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Securing drinking water resources for a coastal city under global change: Scientific and institutional perspectives

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ABSTRACT

Most urbanized coastal cities lack fresh water resources and rely on water supply from adjacent inland watersheds. Numerous threats, including global climate change and various human activities, affect both the quantity and quality of fresh water available. Here we carried out a case study of Xiamen, a coastal city in subtropical China. Long-term data analysis showed the increasing floods and droughts that are the expected main impacts of climate change on water quality and quantity. Increasing eutrophication and harmful algal blooms in recent decades threaten water quality in Jiangdong reservoir, which supplies raw water to Xiamen and other coastal areas. In addition to excessive manganese (Mn) in surface water, other potential threats to water quality and human health include various emerging contaminants; these threats have all been scientifically detected but are beyond the scope of routine water-monitoring programs. Based on lessons learned from water supply management initiatives currently in progress, we proposed a conceptual framework for "source-to-tap" integrated water management in an attempt to secure clean and safe water supply. Long-term monitoring and research, adaptive management and actions to reduce nutrients and other pollutants loading are vital to protect water sources, and measures to adapt to climate change should be considered to achieve these goals. Institutional enablers for transboundary and cross-sector management were also suggested: enacting integrated water policies, developing an ecological compensation policy, authorizing the management institution, improving the incentive mechanism of cross-border compensation and transfer payments considering environmental responsibility, and encouraging multiple-stakeholder involvement.

1. Introduction

The increasing demand for clean and safe drinking water supply has become one of the key challenges facing sustainable coastal socio-economic development, because most urbanized coastal cities lack fresh water resources. The continuous expansion of urban areas and growing populations (Lutz and Samir, 2010) are associated with increasing water demand, both for domestic and non-domestic uses (Rozos and Makropoulos, 2013). Because many coastal urban areas in China rely on water supplied from adjacent inland watersheds, transboundary water management has become a key challenge which may affect both the quantity and quality of available drinking water.

Unregulated human settlements and intensive economic activities within a river catchment often degrade fresh water quality. Chemical pollution, heavy metal pollution and algal blooms are the main types of water pollution in China (Wu et al., 2017). Over-fertilization of agricultural lands and discharges from animal husbandry and domestic wastes, which are usually inadequately treated, have caused nutrient (mainly nitrogen [N] and phosphorus [P]) enrichment in receiving waters, resulting in eutrophication and harmful (toxic, hypoxia-generating, food web-disrupting) algal blooms. Moreover, a large number of dams have been built along river networks for various purposes, including hydropower generation, flood control, irrigation, and even tourism (Miao et al., 2015; Wang et al., 2010). Intensive dam construction may drastically alter river hydrology and biogeochemistry, leading to negative impacts on river ecosystems (Chen et al., 2011; Kelly, 2001; Vörösmarty et al., 2003). One of the most direct consequences for cities located downstream is the reduction of the safe and clean fresh water supplies from the upper reaches of major rivers.

In the context of increased human and climate perturbations, safe and clean freshwater supplies have become an urgent coastal management challenge to sustainable development. Unfortunately, the absence of scientific understanding of pollutant emission and transport, limited investment on pollution abatement, and inadequate monitoring of water quality could continue to hinder sustainable management of water resources (Jia et al., 2010). The lack of robust data and adequate

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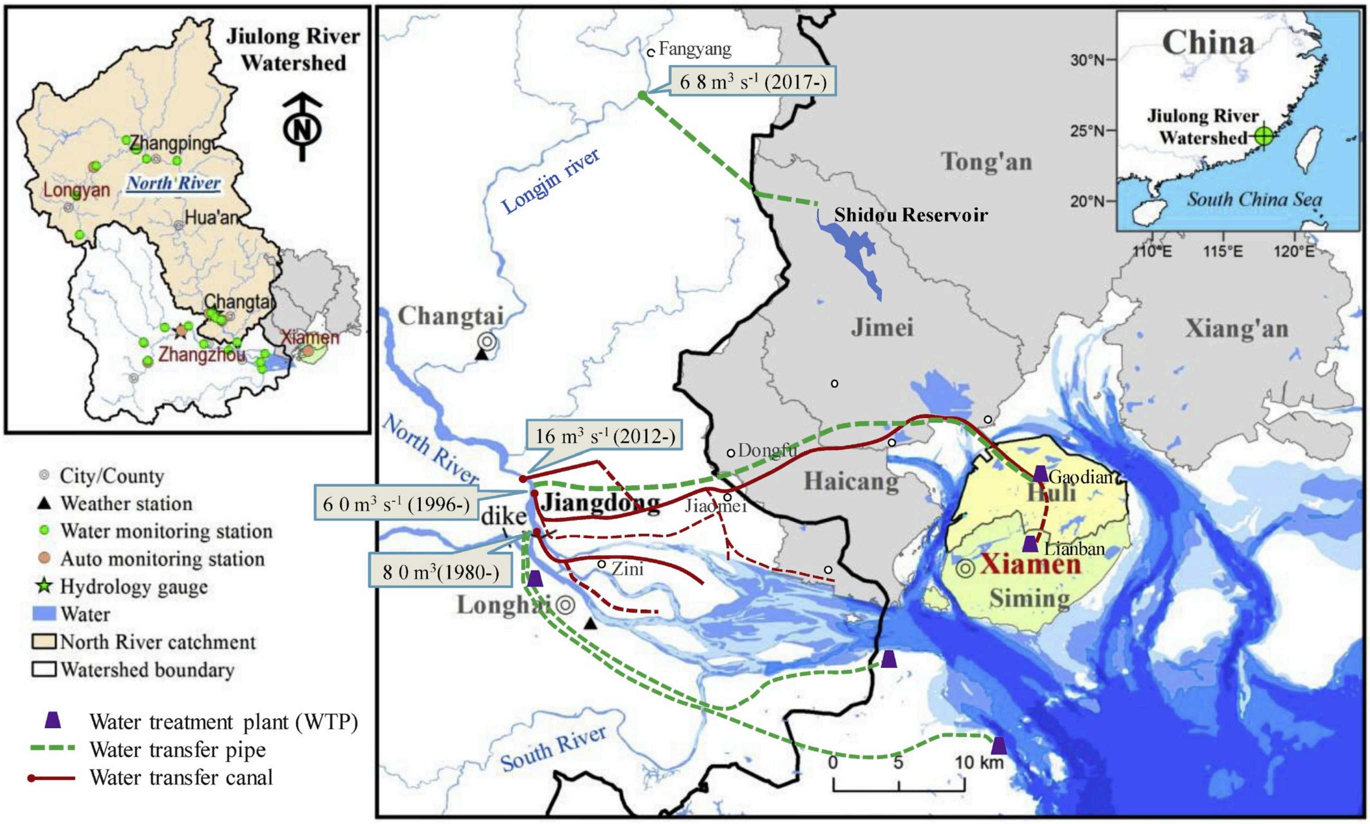


