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Water security in practice: The quantity-quality-society nexus

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ABSTRACT

The study of water resources has evolved from a focus on physical availability to also include social factors such as governance. Increased understanding of diverse physical and social influences has led to a more comprehensive notion of water security, which is defined as an adequate supply of clean freshwater to support humans and ecosystems at all times. Despite the clear recognition that water security encompasses quantity, quality, and societal considerations, discussions often focus on only one or two of these aspects. This practice masks critical ways in which water quality issues intersect with water quantity issues as well as social factors for many water security decisions. This review paper highlights the growing call to consider water security in a more integrated manner by underscoring the complex interactions among water quantity, water quality, and society (i.e., the quantity-quality-society nexus) for six common water management practices. These descriptions highlight the need to understand the tradeoffs between water quantity and water quality associated with water management decisions, especially as freshwater scarcity increases. We conclude with a discussion of emerging opportunities in sociohydrological research and data analysis that have the potential to improve current understanding and management of the quantity-quality-society nexus of water security.

1. Introduction

Water security is defined by the United Nations as "the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [1]. This definition captures the evolution of concerns over water resources, from physical availability (water scarcity) to include socioeconomic issues such as access (water poverty) and impacts of external threats, including extreme events (water vulnerability) [2]. Increasingly, researchers recognize that water security requires analysis from a multidisciplinary perspective that includes issues of governance, economics, social acceptance, and usage needs. Furthermore, some consider the global water crisis to be more governance-based rather than technology-based [3].

Despite the clear recognition that both quantity and quality should be examined from both hydrological and societal perspectives, the traditional paradigm for water security studies is centered on water quantity [4–5]. The tendency to separate water quantity and water quality issues or to dismiss the latter entirely may be motivated by convenience, especially because water quality is broadly conceived and therefore difficult to analyze [7]. For example, some localities may be primarily concerned with reducing natural arsenic uptake, whereas others may be concerned with infrastructure-specific concerns, such as lead leachate from pipes or *Legionella* in cooling towers [8]. Furthermore, our evolving understanding of "safe water" (whereby the specific contaminants we choose to regulate change based on our understanding of their health impacts) makes the notion of "water quality" one that is generally poorly defined and difficult to manage from a siloed perspective [3,9].

This exclusion of water quality from water security discussions, and the tendency to analyze both quantity and quality from an engineering and hydrology perspective rather than a more comprehensive sociohydrological perspective, are problematic. Water uses are impacted by the quality of available water, directly impact water quality, and are influenced by social, political, and economic arrangements and choices that govern the quantity-quality relationship [4]. For example, poor cropland management can result in fertilizer, biocide, and sediment runoff; thermoelectric power plant operation can thermally pollute rivers, especially during low flow periods; and excessive water use can concentrate pollutants and induce saltwater intrusion into coastal aquifers by depleting groundwater [10]. Given the high costs associated with resolving some of these issues, water quality and associated societal influences should be a central consideration in water security

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discussions.

Increased understanding of the complex coupling between water quantity and water quality as well as human influences on them both has driven a growing awareness of the need to assess water security in an integrated manner and from a multidisciplinary perspective [4,5,11]. Further, recent water crises (such as in Flint, USA and Cape Town, South Africa) have highlighted the consequences associated with improper water management [12]. As global dynamics of population growth, economic growth, and climate change influence the state of water resources, recognizing the nexus of water quantity, water quality, and societal factors becomes increasingly important in water security discussions [11]. In the next section, we use six common water management practices as examples to underscore how water quantity, quality, and associated societal dimensions can influence the implementation and effectiveness of securing water for societal needs around the globe. We then conclude with a discussion of emerging opportunities in sociohydrological and data analysis research that can improve accounting for the quantity-quality-society nexus of water security.

2. Water management practices

2.1. Source protection

Source protection measures are motivated by the need to protect the quality of water supplies. Dating back centuries, this practice was originally devoted to protecting water for drinking purposes, and communities around the world implemented rules that restricted certain activities near water sources. For example, the Babylonian Talmud restricted tanneries and slaughterhouse operations within 25 m of a well, while the Yoruba in Africa prohibited bathing and clothes washing near wells [13]. Present-day regulations extend beyond household uses to consider water needs for recreation and the environment (e.g., through wastewater treatment requirements). Although regulating pollution from point sources (i.e., any single identifiable source such as pipe or ditch) has been successful, regulation of non-point source pollution (i.e., contaminants in runoff from land) has been much more challenging.

