and wastewater are escalating infrastructure costs of centralized systems, ecological impacts and water shortages [28]. Biggs *et al*. [29] summarizes the benefits of decentralized systems as follows:

1. reducing the cost of infrastructure for long distance transport and treatment of stormwater, potable water and sewage, along with unnecessary treatment to potable standards of water used for purposes other than drinking and bathing;
2. more efficient use of resource;

3. improving service security;
4. reducing water systems' failure risk;
5. strengthening local economies;
6. regenerating and protecting the natural environment;
7. fortifying community well being.

Decentralized systems also reduce reliance on traditional water sources and provide long-term ecological sustainability [29,30].

Although decentralized systems show significant promise, there are numerous unknowns and uncertainties that need to be addressed [31]. These systems are relatively new compared to centralized systems with limited understanding of ongoing management requirements and operation under dispersed accountabilities. The lack of knowledge around the long term performance of decentralized systems relate to issues such as long term reliability, operation and maintenance costs, interaction with centralized systems, appropriate costing, and adequate governance and guidelines [1,32]. These knowledge gaps impede mainstream acceptance of decentralized systems. Although these technologies are considered to offer benefits in terms of reducing overall potable water use and decreasing peak demand [33,34], they could have implications on the operational performance of the downstream infrastructures and treatment processes. For instance, as water saving through recycling is encouraged by adopting grey water reuse, dual piping systems and sewer mining, the volume of wastewater may decrease, but this could lead to an increasing in the concentration of key contaminants [24]. Increased concentration of contaminants in wastewater has been known to cause sewer problems, such as sewer blockage, odor and corrosion [35]. Therefore, whilst the investment in decentralized water system technologies can be warranted for developments in growth areas of cities, assessing the impacts of decentralized systems on the existing developments remains challenging due to the lack of understanding of the interaction between decentralized and centralized systems [35,36]. Further adoption of the decentralized systems has thus far been limited to demonstration projects [37]. Therefore the main objective of this paper is to examine the existing states of knowledge of these interactions and identifying the critical knowledge gaps.

2.3. Urban Water Cycle

Figure 1 below shows the urban water cycle's main components, pathways and alternative supply options in the urban water system. There are two main subsystems within the urban water cycle: the rainfall-stormwater discharge and supply-wastewater system. These two systems are inter-dependent, interacting to a varying degree depending on the location, season and utilization of wastewater and storm water as a supply source for water applications. There is interconnectedness among water supply, wastewater and storm water along with a broad range of non-conventional water supply technologies such as rainwater tanks, stormwater harvesting, and wastewater reuse within the system. Changes in one component of the water cycle can have impacts on the other components.

Hence, addition of different alternative water service infrastructure can bring changes in the overall urban water system, which has been discussed in the following section.

