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Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks

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HIGHLIGHTS

- This study quantifies the nexus as energy intensity and greenhouse gas potential.
- Baseline water stress and return flow ratio are identified as water risks.
- Source water accessibility significantly contributes to variations in the nexus.
- Water risks have little impact on the nexus of wastewater systems.
- Study on the nexus is suggested to be conducted at regional levels.

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ABSTRACT

The importance of the interdependence between water and energy, also known as the water-energy nexus, is well recognized. The water-energy nexus is typically characterized in resource use efficiency terms such as energy intensity. This study aims to explore the quantitative results of the nexus in terms of energy intensity and environmental impacts (mainly greenhouse gas emissions) on existing water systems within urban water cycles. We also characterized the influence of water risks on the water-energy nexus, including baseline water stress (a water quantity indicator) and return flow ratio (a water quality indicator). For the 20 regions and 4 countries surveyed (including regions with low to extremely high water risks that are geographically located in Africa, Australia, Asia, Europe, and North America), their energy intensities were positively related to the water risks. Regions with higher water risks were observed to have relatively higher energy and GHG intensities associated with their water supply systems. This mainly reflected the major influence of source water accessibility on the nexus, particularly for regions requiring energy-intensive imported or groundwater supplies, or desalination. Regions that use tertiary treatment (for water reclamation or environmental protection) for their wastewater treatment systems also had relatively higher energy and GHG emission intensities, but the intensities seemed to be independent from the water risks. On-site energy recovery (e.g., biogas or waste heat) in the wastewater treatment systems offered a great opportunity for reducing overall energy demand and its associated environmental impacts. Future policy making for the water and energy sectors should carefully consider the water-energy nexus at the regional or local level to achieve maximum environmental and economic benefits. The results from this study can provide a better understanding of the water-energy nexus and informative recommendations for future policy directions for the effective management of water and energy.

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1. Introduction

Water and energy are two key components in the global search for sustainable development [1] in response to the United Nations Sustainable Development Goals. Thus, the water-energy nexus is increasingly highlighted as an important issue for future sustainability planning and strategic policy considerations in literatures [2], especially since the two resources are highly vulnerable to the impacts of global climate change [3]. The Ontario Government has identified the water-energy nexus as deeply connected within the context of climate change [4]. In addition, a large share the global population is experiencing water scarcity due to climate change [5]. Lack of understanding of the interdependence between water and energy (or even among other key natural resource sectors) within a system may lead to overuse and mismanagement of resources [6]. Several countries have initiated projects to study the extent of their energy-water nexus and have sketched out future policy directions. In the USA, the Energy and Water Research Integration Act of 2011 was formulated (but was not enacted) to draw policy attention to integrate water considerations into energy-related research [7]. South Africa, Morocco, Mexico and China [8] are also working on incorporating water constraints into their energy plans [9]. However, most of the studies have been based on energy systems (e.g., because of the relative priority and importance of the impacts of energy production and usage) [10]. The energy requirement by water systems (i.e., energy for water) has been less studied [11] and the urban water systems are often managed separately [12].

Water systems are one of the major users of energy resources [13]. The level of energy requirement per unit of water (e.g., energy intensity) strongly depends on the processes involved and the water quality level before end use [14]. For instance, in Spain, the specific level of energy consumption per unit of delivered water is reported as 0.21, 0.34 and 0.56 kWh/m^3 for urban users, agriculture and wastewater treatment for recycling, respectively [14]. Fig. 1 summarizes the range of energy intensity at various stages of a typical urban water cycle using average values of benchmarking studies. Differences in these values also reflect the variety of boundary conditions of the studies, as well as other influential factors such as the type and quality of the source water and the efficiency of the water treatment and delivery system [15]. This suggests that greater focus on the energy requirement of the water systems will be a crucial point of the policy response to the sustainable management of the systems.

For sustainable management of urban water systems, a significant effort needs to be undertaken to improve water and energy use efficiency, which can consequently reduce their associated environmental impacts [16]. Jointly improving these efficiencies has been regarded as a win-win contribution to human well-being and environmental sustainability for current and future generations [6]. The experiences from the United States, Australia and several European countries (including Spain, Norway, Italy, etc.) have provided informative suggestions for future policy directions for resource management [17] and the need to study water-energy sustainability within an urban water system. A study of energy use by urban water systems in major Australian cities reported that electricity consumption could increase remarkably if alternative water sources such as desalination and wastewater recycling were implemented [18]. In an energy-water nexus analysis of water supply scenarios in coastal communities (Tampa Bay and San Diego) in the USA, maximizing water reclamation was found to be a better solution compared to desalination from embodied energy, greenhouse gas (GHG) emissions and energy cost perspectives [19]. However, a study of the energy requirements needed to deliver reclaimed water up-gradient of six watersheds indicated that the water needed for the energy exceeded the amount of water that would be pumped to the various delivery locations [20]. Another study considering the Middle East and North Africa showed a relatively weak dependence of energy systems on seawater (rather than fresh water) but a strong dependence of water systems (mainly abstraction and production) on energy [21].