Degradation of watersheds either through land use change or intensive agriculture can impact sediment and nutrient runoff and require downstream users to invest more in water treatment, an issue observed in cities around the world [14]. For example, nutrient pollution runoff from upstream agricultural fields required the city of Des Moines, Iowa, to install a $4.1 million nitrate removal facility to maintain compliance with drinking water standards [15]. Similarly, upstream pollution sources have impacted the water quality of receiving bodies such as the Chesapeake Bay and the Gulf of Mexico, resulting in hypoxic areas and dead zones. Given the diffuse nature of users and contaminants, the question of how to manage these non-point sources is often vexing.

One example of effective non-point source pollution governance is New York City's management of the Catskill-Delaware watershed, the primary source of the city's drinking water. In the 1980s, the city invested resources to develop new sewage and storm water infrastructure, acquire land and conservation easements in critical areas, and implement a "whole farm" planning program that funded a technical team to develop custom pollution control measures for each farm in the Catskill-Delaware watershed [16]. These initiatives were informed by a participatory governance approach that helped to resolve conflicts with local residents and incorporated their voices in the discussions; ongoing education and outreach programs also helped to improve communication between farmers and city officials [17]. These measures helped the city to avoid the need for installing filtration equipment for its drinking water treatment plant, a potential multi-billion dollar expense. As the natural buffering capacity of the local ecosystems are being exceeded and climate change-induced weather variability impacts chemical cycling, such innovative governance practices (e.g., nutrient trading programs, performance-based payments, and urban-rural partnerships) will be needed to improve protection of water sources for multi-sectoral uses [5,15,18].

2.2. Point-of-use

Point-of-use (POU) (or "fit for purpose") water treatment describes the practice of end-user-oriented treatment, where the level of treatment depends on the particular end-use. This measure is motivated by the recognition that treatment need not be uniform across sectoral uses; for example, the quality of irrigation water need not be as high as the quality for household uses [19]. Water quality requirements in industry also depend on the specific application, e.g., semiconducting manufacturers requiring ultrapure water to clean the electronic pathways of computer chips [20]. Often, water that requires POU treatment is self-supplied, where water services are obtained and financed by individual (s) rather than a central entity [21]. In the U.S., about 14% of the water withdrawn for household domestic use in 2010 was self-supplied, whereas self-supplied water for industry and total water for agriculture accounted for 36% of all the freshwater withdrawn in the country [22].

POU treatment considerations are influenced by regulations, perceptions, and available technology. Water quality guidelines and technology recommendations for domestic use have been put forth by multiple agencies including the Center for Disease Control and the World Health Organization [23,24]. Regulations have also been put forth for agricultural applications by the US Food and Drug Administration and the European Commission because contact with untreated irrigation water can contaminate produce with pathogenic microorganisms (such as *E. coli*), which can lead to widespread disease outbreaks [25–27].

POU treatment for household use is common in many developing countries and even in parts of the developed world where a central water treatment facility is not feasible. The treatments employed vary from boiling the water and using chemical disinfectants to use of solar disinfection methods and reverse osmosis units [28]. In resource-poor regions of the world, such as rural Kenya, clear plastic soda bottles or polyethylene terephthalate (PET) bags are filled with water and exposed to sunlight for ultraviolet disinfection. Sometimes the filled bottles and bags are shaken to aerate the water and placed on a black surface to further promote bactericidal and thermal effects respectively [28]. This method, which provides a relatively inexpensive means to improve water quality, has been shown to reduce diarrheal incidence in the public [28]. Even households that receive treated water may further filter the water prior to consumption for taste purposes, as in the case of household water filters in the US. Generally, the level and type of POU implemented is influenced by end-use requirements, associated regulations, and available resources (including technology access and economic capacity).