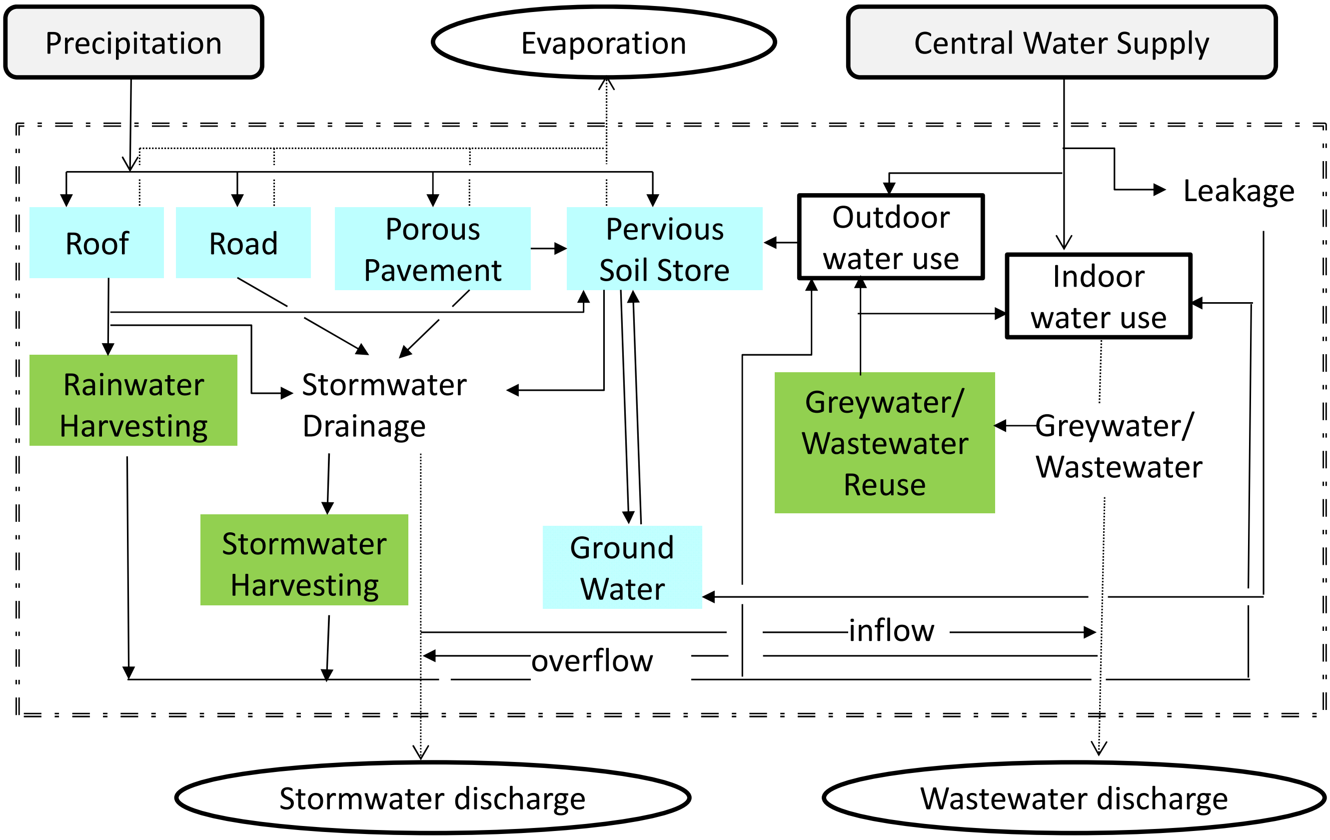

Figure 1. Urban water cycle's main components, pathways and novel technologies (Green colored boxes indicate decentralized components of water cycle).

3. Effects of Alternative Water-Service Infrastructure on Centralized Water System

Integrating centralized and decentralized water supply and wastewater management, along with water reclamation and reuse, distributed water treatment, and rainwater harvesting, can offer the potential for increased urban water system security and sustainability due to a number of reasons [12]. For instance, a combined water supply system reliably accommodates growing water needs and reduces net urban water use, freeing up water supplies for other uses. Further, the hybrid centralized-decentralized systems decrease resource consumption because of reduced conveyance requirements and the need to treat all water to the same high standards. An integrated decentralized-centralized approach can offer flexible solutions, wherever certain thresholds of population density are exceeded [38,39]. Further, various combinations of centralized and decentralized systems may have positive results in terms of sustainable water supply. For example, in the case of greywater reuse along with rainwater harvesting, greywater use can meet some of the demand with more concentrated flows going to the sewage while rainwater harvesting increases the flow of sewage and hence decrease the sewage concentration. Similarly, water conservation along with rainwater harvesting can significantly reduce potable water demand from centralized systems, and rainwater-harvesting system can improve stormwater management, wastewater treatment and an appreciation of the water resource in urban environments.

However, such approaches are relatively new compared to traditional centralized approaches due to limited information available on their planning, design, implementation, reliability and robustness. Hence, to enable hybrid water supply systems as a viable option, it is necessary to understand their performance and impacts. In the next section, we provide a brief background of various alternative water service infrastructures that helps to better understand and analyze the effects of decentralized infrastructures on centralized water systems.