Fig. 1. Map of study area showing monitoring networks (a) and water transfer via pipes and canals from the North Jiulong River (Jiangdong Reservoir) to coastal cities (Xiamen and Longhai) (b). A new Water Transfer Scheme, which was completed in early 2017, will soon transfer water from a tributary (Longjin stream) to Shidou Reservoir first, before its distribution to Xiamen suburban area (Jimei, Tong'an and Xiang'an districts).

information and management tools could also severely affect the effectiveness of the design and implementation of water management programs. In this study we chose Xiamen, which is a rapidly urbanizing coastal city in subtropical China, as a case study to explore climate change impacts on water resource availability, and to identify major anthropogenic threats to water quality. We propose a conceptual framework of "source-to-tap" integrated water management, and suggest institutional enablers for transboundary and cross-sector management. We highlight how to secure drinking water resources for coastal cities in the context of global change.

2. Materials and methods

2.1. Description of the study area

Xiamen, historically known as Amoy, is a major city on the southeast (Western Taiwan Strait) coast of Fujian province, China (Fig. 1) with a population in 2016 of 3.92 million. The administrative area (1699 km^2) is divided into six districts: Siming (south Xiamen Island, Gulangyu Island), Huli (North Xiamen Island), Haicang, Jimei, Tong'an, and Xiang'an (all suburban mainland), and also borders Quanzhou City to the north and Zhangzhou City and Longhai City to the West.

Xiamen has a monsoon subtropical climate, characterized by long, hot, humid summers and short, mild, dry winters. Typhoons typically occur in late summer and early autumn, and the annual average rainfall (1350 mm) is relatively high. However, rapid urbanization, population growth and climate change in recent years, together with rapidly increasing demand for safe and clean drinking water, continue to pose a major challenge, and total water supply increased sharply from 295 million to 419 million m^3 between 2009 and 2014. Furthermore, 80% of the water supply to Xiamen City is taken from the North Jiulong River, which is the second largest river system in Fujian (drainage area of 9570 km^2 and mean annual discharge of 8.23×10^9 m^3; see Fig. 1). Other minor water sources include local reservoirs (Tingxi, Bantou, etc.) in the suburban area.

There are four administrative areas (Longyan City, Zhangping County, Hua'an County, and Changtai County) as well as part of Zhangzhou City in the North Jiulong River watershed; the total population is about 1.5 million, 43% of whom live in urban areas or towns. Longyan City, which is in the area furthest upstream, has recently experienced a rapid increase in livestock breeding, while other counties are predominantly agricultural and forest lands, and (with the exception of downstream areas closer to Xiamen) have relatively low population densities.

2.2. Data collection and analysis

Data were gathered from various sources (e.g., monitoring programs, research reports, statistical yearbooks and publications). Climate data (daily rainfall 1960–2016) at two national monitoring stations (Xiamen and Zhangzhou) were obtained from China Meteorological Data Service Center (http://data.cma.cn). Daily river discharge was obtained from a hydrological station (Punan) and was extrapolated to the sampling site (Jiangdong reservoir) using the ratio (1.08) of the drainage area between them (Fig. 1). Water quality data at Jiangdong was cited from recently completed reports (unpublished data). Socio-economic data were compiled from statistical yearbooks. Data compiling, calculation and statistical analyses were conducted on a variety of software, including Microsoft Office Excel (2010), Statistical Package for the Social Sciences (SPSS 17.0).