While there is an increasing interest in understanding water-energy interdependences and associated management implications for urban water systems, most of the studies considered only a partial rather than full urban water system. Research on the water-energy nexus frequently

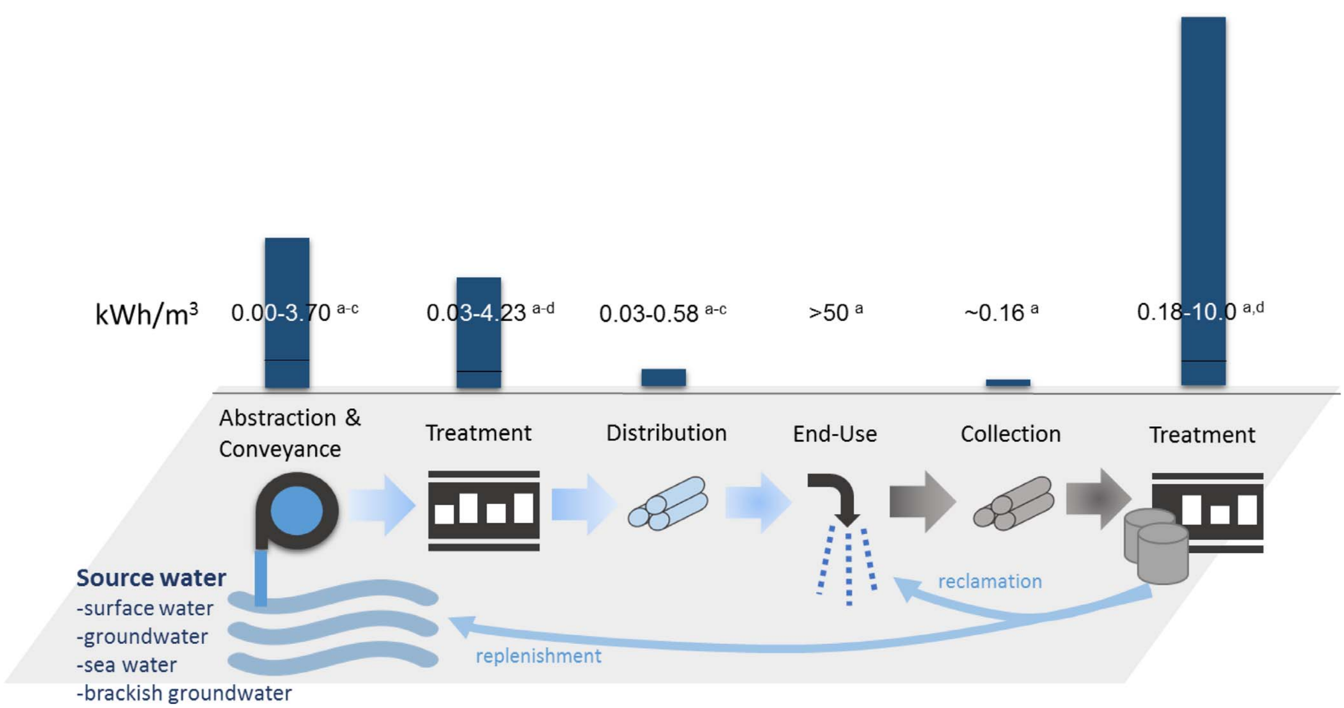

Fig. 1. Ranges of energy intensity within an urban water cycle using average values of benchmarking studies. This figure also illustrates selected urban water systems used in this study, including water abstraction and conveyance, potable water treatment, potable water distribution, wastewater collection and wastewater treatment, but excluding the end-use stage. Brackish groundwater or seawater desalination is included in the water treatment system. Data sources: [a] typical reported values for major regions of the USA, Australia, and Sweden [22]; [b] based on authors' calculations for California and Germany [23]; [c] based on a study conducted in California [24]; [d] based on a study conducted in the USA [25].