3.1. Water Reclamation and Reuse

Reclaimed water can be defined as the treatment of wastewater for subsequent use as a water supply [7]. Common uses are both landscape and agricultural irrigation [40,41]. Other reuse options include industrial reuse such as cooling water, process water, and boiler feed water [42]. In some regions, reclaimed water is used for groundwater recharge to replenish depleted aquifers and to prevent salt water intrusion [7]. It can also be used for non-potable uses such as toilet flushing, air conditioning and fire flow [43]. Due to the difficulty of developing new freshwater resources, water reclamation and reuse are important additional water resources. This is a very reliable alternative water resources because of its supply reliability and lower pollution level of reclaimed water [44]. It can provide fit-for-purpose water supply under local control and avoid or delay construction of new large-scale water supply infrastructure. Additionally, it reduces the quantity of treated wastewater discharged to surface waters [45]. It is considered as one of the main options to remedy water shortage caused by increasing water demand, climate change and population growth [46]. Wastewater reuse can provide relatively constant supply because its source is the used potable water, which remains relatively constant throughout the year [47]. Moreover, recycled supply can significantly reduce the peak demand on potable water supply infrastructure [48].

Wastewater recycling may be beneficial if the solids are also removed and disposed via the solid waste system [49]. Solid deposition in sewer system had been known to have adverse effects on the hydraulic performance of the system and also on the environment [50]. It can alter the hydraulic radius of the pipe changing the self-cleansing velocity requirement for the pipe [51]. Hence, if only the water is intercepted and the residuals are discharged back to the sewerage networks, there will be a potential for frequent sewer blockage [35]. Further, if recycling of such water is for household non-potable use, then a potential drawback is the cost of establishing second system of household plumbing with safeguard against cross-connection [52].

3.2. Grey Water Recycling and Reuse

Greywater is defined as wastewater generated from all domestic sources except the toilet [53,54]. Almost 50%–80% household wastewater is greywater [55]. Grey water can have many uses depending upon the quality of greywater and treatment it has received. Two common uses for greywater are toilet flushing and lawn irrigation. Untreated greywater can be used for subsurface irrigation [56]. Grey water reuse can help to reduce reliance on traditional water sources that are under stress and it can also significantly reduce wastewater discharge [57,58]. Because the amount of greywater produced in a household and the amount of water used for toilet flushing in a household are nearly the same, grey water systems have the potential of more or less replacing the household water demand for toilet flushing thus potentially reducing potable water usage by up to 30% [59–61].

Water recycling can help achieve control of sewer flooding. It reduces the quantity of wastewater that is produced, and thus the capacity of the sewer network to cope with heavy rainfall events will be increased in case of combined sewers [62]. Bertrand *et al.* [63] mentioned that greywater recycling has the capacity to significantly reduce sewer flooding for storm events of up to five years return period. Also, it is less vulnerable to climate variations compared to the traditional sources of water [64,65]. Radcliffe [66] states that it may reduce the environmental impacts of treated sewage that would be otherwise discharged to the environment. Moreover, this local water recycling reduces the need for further expansion of the main water infrastructure as the population density increases [67].

However, the implementation of greywater recycling involves a reduction in the volume of wastewater discharged and an increase in concentration of pollutants [53,68]. This reduction in wastewater volume increases the potential for septicity, odors, contaminant impacts and corrosion in the assets [24]. Similarly, greywater irrigation (domestic garden irrigation with household wastewater) can cause dry weather pollution (drainage effluent from greywater irrigation) of receiving waters [49]. In such situations, water reuse can aggravate the environmental problems.

3.3. Rainwater Harvesting

Rainwater harvesting is the collection and use of rainwater for domestic purposes. This supplements municipal drinking water supply and is believed to minimize stress on stormwater infrastructure [7,69–72]. It can potentially save a significant amount of domestic water demand [60,73,74]. An Australian study showed a savings of 12.3% to 25.1% in potable water use when harvested rainwater was used for toilet flushing and garden irrigation [56]. Moreover, this rainwater is a relatively high quality water source that can be directly used for non-potable uses, or with filtration and disinfection for potable uses [75,76]. The use of tanks to harvest and store rainwater also has the potential to restore some aspects of pre-development flow regimes in receiving water [77]. The use of rainwater harvesting is also beneficial to sewers and improves wastewater treatment in the case of combined sewer networks [35,63,70]. An additional benefit of the use of rainwater tanks to supplement the existing water supply is to reduce localized urban flooding, improve stormwater quality (as these pollutants will remain in the tank) and minimize influx of stormwater into the sewer system [78,79]. Study from Zhang *et al*. [56] shows residential use of rainwater can decrease the stormwater runoff by 23.4% to 48.1%. According to Gardels *et al*. [80] rainwater runoff contains a nutrient such as nitrogen, so capturing rainwater reduces nitrogen loadings in receiving water bodies. Further, this nitrogen loading in the rainwater, if used for landscape irrigation, can also reduce the amount of fertilizer needed for the landscape [80].