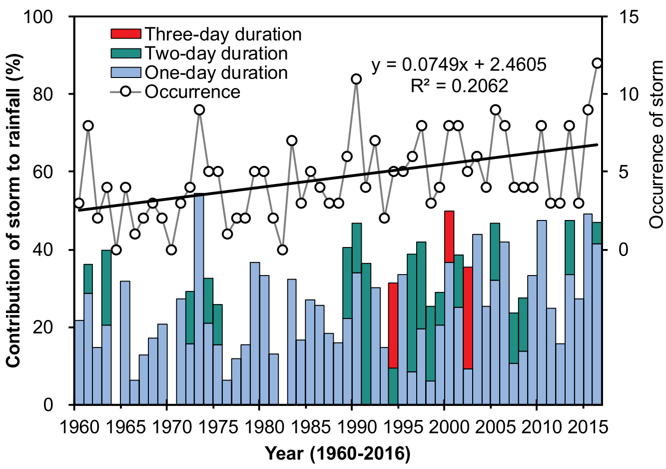
3. Results and discussion

3.1. Climate change and its impact on water resource availability and water quality

Analysis of daily precipitation data recorded at two national meteorological stations (Xiamen in the coastal area and Zhangzhou in the Jiulong River watershed) showed that rainstorm occurrence (defined as daily rainfall greater than 50 mm) in Xiamen and Zhangzhou increased during the period 1960–2016 (Fig. 2), and the contribution of these storms (last 2–3 days) to the annual rainfall total has increased since the 1990s. Meanwhile, the number of successive rainless days (defined as daily rainfall less than 1 mm) has slightly increased (although this result is not significant at the $p < 0.05$ level) and a maximum period of 70 rainless days were observed at both stations in the 1990s (Fig. 3). Analysis of extreme climate events indicated a clear trend of increasing major storms in the summer wet season and more droughts in autumn and winter dry season. Given the close link between global climate change and hydrological processes, strong seasonal and inter-annual fluctuations in rainfall are very likely to cause adverse impacts on water resource availability to coastal cities like Xiamen.

Floods and droughts are also the main ways in which climate change will impact water quality (from source to tap). A review by Delpla et al. (2009) concluded that there is a deteriorating trend of drinking water quality leading to an increase in potential health risk situations as a result of climate change. Extreme events (heavy rainfalls and droughts) accompanied by hydrological variations, water temperature rise and increases in turbidity, organic matter, nutrients, micropollutants (e.g., cyanotoxins) and pathogens, will further impact drinking water treatment and disinfection by-products (DBPs) formation (Nikolaou et al., 2004; Rodriguez et al., 2000; Rodriguez and Sérodes, 2001; Shin et al., 2012). Water borne diseases could be strongly linked to climate change impacts but few studies have been conducted.

(a) Coast (Xiamen)



(b) Watershed (Zhangzhou)

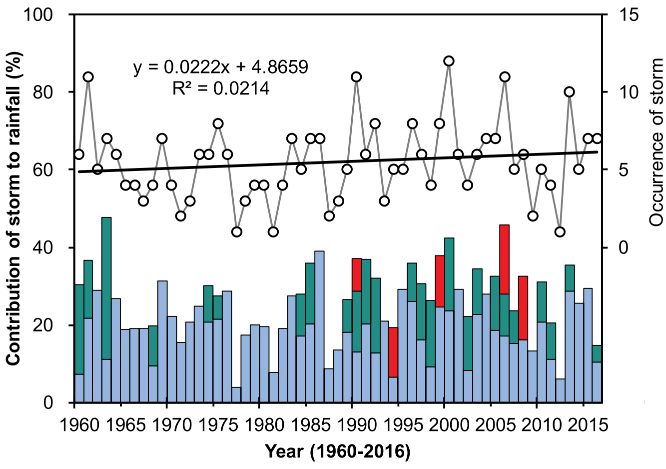
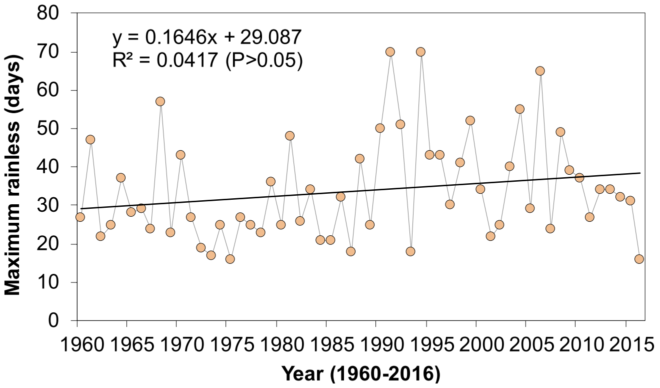


Fig. 2. Temporal variation of storm characteristics at (a) the coast and (b) the Jiulong River Watershed. A rain storm is meteorologically defined as daily rainfall greater than 50 mm.