2.3. Wastewater reuse

Wastewater from multiple sectors (including municipal, agricultural, and industrial) can be reused if treated appropriately. Reuse can provide additional water and reduce reliance on external water sources but raises concerns regarding water quality. For example, direct potable water reuse requires significant treatment but could reduce energy needs associated with transporting water from distant sources and limit the effects of water withdrawal on ecosystems [29]. Even though the de facto reuse of wastewater effluent is high (a large fraction of drinking water treatment plants use water that originated as wastewater effluent from upstream sources; [30], direct potable reuse suffers from public perception issues (the "yuck" factor) and concerns from water-supply organizations about public health risks and liability if there is a safety failure [31]. These safety perception concerns are addressed by direct nonpotable reuse to some degree, but there are complex rules governing the level of treatment required with respect to the type of nonpotable use. Reclaimed wastewater is usually distributed separately in urban areas through systems known as "dual reticulation" that use different-colored pipes (e.g., purple in USA) to distinguish them from potable water supply pipes. Although the system can be an efficient source of supply for large commercial customers, it requires new infrastructure, and costs can be prohibitive [32].

A variant on water recycling that addresses some of the perceptual concerns is indirect recycling, which can occur through agricultural exchanges and aquifer recharge projects (latter discussed in Section 2.6). Agricultural exchanges allow an urban entity to sell their treated water to a rural system in exchange for access to water that the rural system can access. The rural system is then able to use the treated urban water for agriculture, but the specific agricultural applications may be driven by water quality considerations. An example of an urban-rural exchange system can be found in the desert city of Phoenix, Arizona, USA, which sends its treated wastewater to the Roosevelt Irrigation District for non-edible crops in return for credits to withdraw an equivalent amount of water elsewhere in the aquifer [33,34]. The city also has direct nonpotable recycling, where reclaimed water is made available to a nuclear power plant. A dual reticulation system, which existed in parts of the city, was closed in favor of an "in lieu" recharge exchange agreement. However, the state government of Arizona recently approved direct potable recycling practices (provided that there is extensive treatment and monitoring), that could impact future practices [35]. Perception concerns with wastewater reuse have also been addressed through strong policy enforcement of wastewater discharge requirements and public education efforts, such as in Singapore [36]. This case study highlights how wastewater reuse can provide an alternate source of water assuming societal concerns regarding water quality safety and costs are addressed.

2.4. Water conservation

Water conservation is often considered the least expensive strategy for securing "new" water supplies [37]. This strategy focuses on demand-side management of water needs and can be applied in any sector using multiple approaches. The basic tenets of water conservation programs span technological, financial, legislative, maintenance, and educational categories, such as promotion of water-saving and water-efficient technologies, economic policies that use market-based approaches, local and national regulations that include mandatory restrictions for specific water use (often the case during droughts), programs to reduce water leakages, and campaigns to increase public awareness [37,38]. Water conservation is often conflated with water-use efficiency, and although related, they are distinct concepts since there are situations where water-use efficiency can actually lead to increased water use [39]. Water conservation requires participation by many entities, including regulatory bodies, households, farmers, commercial businesses, and industrial plants. Thus, complex governance and sociotechnical interactions influence this practice, including coverage of extreme events (such as drought) in media, public engagement by local officials, and local political preferences for the types of measures implemented [40,41].

Successful water conservation programs have been implemented throughout the world. Israel, for example, has a national strategy that incorporates both diffusion of water-efficient technology and regulations across sectors [6]. Implemented technologies in the country range from double-volume toilet flushing in households to drip irrigation in the agriculture sector; the latter delivers nutrients and oxygen directly to the root zone (sometimes assisted with computerized technology), thereby reducing the total water delivered [6]. Drip irrigation methods have also led to improvements in the quality and quantity of groundwater in the root zone [42]. Israel's regulatory practices include a total water metering system that helps with monitoring and setting the price for water use across the country (a block rate system that varies by user) and a national water carrier that enables water users to sell or temporarily trade their water allocations to drive more efficient use [37].