But, wastewater from rainwater harvesting has higher level of metal content (lead and iron) [81], which may react with dissolved sulfide to form metal sulfide precipitates and can cause corrosion in the pipes [35]. Also, there is difficulty in managing rainwater tanks as currently there is no mechanism in place to make sure that the household rainwater collection systems are maintained and in a good condition [82].

3.4. Stormwater Harvesting

Stormwater is the runoff from pervious and impervious areas collected via the drainage system [83]. Stormwater is considered fit to cater for non-potable water demands and is emerging as a viable option to augment increasingly stressed urban water supply systems [84,85]. The other merit is that it slows stormwater flow, thereby reducing peak flows in waterways [86]. Hence, they have the dual purpose to provide water supply as well as reduce urban flooding [87].

However, excessive harvesting of urban stormwater runoff could be detrimental to stream health if critical aspects of the flow regime were changed away from, rather than toward, their pre-urban condition [88] and most of the environmental flow problems arise from this practice [89]. Hering *et al.* [90] also urges that more research is needed in stormwater harvesting mainly to assess the water quality implications of this practice.

Having discussed various decentralized water supply systems, it has been identified that combining such systems with centralized system may potentially resolve many existing challenges in the urban water system such as meeting rising needs of water and offering a wide range of flexibility in implementation.

4. Hybrid Water Supply Systems

Following the literature review, the definition of hybrid systems provided by Daigger and Crawford [12] has been adapted to develop a generalized definition of hybrid water supply systems. Hybrid water supply systems can be defined as systems provided for water services through a centralized water supply system in combination with decentralized water supply options such as rainwater tanks, storm water harvesting, and water reuse.

Internationally, hybrid water systems have been referred in different ways such as semi-centralized supply and treatment [38,39,91,92], distributed water supply system [29,81,93,94], semi-decentralized systems [95] and hybrid system [12,96]. These systems can be considered as part of a sustainable urban water management strategy whereby there is adoption of alternative water supply and wastewater management approaches while the predominant model of service remaining the centralized water supply system [5,16]. These types of hybrid water supply systems can be also compared with "The Soft Path of Water" [97] approach, which not only uses centralized infrastructure but also takes advantages of the potential for decentralized facilities to meet the water related needs. These innovations in water management help to reduce the volume of water imported to cities, and decrease the volumes of wastewater and storm water discharged into the environment [78]. On the other hand, such transition of traditional urban water system to hybrid water supply systems have significant effects on central networks [13], particularly the sewage network and storm water drains. The use of decentralized water supply options changes both the wastewater and stormwater flow regimes and contaminants' composition [36,93,98]. Thus it can be argued that while these hybrid water supply systems seem to be promising, there are some inherent challenges such as public acceptance, particularly for new technologies and unfamiliar practices (e.g., greywater recycling), unknown impacts, understanding the interaction between centralized and decentralized services and diverse infrastructure management. The following sections shed light on inertia in water infrastructure, and various prospects and challenges of hybrid water supply systems.

4.1. Inertia in Water Infrastructure and Hybrid Water Supply Systems

As shown in Figure 2, there are two contrasting approaches to urban water management, a conventional paradigm based on traditional centralized approaches (common in practice); and an emerging paradigm around decentralized infrastructures [99]. Currently, there is a debate between fully centralized or decentralized approach to urban water service provision. The traditional, centralized water servicing system provides clean drinking water, sanitation and protection from urban flooding [100]. These systems are cost effective and reliable [5,100]. In contrast, decentralized system is based on principle of ecological sustainability and can manage water cycle by protecting the natural environment. There are diverse supply sources in decentralized system, which makes the system more flexible. Hybrid water systems combine the merits of both the centralized and decentralized systems. Furthermore, achieving a paradigm shift in water management may be a hard task due to the inertia that accompanies existing technological regimes [101]. Sunk investments and well-established socio-technical regime creates the path dependencies that favor the prevalence of the existing centralized model [102]. In addition to this, there are other factors such as institutional barriers, public health issues, peak demand (for example fire fighting demand) and supply safety that impedes the adoption of decentralized system. Other impediments to decentralized water system can be found in various literature sources [102–105]. Hybrid Systems can provide a balance between them and act as a transition towards more sustainable urban water systems.