(a) Coast (Xiamen)



(b) Watershed (Zhangzhou)

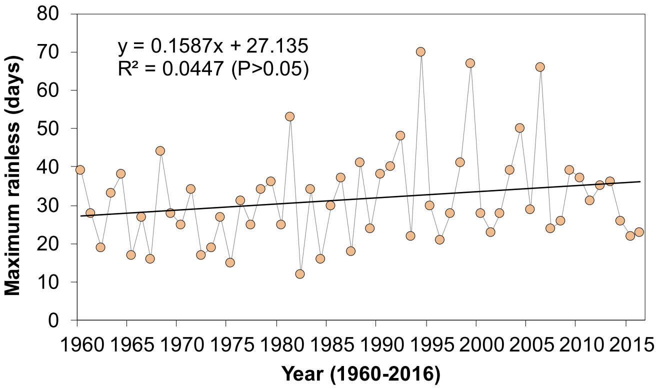


Fig. 3. Temporal variation of maximum successive rainless days at (a) the coast and (b) the Jiulong River Watershed. A rainless day is meteorologically defined as daily rainfall less than 1 mm.

3.2. Increased eutrophication and harmful algal blooms threaten water quality

Eutrophication and harmful algal blooms (HABs) in surface water are common phenomenon worldwide and have been linked to increasing nutrient loading (Heisler et al., 2008; Smith et al., 2006); they are considered the greatest water quality threat to public health and environmental risk (Brooks et al., 2016; Gobler et al., 2012). Increasing human activities within the watershed and external nutrient loads over the past thirty years are the main causes of water degradation and eutrophication in the Jiulong River (Chen et al., 2013). Anthropogenic N inputs (fertilizer runoff, manure and sewage discharge) contribute 61–78% of riverine N export from the North River watershed, which increased from 337 kg N km^{-2} yr^{-1} in the 1980s to 1662 kg N km^{-2} yr^{-1} in the 2000s (Yu et al., 2015). The observed total dissolved N (TDN) and total dissolved P (TDP) loads to the Jiangdong Reservoir currently exceed the allowable total maximum daily load (TMDL) set by the national water quality criterion (TN = 1.0 mg N L^{-1}, TP = 0.05 P mg L^{-1} in grade III waterbody for drinking water source) (Fig. 4).

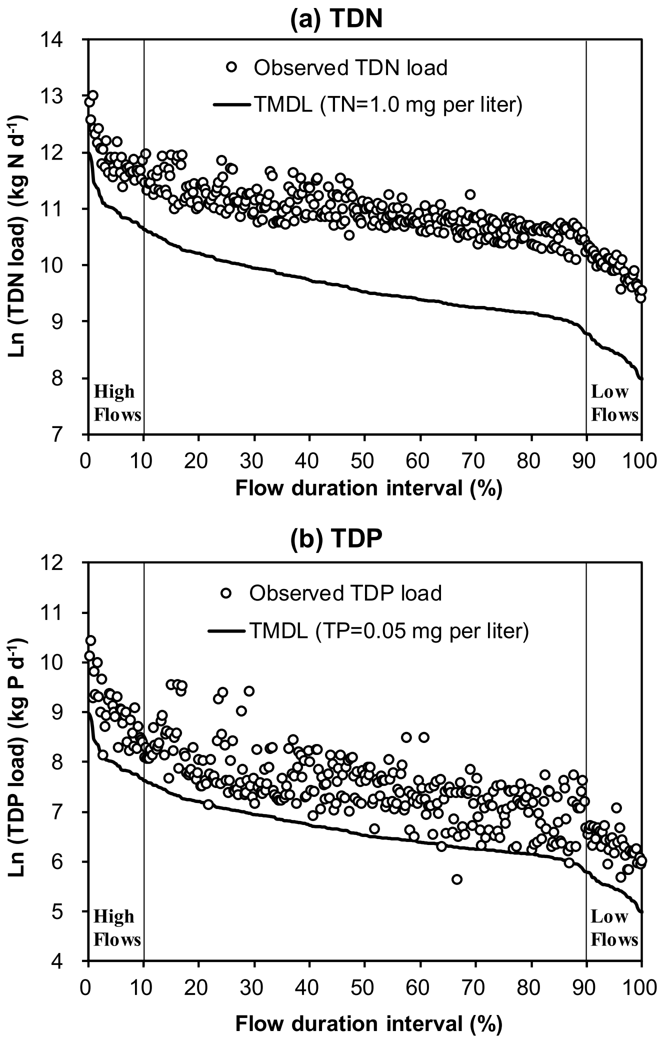


Fig. 4. The observed nutrient load into Jiangdong Reservoir in 2014, compared with the allowable total maximum daily load (TMDL) over flow regime. By adopting the load duration curves approach (USEPA, 2007), the allowable TMDLs were determined by national water quality criterion ($TN = 1.0\,mg\,L^{-1}$, $TP = 0.05\,mg\,L^{-1}$) and corresponding discharge.