However, implementation of water conservation practices is not exempt from water quality concerns, especially in the distribution and plumbing systems. Drip irrigation pipes, for example, are susceptible to clogging by bacterial slime and mineral precipitation [6]. In large distribution systems, lower flows (and hence longer travel times) can lead to water stagnation in pipes, which could lead to loss of disinfectant residuals and create more conducive environments for microbial and pathogen growth, such as *Legionella pneumophila* and *Mycobacteria* species [8,43]. Prolonged contact between the water and distribution pipes could also increase mobilization of trace metals, corrosion, and disinfection byproduct levels [44]. Furthermore, reduced water usage can reduce hydraulic loadings and increase quality concerns (such as biochemical oxygen demand) that would impact the performance of wastewater treatment systems [45]. Recognition of these issues has motivated research into "right-sizing" of the water distribution system so that pipes not only meet water quantity but also water quality objectives. Thus, water conservation requires both participation among various societal groups as well as technological improvements to address water quality concerns associated with lower usage rates.

2.5. Desalination

In response to increasing scarcity of freshwater sources, many nations have started to invest in desalination technologies that allow conversion of seawater and inland brackish waters to meet local needs. As of mid-2015, 18,500 desalination plants with more than 86.8 million m^3/day of installed capacity were operating globally [29]. Using either thermal-based or membrane-based methods, desalination processes focus on separating source water into product (or freshwater) and brine (or concentrate) streams [29]. Depending on the source water quality, the volume and quality of concentrate may vary significantly, ranging from 2.5 g/L of total dissolved solids (TDS) for brackish water to 80 g/L TDS for seawater. In addition to higher salt content, contaminants (such as nitrate, heavy metals, and naturally occurring radioactive materials) can become 2–10× more concentrated in the brine [46]. Management of this concentrate is an increasing challenge influencing the implementation of desalination operations.

When brine disposed of in an ocean outfall settles on the floor, it can be toxic to bottom-dwelling marine life and can lead to hypoxic conditions. To reduce these adverse impacts, seawater desalination facilities often design outfalls with diffusers to improve mixing conditions of the discharged brine in the oceans [29]. For example, Australia's first seawater desalination plant in Perth uses an outfall that contains 40 diffusion ports along the last 200 m of the 600-meter pipe [47]. To ensure that the discharge has minimal impact on local marine life, environmental surveys and a series of toxicity tests are conducted in the zone of dilution. Continuous monitoring of discharge turbidity and conductivity revealed that the Perth plant continues to operate within established criteria [47].

Concentrate disposal options for inland facilities are similarly influenced by physical constraints and governance factors. Local regulations about discharge limits and permitting requirements greatly impact the size of desalination plants and the waste disposal strategy implemented: discharge to surface water, deep well injection, or evaporation ponds [46,48]. Currently in the United States, requirements regarding monitoring, well construction, and water quality standards vary not only between states but often at the county-level [49]. This lack of regulatory certainty has prompted significant research into zero liquid discharge approaches that reduce the total volume of managed waste and improve cost-effectiveness by recovering valuable minerals from brines at inland facilities as well as integrating renewable energy to offset high energy requirements of desalination [48]. Such technological advancements along with evolving regulations will continue to influence the approaches for dealing with water quality concerns associated with desalination, especially at inland facilities, in the coming years.

2.6. Managed aquifer recharge

The use of surface water to recharge aquifers artificially provides a useful and feasible way to improve water security in many regions of the world by avoiding negative impacts of overexploitation of groundwater, by storing water in seasons of plenty, and by making water available in seasons of surface water scarcity [50]. The intentional banking of water in aquifers is referred to as managed aquifer recharge (MAR) [51]. MAR has been practiced for more than a century in numerous environments using a variety of methods [50,52]. Because of its effectiveness and feasibility, MAR is widely used with diverse sources of water, including harvested rainwater and river water [53]; also see https://www.un-igrac.org/ggis/mar-portal). MAR has also facilitated reuse of wastewater wherein treated, recycled water is returned to the aquifer for withdrawal at a later time [54].