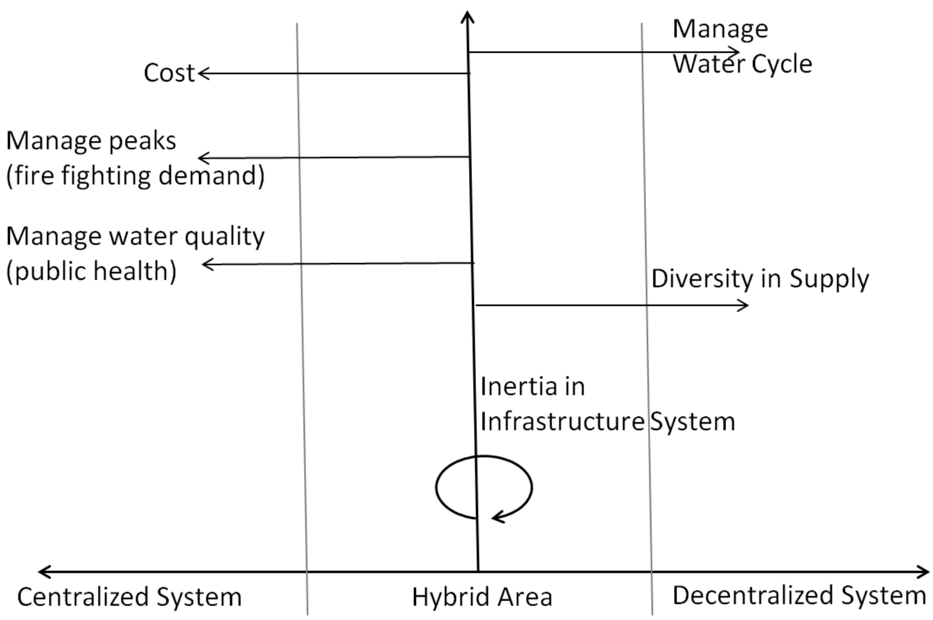

Figure 2. Inertia in water infrastructure system.

4.2. Advantages of Hybrid Water Supply Systems

Hybrid water supply systems are innovative approaches to respond to water scarcity caused by population growth and uncertainties in climate change. They can enhance the water security through local source diversification [16]. Such diversification of water sources using alternative local water sources reduces the amount of water abstracted from waterways, groundwater or dams and hence improves water security [20,106]. They can build adaptive capacity by increasing the diversity and flexibility of water supply systems [29]. According to Weber *et al*. [39], planning and construction time of such systems is shorter compared to centralized system. At the same time, they are more flexible as it is easier to adapt the design to local conditions. Similarly, in a case study carried out in Qingdao, China [38], it is shown that the integrated semi-centralized approach offers flexible solutions to cope with the new demands wherever certain thresholds of population density are exceeded. These are not only effective in the cities like Qingdao where population growth is high but also would be in cities of East Germany where population is shrinking [107]. Research shows that these types of systems have lower entry costs and are more flexible to adapt to demographic changes [108]. In this context, semi-centralized supply and treatment systems can open a wide scope of possibilities in resource management, especially by reducing fresh water demand of new urban areas. Further, it can reduce social, economic and environmental vulnerability to climate change by creating distributed water systems through infrastructure design choices at a range of scales from household to regional level. This ensures greater flexibility. In addition, the, planning and operation of decentralized systems being of a smaller scale, entail a lower level of implementation and operational risks [38]. Additionally, water infrastructure systems consisting of semi-centralized systems would be more resilient because a failure in these systems would only affect a small part of the urban area [107]. In addition to this, there are large savings potential in daily potable water demands through intra-urban water reuse [92]. Similarly, integrated systems can achieve energy reductions by onsite treatment of different wastewater flows as such treatment of sewage sludge and waste can reduce the greenhouse gas (GHG) emissions such as those arising from the sanitary landfills [38]. At the same time, sludge and waste fractions can be utilized for energy production and nutrient recovery [109]. Daigger and Crawford [12] and Daigger [7] have also demonstrated the capability of hybrid water systems to reduce potable water use and energy consumption and increase the potential for nutrient recovery on large urban areas.