Algal bloom events have been monitored in North Jiulong River reservoirs since 2009 (Li et al., 2011), and threaten water treatment and supply to coastal cities. It is suggested that nutrient enrichment in dam reservoirs with limited retention efficiency (e.g., permanently removal from waterbodies by nitrification and denitrification) are responsible for the proliferation of algal blooms (Chen et al., 2014; Lu et al., 2016). Monthly observation at a dam reservoir during 2013–2014 indicate that phytoplankton blooms occur in spring due to ammonium and phosphate enrichment across the dry–wet transition (Mo et al., 2016). The reservoir ecosystem was vulnerable to pulse input from storm runoff and the Cyanophyta bloom was likely fueled by phosphate and ammonium (Chen et al., 2018). However, phytoplankton communities in Jiangdong Reservoir varied across seasons and were associated with changing river discharge, irradiance, water temperature and nutrient concentrations (Tian et al., 2014). HABs are typically triggered by excessive inputs of nutrients (N and P) from anthropogenic sources (Paerl, 2008), and increases in water temperatures and nutrient concentration cause cyanobacteria blooms in many waterbodies (Hunter, 2003). Given that aquatic ecosystems are complex and site-specific, more research on the North Jiulong River and reservoirs are needed to quantify the role of nutrient-induced eutrophication on algal bloom events.

3.3. *Other potential threats to water quality and human health*

There are many other important threats to water quality and human health. For example, dissolved manganese (Mn) concentration in the Jiangdong Reservoir averaged $0.12\,mg\,L^{-1}$, and total Mn was $0.20\,mg\,L^{-1}$ (based on 38 monthly measurements during 2014–2017; unpublished data from Xiamen Environmental Monitoring Center). These values exceed the national water quality criterion (0.1 Mn mg L^{-1}). The widespread presence of red soils (rich in Fe/Mn oxides) and high levels of soil erosion and mining in upstream areas might result in adsorption of manganese from soil particles as pH decreases ($pH < 7.2$) in the lower river (unpublished data). Some studies have suggested that children's intellectual development could be affected by excessive exposure to manganese in drinking water (Menezes-Filho et al., 2011; Wasserman et al., 2004), and manganese exposure can also cause symptoms of neurobehavioral and neurological disease (e.g., parkinsonism) (Zoni et al., 2007).

Emerging waterborne pathogens (EWPs) and antibiotic resistance genes (ARGs) have been detected in the North Jiulong River and a drinking water treatment plant in Xiamen (Lin et al., 2015; Wang et al., 2012). EWPs and ARGs are emerging contaminants which are considered to be closely linked to the widespread use of antibiotic pharmaceuticals in humans and animals (Pruden et al., 2006). In addition, pesticides (including DDTs, triazophos, fenvalerate, bifenthrin and cyfluthrin) have been investigated and present a high eco-risk in the area (Zheng et al., 2016). All these emerging contaminants and new pesticides present potential risks to human health and have received considerable scientific and public attention. However, they are not included in current national laws and water quality standards and are beyond the scope of routine monitoring programs for both raw and treated water.

3.4. *A scientific framework for “source-to-tap” integrated water management*

We propose a conceptual framework for “source-to-tap” integrated water management with the goal of securing a clean and safe water supply in coastal cities under global change (Fig. 5). Urban water supply systems are generally composed of water sources, transfer pipes, treatment plants, and distribution networks from source to tap. Management goals and potential measures for each component to secure drinking water resources are illustrated in Table 1.

Surface freshwater (rivers, reservoirs, lakes) are main water sources for coastal cities. Groundwater, recycled water and desalinized water could become important supplementary water sources in urbanizing areas with increasing water demand, both for domestic and non-domestic uses. Appropriate scientific information and management tools are essential for addressing water threats and risks related to intensive human activities and climatic perturbation. Given the complexity and uncertainty of interactions within and between the natural ecosystem and socio-economic system, sustainable water security for coastal cities can be achieved only by using an adaptive management approach. Based on continuous comprehensive monitoring, periodic evaluation and plan amendment, water quality can be improved through implementing a series of projects such as pollution abatement, soil and water conservation, aquatic restoration and remediation, and upgrade of water treatment technology to remove emerging pollutants. Although the control of eutrophication and HABs face considerable institutional, financial, and technical constraints, stricter nutrient management will likely be the most feasible and practical approach in a warmer, stormier and more extreme world (Paerl and Paul, 2012). In response to climate change and urbanization, ‘Sponge City’ has been proposed for China's urban planning to improve stormwater management and reduce water shortages in urban areas (Xia et al., 2017). Other measures to mitigate losses from extreme weather hazards and to reserve water sources are also necessary. There is a need to initiate