Because the interaction of surface water injected into an aquifer with the aquifer material changes the chemical composition of the stored water, a variety of water quality issues (including salinity, turbidity, nutrients, organic and inorganic chemicals, and pathogens) arise in evaluation of MAR [55]. Although many changes in water chemistry are benign (e.g., an increase in calcium concentrations to levels well within drinking water guidelines), care must be taken so that naturally occurring contaminants such as arsenic are not mobilized [56]. Recharge of water from urban runoff or from treated wastewater can introduce a variety of contaminants, some of which may be attenuated by natural processes in the aquifer while others may persist and pose a risk to human health [50]. Concerns about MAR water quality have led to an emphasis on guidelines and regulations for ensuring that measures are taken to protect groundwater resources [51].

Examples of successful MAR implementation are present throughout the world, including in southern India, where check dams are constructed across rivers to impound surface runoff and increase groundwater recharge [57]. In addition to increasing groundwater levels, studies have shown that these dams have improved water quality, notably by reducing salinity levels as well as arsenic and fluoride concentrations in the groundwater [57]. Furthermore, livelihood impacts such as improved farm productivity and reduced time spent by women to fetch water have also been documented [57]. Although economic evaluations typically show that benefits of MAR outweigh costs, studies that consider stakeholder preferences often show that MAR is not seen as a high priority option due to concerns about maintenance requirements [58–60]. Social acceptance of MAR is also dependent on public perceptions involving fairness, trust in governing institutions, and effectiveness of protection measures for water quality [61]. Although MAR has many advantages, these complex interactions highlight how local variabilities in societal concerns regarding the quality of water used to recharge aquifers and associated management needs will influence the adoption of this water management practice by communities around the world.

3. Discussion

The management practices described above are not mutually exclusive inasmuch as benefits of one approach can facilitate implementation of another. For example, desalination technologies can help remove constituents of concern in municipal wastewater, thus addressing water quality concerns associated with reusing this water source [29]. Similarly, the water conservation practice of drip irrigation in Israel has enabled safer use of lower quality water for irrigation because the distribution pipes limit direct human contact [6]. The interactions between practices can also be adverse; for example, implementation of desalination could impact consumers' perception of water scarcity and thus limit engagement in water conservation practices [41]. Similar feedbacks influence implementation of other water management practices, such as interbasin transfers, use of bottled water, and virtual water trade. The quantity-quality-society nexus impacts not just the implementation of each water management practice but also amongst practices within a portfolio and underscores the need to manage water resources from a systems perspective [4].

Integration of quantity, quality, governance, and other social dimensions of water security is a direct aim of the emerging field of sociohydrology. By including human agency, sociohydrologists explicitly aim to account for social interactions with the physical system [62]. This emerging field has primarily focused on water quantity aspects, but water quality aspects and changing social factors (such as affordability considerations or the promotion of urban-rural partnerships) fit well within the interdisciplinary framework. Future sociohydrological analyses also need to consider the effectiveness of water governance measures, including the extent to which existing policies enable effective implementation and safeguard against opportunistic behaviors that try to circumvent policies [17]. Integrated analyses are facilitated by advancements in remote sensing and data science, as well as open data efforts to share information more broadly [63]. The availability of large volumes of data from many sources has the potential to improve our understanding of cross-scalar and cross-sectoral quantity-quality-society feedbacks in water security (including outsourcing of water-polluting activities) [38,64].

Increased demand for water resources due to population growth and lifestyle changes will likely result in increased competition for limited resources [10]. As highlighted in the six water management descriptions, the quantity-quality-society nexus can help identify opportunities for improving water security around the globe. Continued evaluation of the complex interactions between water quantity, water quality, and societal requirements (especially through sociohydrological and data science approaches) will be critical for moving us from a trial-and-error water management process towards a proactive approach that limits unintended consequences of our water resources decisions [5,6].

4. Conclusion

As precipitation patterns shift and as water is ever more intensively exploited, managing water resources in an integrated manner will be increasingly imperative to ensure water security in the future. As highlighted by the descriptions of the water management practices, successful management of water resources needs to account for water quantity and water quality aspects of the physical resource as well as associated societal dimensions of both. Being mindful of this quantity-quality-society nexus can help ensure current and emerging opportunities (e.g., in sociohydrology and data science) capture critical interactions in water management decisions, account for cross-sectoral and cross-scalar dynamics using interdisciplinary methods, and provide guidance on successful implementation of water management practices in a changing world.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://

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