Hybrid systems can also help defer augmentation of existing infrastructure. For example, traditional water and wastewater pipe network design is driven to a large extent by the need to cater for peak demands. Mitigation of these peaks can be achieved through the use of decentralized solutions [34,48,110–112]. For example, Willis *et al.*, shows a huge reduction on diurnal peak of potable water demand with the use of recycled water supply for irrigation and toilet uses [48]. Speers and Mitchell [113] have also demonstrated that mitigation of these peaks can produce substantial cost reductions.

Distributed used-water reclamation and reuse systems offer significant advantages including being close both to the source of wastewater generation and to potential water reuse [26]. This approach not only reduces the size of the non-potable water-distribution system but also reduces the required size of the used water conveyance system downstream of the diversion point, which can allow significant savings in the system in terms of cost and energy [96]. Biggs *et al.* [29] also illustrated the similar benefits from hybrid water systems using cases from Australia, Europe and the United States. The study assesses these cases based on their ability to reduce costs and resource uses improve service security and protect natural environment.

Another advantage of hybrid water supply systems is that it helps in staging the infrastructure investment. In case of conventional centralized water supply systems, we need to forecast the ultimate development, and have to invest large sums that may not be fully utilized for 10, 20 or 30 years. On the other hand, in case of decentralized services, we can build small modular infrastructure elements as needed, rather than building a large water infrastructure. This supports the idea that hybrid systems can turn out to be cheaper in the long run. Further, this type of system recognizes the complexity of water economics and management including the power of economies of scope by integrating planning across competing interests [97]. Such integrated approach helps a combined decision making process that allows specific services or benefits to be delivered at lower cost than would result from separate decision making process. For example, water agencies and flood control authorities can often reduce the total cost of services (such as flood protection) to their customers by understanding and integrating factors that none of them can account for alone, such as rainwater harvesting. Furthermore, hybrid systems feature both the financial advantage of the onsite system (capital investment) and the superiority of centralized systems in terms of operation and maintenance [95,111]. There is also a benefit from the diversification of supply sources from a risk-management perspective in terms of urban water security [114]. However, such benefits are hard to monetize.

4.3. Challenges of Hybrid Water Supply Systems

Despite having promising prospects, it can't be ignored the fact that hybrid water supply systems are not free of challenges. Among these challenges, are extensive collection and distribution systems required for used-water reclamation and reuse particularly in the case of centralized, non-potable systems that need separate distribution for potable and non-potable water? The need for dual water-distribution systems presents a significant cost barrier, especially in existing urban areas, as well as a substantial increase in energy to convey both water supplies [96]. Furthermore, as a water source, the treatment of wastewater involves energy use that may be greater than surface water [115]. Further, there are challenges related to retrofitting, which is associated with limited land and high cost [114]. Another challenge in transforming the model of service provision from centralized to hybrid water supply systems is the investment cycles for infrastructure. This often occurs over timescales that are too short (e.g., five years) for decentralized water supply options while central infrastructure has a life span of decades [116]. In addition, significant gaps remain in terms of quantifying the benefits of recycled water scheme and thus it makes difficult to set the price of such water [117].

The implementation of decentralized water systems, particularly for non-potable use could increase the complexity of urban water systems, with water collection, storage and distribution occurring over multiple scales (household, neighborhood and city scales) [55]. The extensive implementation of hybrid water systems could increase self-similarity in urban systems, adding replication of functions in water circulation to the replication of form seen in a dendritic structure of sewerage and drainage networks [118]. Such water collection and circulation at multiple scales could lead to greater complexity and new patterns of order emerging out of the critical state of water infrastructure.

Different utilities or different departments often manage various components of urban water and resource management systems separately. This type of hybrid system requires a new institutional and management structure, which could involve the institutional reform in water management sector. Furthermore, management of a hybrid system is more complex compared to a conventional system. Integrated potable and non-potable water supplies, distributed wastewater treatment, stormwater and used water significantly increase the complexity of management and will require the development of new managerial system. In addition, there is an issue of changing the responsibility for partial system management from public to private hands, as there will be more onsite water use and treatment facilities. Hence, challenges remain in ensuring public health, environmental protection, and managing new responsibilities at the household levels, regulatory structures, and governmental levels [119]. Also there is potential for cross-contamination of pathogens or chemicals in dual pipe systems that may compromise safety. Besides, if there is a daily water demand reduction in a hybrid water system, it might have a negative effect on the travel time in the centralized water supply system and this may create a high water age and potable water quality issues due to stagnation in the pipe network [120].