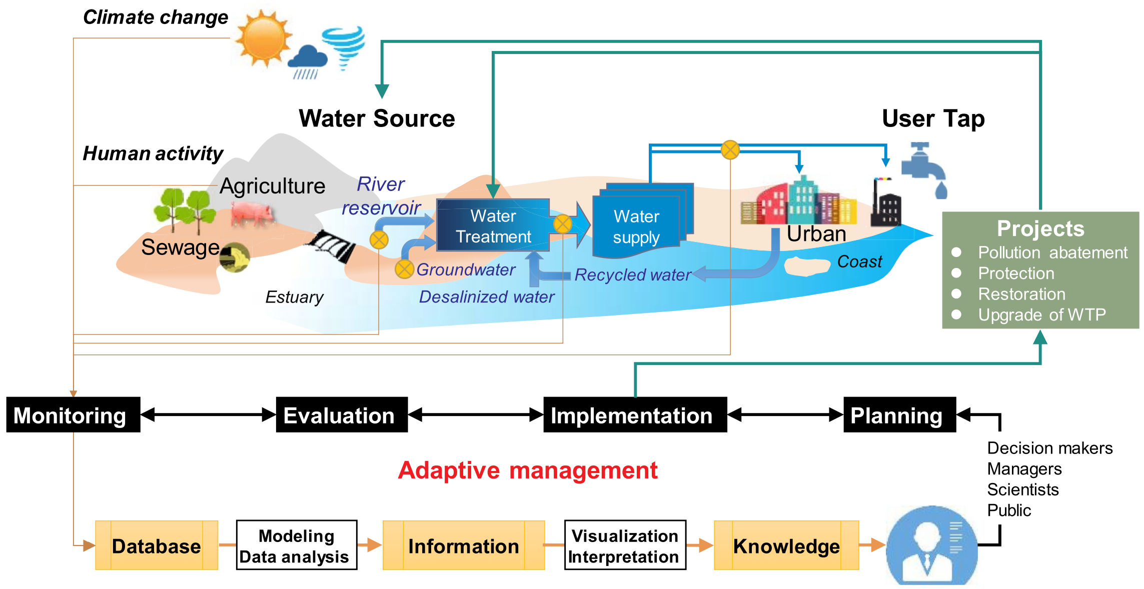


Fig. 5. A conceptual framework for "source-to-tap" integrated water management in coastal region. Urban water supply systems are generally composed of water sources, transfer pipes, water treatment plants (WTP), and distribution networks from source to tap.

strategic planning to address the problems of increasing coastal flooding and wetland losses due to global sea-level rise (Nicholls et al., 1999). Overall, coastal urban water supply systems are exposed to a variety of uncertain threatening hazards (natural, human-made, and operational). Risk and vulnerability assessment models must be used to identify threats, their probability, and consequences of each element of these systems against the hazards (Pagano et al., 2014; Roozbahani et al., 2013). Long-term monitoring and systematic scientific research and associated data can be integrated and processed into models and quantitative analysis, and further inform and support sound decision-making and management. Moreover, sharing and exchange of water-associated information and close collaboration between decision-makers, managers, scientists, and publics will facilitate "source-to-tap" water management.

A robust multi-sourced database could be established through a comprehensive monitoring network encompassing water sources (e.g., reservoir and its upstream, groundwater), water transfer canals/pipes and water treatment plants (WTP), and even water distribution to user taps. In addition to conventional sampling and laboratory-based techniques that impose a significant financial burden, real-time water quality monitoring systems are also useful (O'Flynn et al., 2010). For the Jiangdong Reservoir, continuous monitoring of nutrients (ammonium [NH_4^+-N], total nitrogen [TN], total phosphorus [TP]) through a bank-based automatic system and *in situ* sensor-based measurement of physicochemical variables (temperature, pH, dissolved oxygen, turbidity, conductivity, chlorophyll *a*, etc.) are operated by the Environmental Agency. However, the monitoring program could be expanded to embrace more nutrient forms (e.g., nitrite, nitrate, phosphate) and phytoplankton and combined with flow rate measurement. High temporal-resolution monitoring is likely to capture the fluctuating

Table 1
Management goals and potential measures for securing drinking water resources in coastal cities.

Components	Management goals	Potential measures	Responsible Agencies
Water sources	Protection of water resource	Water resources planning; regulation of dam outflow; monitoring of river discharge; monitoring of ground water	The Ministry of Water Resources
	Adaption to climate change	Monitoring of precipitation; prediction of extreme weather hazards Drought and flood control; allocation of water flow from river reservoirs; enable reserved water source	The Meteorological Administration The Ministry of Water Resources
	Reduction of water pollution	Control of agricultural runoff, sewage, animal wastes; control of soil erosion	The Ministry of Agriculture, The Ministry of Forest; The Ministry of Water Resources, etc.
	Reduce water shortage	Development of Sponge City and Ecological City; storm water management; recycled water; desalinized water	Ministry of Housing and Urban-Rural Development
	Protection of water quality	Environmental planning and pollution reduction; monitor water quality; early-warning of algal blooms; deal with emergent pollution events; set up source water protection zone	The Ministry of Environmental Protection
Water treatment	Clean and safe water	Monitoring of transfer pipes; upgrade of water treatment technology; monitoring raw water and treated water	Municipal Engineering Bureau; Water Supply Group
Water supply	Clean and safe water	Monitoring of transfer pipes; maintain distribution networks; monitor water of user taps; reserve water in case of disaster	Water Supply Group; The Ministry of Health
Integrated urban water supply system	Holistic plan, coordinative governance, adaptive management	Coordination; integrated water resources planning; project implementation; guidance and supervision; financial support; ecological compensation; development of big data center and intelligent monitoring system; modeling and data analysis; set up expert group and advisory committee; share information and knowledge with stakeholders and public	The Joint Commission Office

Note: The responsible agencies in China are listed here as an example.

Table 2

Selected policies, regulations or standards addressing water resource and water quality management.

Policies, Regulations or Standards	Year	Authority
Water Law of the People's Republic of China	amended 2016	Ministry of Water Resources of PRC
Environmental Quality Standards for Surface Water (GB 3838-2002)	amended 2002	Ministry of Environmental Protection of PRC
Standards for Drinking Water Quality (GB 5749-2006)	2006	Ministry of Health of PRC
Control Action Plan of Water Pollution	2015	Ministry of Environmental Protection of PRC
Regulations on Prevention and Control of Pollution of Livestock and Poultry	2013	Ministry of Agriculture of PRC
Management Rule of Special Fund of Watershed Environmental Protection	2012	Fujian Provincial Department of Finance and Department of Environmental Protection
Administrative Measures on Pollution Discharge Permit of Fujian Province	2015	Fujian Provincial Department of Environmental Protection
Management Regulations on Assessment of Surface Water Quality in Fujian Province	2016	Fujian Provincial Department of Environmental Protection
Regulations on River Channel Conservation Management of Fujian Province	2015	Fujian Provincial Department of Water Resources
Regulations on Soil and Water Conservation of Fujian Province	2014	Fujian Provincial Department of Water Resources
Management Regulations on Water Resources in Fujian Province	2017	Fujian Provincial Department of Water Resources
Regulations on Water Intaking Permit of Fujian Province	2006	Fujian Provincial Department of Water Resources
Management Regulations on Sand Dredging in River Channel of Fujian Province	2005	Fujian Provincial Department of Water Resources
Management Regulations on Water Resources Fee of Fujian Province	2007	Fujian Provincial Department of Water Resources
13th Five-Year Plan of Water Conservation Project of Fujian Province	2016	Fujian Provincial Department of Water Resources
Management Regulations on Wetland Protection of Fujian Province	2016	Fujian Provincial Department of Forestry
Six Measures to Strengthen the Prevention and Control of Pig-Breeding	2014	Fujian Provincial Department of Agriculture
Special Fund Management Regulations on Standardized Aquaculture Pond	2012	Fujian Provincial Department of Ocean and Fisheries
Water Pollution Prevention and Control and Ecological Protection Regulation in JRW	2001	Joint Commission of Jiulong River Watershed Program
Total Emission Quantity Control Standard of Water Pollution In JRW	2001	Joint Commission of Jiulong River Watershed Program
Prohibition and Restriction Zoning Scheme of Livestock and Poultry Raising in JRW	2001	Joint Commission of Jiulong River Watershed Program
Marketization of Sewage Plant Scheme of Longyan City	2002	Longyan Municipal Administration

Note: PRC- the People's Republic of China; JRW- the Jiulong River Watershed.

hydrologic environment under climate change scenarios (more floods) and provide an accurate estimation of pollutants loading to the reservoir (Chen et al., 2012, 2015). Appropriate monitoring of water transfer and distribution systems is also vital to guarantee meeting drinking water quality standards. Meteorological and watershed characteristics data (temperature, precipitation, irradiance, soil, vegetation, elevation, land use, fertilizer consumption, population, river morphology, etc.) are also important input parameters for models to predict water quality (Arnold et al., 2012; Ernst and Owens, 2009; Wagenschein and Rode, 2008). In other words, good data availability and efficient management tools (models) would provide a solid basis for integrated source-tap water management.

Taking Xiamen as an example, a water security program was initiated immediately after the first harmful algal bloom (dominated by *Peridiniopsis* sp.) occurred in North Jiulong River reservoirs in early 2009 (Li et al., 2011). This effort addressed drinking water issues with a focus on water quality management at the water source level (Jiangdong Reservoir). Funded by the Xiamen government, the Jiulong River Watershed Information System (JRWIS) was designed and developed by the research team in Xiamen University, in collaboration with Xiamen Environmental Monitoring Center (XMEMC) and a software company (Fujian Strong Soft Co., LTD.). A group of models (SWAT + EFDC + WASP) were integrated into JRWIS to simulate river runoff and water quality (e.g., NH_4^+-N, TN, TP, dissolved organic P [DOP], chemical oxygen demand [COD], and chlorophyll). The JRWIS was finally operated and managed by the Xiamen Environmental Information Center since 2011; it is a Web-GIS system that enables users to log in and use the system anywhere and at any time via the internet. Nevertheless, more efforts should be made to develop a robust, comprehensive, and fully coordinated surveillance system for monitoring water quality. The development of an operational dynamic model and application of real-time monitoring technologies in the fields of meteorology, hydrology, water quality, nutrient fluxes and remote sensing would facilitate multi-dimensional diagnosis of water issues and emergency response in case of sudden pollution accidents. The current JRWIS is technically accessible and opened to other agencies (managers) but requires institutional improvements to promote its role in coordinated management from water source to tap (see discussion below).