Cook *et al*. [81] demonstrate the impact of source management practices (SMPs) on the quality and load of wastewater. Marleni *et al*. [35] argue the need of further research to assess the potential impact that might arise from the implementation of alternative water sources such as grey water recycling, rainwater harvesting and wastewater recycling on sewage infrastructures. It is not yet clear whether these types of systems will affect water quality either adversely or favorably [121]. This echoes the finding from the analysis by Moglia [122] that shows the risks of decentralized water systems are yet to be understood. Makropoulos and Butler [93] have identified some of the main research needs in the area of hybrid water supply systems, especially in relation to the effects of the changing quantity and quality of wastewater and storm water on the existing infrastructure and the interactions between distributed water, energy and waste infrastructures. Speers and Mitchell [113] have also recognized that urban water systems are very complex and inter-related. Furthermore, they mention that changes to any part of system can have both downstream and upstream impacts that affect costs, performance, and future opportunities. The use of hybrid systems increases the complexity in our urban water system by adding more challenges. There will be differing water qualities and changing end use patterns and greater complexity, all resulting in new and increased risk to manage [123]. This leads to dynamic changes across multiple temporal and spatial scales that are often not intuitive even to experts [16]. Management of such complex system may need a high degree of monitoring with real time direct feedback for operations and water quality purposes, as well as monitoring of assets including pipes and water treatment systems [123]. This kind of monitoring can be very costly. Moreover, public acceptance of such systems is challenging. There is a significant research gap in the knowledge base of social drivers specific to the acceptance of these systems and the factors contributing to its widespread use [124].

Thus there is a large knowledge gap on operational performance, cost and energy usage of hybrid water supply system. For instance, there is a wide divergence in informed opinion on the levels of energy consumption for rainwater tanks and use of their water in household situations. Also, the level of externalities involved in wastewater discharge to aquatic ecosystems is often difficult to value, particularly for nitrogen discharge, and information is required to develop valid evaluation criteria.

4.4. The Need for Framework for Assessment of Hybrid Water Supply Systems

After discussing the advantages and disadvantages of hybrid water systems, this leads to the question "can a mixture of decentralized and centralized system combine the advantage of both systems?" To answer this question, we need a robust methodology to assess the performance of hybrid systems. Traditionally, integrated assessment studies have presented an either/or approach, assessing one technology against another for a number of alternative systems and exclude options for partial contributions from multiple alternatives [99]. For example, Cook *et al*. [81] analyzed seven alternatives and Abrishamchi *et al*. [125] analyzed eight systems; but these methodologies exclude options of combined system and their benefits. Further, none of these methodologies evaluates the impacts of hybrid systems in terms of interaction between centralized and decentralized infrastructures.

Also, though some of the frameworks evaluate the environmental impacts of hybrid systems [30], but do not evaluate the impacts from the implementation of hybrid systems on the quantity and quality of wastewater and stormwater in the existing centralized systems. Hence there is a need of comprehensive methodology for assessing the full range of technological alternatives available. The closest to a methodology for assessing the hybrid water system to date is presented in the paper by Sapkota *et al*. [4]. However this is a basic theoretical methodology that requires further empirical study to validate it.

5. Discussion

The literature shows that centralized urban water supply systems are unlikely to meet the increasing water demand in the context of growing urban population and climate change. The significant body of work within the literature asserts that changes in the current model of urban water service provisions are necessary. Besides, there seem to be opportunities in the use of decentralized water supply systems, such as rainwater tanks, stormwater harvesting and wastewater reuse; combined with centralized water supply (hybrid water supply) to meet this increasing water demand. Such a hybrid water supply systems are expected to help meet the increasing water demand with minimum impacts on urban water cycle and produce more benefits compared to traditional centralized water supply provisions. The study primarily focuses on the situations where water demand is increasing due to population growth, climate change and economic growth. However, hybrid systems would have been more effective even in the places where water demand is decreasing although this is not the main focus of the research.

This review highlights a range of decentralized water supply systems each with their specific advantages, issues and challenges. It also highlights that an adequate understanding of decentralized water supply systems and their interaction with central water infrastructures is necessary to bring significant environmental benefits and to enable deferring augmentation costs of large potable water supply, sewage and drainage systems. In areas with full use of existing centralized water supply system decentralized techniques such as rain water harvesting or recycled water supply can help to meet the additional water demand. The aim is to supply water services without changing the capacity of centralized system and subsequently reducing the cost of larger centralized water infrastructures.

The impacts of hybrid water supply systems on aspects such as changes to flow, nutrient and sediment regimes, energy use, greenhouse gas emission, and the impacts on rivers, aquifers and estuaries are unknown. For instance, sophisticated wastewater treatment technology requires a significant amount of energy, which is a concern for water services authority. However, it might be possible to utilize the sludge from wastewater treatment to simultaneously produce energy. This approach can contribute in the sustainable use of alternative water sources but it has not yet been properly investigated. Along with this, there are critical factors associated with the implementation of hybrid water supply systems. Some of them are public health, resilience to different operating environments, reliability and maintenance/monitoring needs. Hybrid water supply systems are expected to use fit-for-purpose water, approach that focuses on the attributes of water that makes it fit for various purposes depending on its quality and the use to which it is applied. For example, there might be low quality water supply for a certain purpose; although it might have impact on public health when it gets in direct contact with people. Moreover, as hybrid water supply technologies are very new, further research is required in terms of their contribution to building resilience to climate change and environmental sustainability. Equally important are water supply reliability issues as these systems have been in use only recently unlike centralized water supply system, which is in practice for more than 100 years. Also, hybrid systems use various combination of decentralized water supply system with centralized system, which is complex and requires a high level of water system monitoring and maintenance. The stakeholders for water supply might include a combination of government and communities, which require clarity in water management roles and responsibilities.

Thus, it is necessary to evaluate how the existing system integrates with alternative water supply options and what might happen over time. Though we can say it makes sense to utilize decentralized systems along with centralized services, difficulties increase when issues such as regulatory, political, cost shifting, management and responsibilities arise. These issues may also give rise to larger costs and such risks need to be addressed before proceeding with their implementation.

In the beginning it is essential to find potential impacts of alternative water supply options combined with centralized systems on the overall performance. Evaluation of their performances both at a pilot case study and a full-scale project need to be conducted. For this it is necessary to collect data for the assessment of system-level performance of urban water infrastructures. Next, there is a need for an assessment framework in order to evaluate the hybrid water supply systems. Such framework should be broad and comprehensive and be able to account for multiple benefits and costs including environment, green house gas emission, supply reliability and societal factors. For this, the framework needs to be integrated with various tools and models of the water cycle concept to provide a systematic approach for capturing the complexity in the range and behavior of components and water fluxes that characterize the urban water cycle. These include runoff, water demand and supply, wastewater, infiltration, evapotranspiration and contaminant balance. These assessments should be carried out at a variety of spatial scales. The temporal scale should be at least hourly to capture the diurnal peaks, a factor that is very important in terms of sizing of the water infrastructure. Finally, in addition to technical criteria (e.g., change in water quantity and quality of wastewater and stormwater); the framework should also incorporate other criteria that are needed to assess such systems including economic, health and energy usage.

6. Conclusions

This review gives an overview of hybrid water supply system and its impacts in the context of meeting the increasing water demand. It is important to note that hybrid water supply systems can have implications on the operation and performance of the existing centralized infrastructure. This paper briefly discussed the possible impacts of hybrid water supply systems on changes in wastewater and stormwater quantity and quality. It also discussed the prospects and challenges of hybrid water supply systems. The literature survey concludes that the interactions between decentralized and centralized systems are highly complex. Furthermore, implementation of hybrid water supply systems has other challenges including energy usage, operational performance, asset management, cost and public acceptance. To overcome these issues, better understanding of the overall system is inevitable, which highlights the need for valid assessment criteria of hybrid water supply systems in terms of the interaction between the decentralized and centralized systems. This paper accordingly concludes that the water industry is in need of a methodology to collectively assess the reliability, resilience, water quality, cost and sustainability of infrastructure to help determine when centralized, decentralized and/or hybrid solutions are the most appropriate.

Conflicts of Interest

The authors declare no conflict of interest.

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