3.5. Institutional enablers for facilitating transboundary and cross-sector management

Water transfer across different municipal units (cities) requires efficient transboundary management to secure water quality. Xiamen City acquires drinking water from Jiangdong Reservoir in the lower North Jiulong River which is within the jurisdiction of Zhangzhou City (Fig. 1). A coordinating mechanism can only be established at a higher hierarchy level rather than between the cities themselves (Xiamen and Zhangzhou). Fujian provincial government initiated the Jiulong River Watershed Program (JRWP) in 1999 to address the key environmental and resource problems at the watershed scale. The key coordination mechanism of the JRWP is the Joint Commission Office chaired by the deputy secretary general of the provincial government with members from sector chiefs of related provincial government agencies and deputy mayors of three involved cities (Longyan, Zhangzhou and Xiamen). Although the JRWP has succeeded in establishing a high-level coordinating mechanism, innovative eco-compensation system and strict binding mechanisms, it has not yet fully achieved its desired objectives. In a previous analysis, we concluded that the ineffectiveness of JRWP could be attributed to the following problems. (1) Flaws in the program design, including a lack of technical details necessary for watershed planning and implementation, inadequate coordination of components of the plans, limited authority and resources of the lead agency (Provincial Environmental Protection Bureau, PEPB), inadequate financial mechanisms (watershed ecological compensation, transfer payments), and lack of an integrated watershed policy. (2) China socioeconomic and political issues, including economic primacy and resulting “GDP first” incentives, as well as fiscal difficulties resulting from the current financial policy together with a centralized political structure, have led to weak political willingness and financial capacity of local governments in watershed management (Peng et al., 2013).

A number of policies, regulations and water quality standards have been issued by national, provincial and local governments, but the majority of them reflect single-sector concerns (Table 2). The Chinese expression “nine dragons control water” reflects the fact that there are many agencies (sectors) which have been involved in water resource allocation and environmental management. The traditional fragmented management approach means that responsibility and authority are not clearly defined, and conflicts in water resource allocation and water environmental protection exist among administrative sectors (e.g., agriculture, industry, hydropower generation, drinking water supply) and geographical units (upstream versus downstream). The complicated coordinating scheme somewhat impedes transboundary and cross-sector integrated management, largely due to the lack of holistic planning and integrative management measures.

From an institutional perspective, a holistic and comprehensive approach in transboundary and cross-sector integrated management can be enabled through the following measures. (1) Enacting water resources management by an integration of policies, regulations and standards for surface water, ground water, water transfer and distribution. The current policy conflicts should be mitigated by improving consistency and coordination between administrative sectors. (2) Granting the Joint Commission of Watershed Program sufficient authority and human and financial resources to conduct holistic planning, implementation, evaluation and adaptive management. (3) Developing an ecological compensation policy that is conditional on ecological restoration (Fang and Elliott, 2016). (4) Improving the incentive mechanism (cross-border compensation and transfer payments). Since 2003, Xiamen and Fujian province provided financial compensation to less developed upstream regions (Longyan and Zhangzhou) for their management practices. Environmental responsibility should be well-defined based on targeted water quality criterion and allowable TMDLs across administrative borders. Such an environmental responsibility mechanism could be introduced into the current “river chief system”, which is an innovative environmental supervisory mechanism requiring the mayor of the municipality to be responsible for pollution abatement in the river reach of each administrative region. (5) Encouraging stakeholders to become more involved in watershed plan development and implementation. Apart from “top-down” decision-making process led by government agencies, a “bottom-up” approach is also important in adaptive planning (Butler et al., 2015). Multiple-stakeholder (large and small firms, local residents and scientific communities) involvement is the key to form a common vision, goals, objectives, and scientific inputs to integrated water resource management. In addition, the recently proposed concept of water-energy-food nexus, with the significance of water-energy-food linkages and their direct impacts on water allocation, is a potentially appropriate approach to enhance transboundary and cross-sector management (Keskinen et al., 2016; Strasser et al., 2016).

4. Conclusions

Coastal cities like Xiamen experience many threats under global climate change and increased human activities. Strong seasonal and inter-annual rainfall fluctuations have adverse impacts on water resource availability in the Jiulong River watershed. Increasing floods and droughts in the past decades are the main expected impacts of climate change on water quality and quantity. Increased eutrophication and HABs threaten water quality in Jiangdong reservoir from where raw water is transferred to coastal cities for further treatment. We also identified other potential threats on water quality and human health, including excessive dissolved manganese (Mn), emerging waterborne pathogens (EWPs) and antibiotic resistance genes (ARGs), emerging organic contaminants and new pesticides, most of which are beyond the routine monitoring program and have not been addressed by the current national policies for water quality management.

A conceptual framework for “source-to-tap” integrated water management was proposed in an attempt to secure a clean and safe water supply in coastal cities under human and climate perturbation. Long-term monitoring, holistic planning and adaptive management and actions to reduce nutrients (N and P) and other pollutants loading are essential to protect water sources. Adaptive measures to climate change should be considered to achieve these goals. The JRWIS has proven to be a science-based information system which can serve as an interactive platform for a variety of users to monitor and predict water quality. However, further efforts should be made to develop a robust, comprehensive, and fully coordinated surveillance system for monitoring water quality from water source to user tap. Given the complexity and site-specific characteristics of aquatic ecosystems and unpredicted socio-economic perturbation, development of an operational dynamic model and application of real-time monitoring technologies are urgently needed to provide scientific information that will support effective integrated water management.

Securing drinking water resources for coastal cities also face considerable institutional constraints given water flows and transfers across different municipal units (cities). The traditional fragmented management approach means that the responsibility and authority of each sector and administrative unit is not clearly defined. From an institutional perspective, the best opportunity to facilitate efficient transboundary and cross-sectoral management can be obtained by enacting integrated water policies, developing an ecological compensation policy that is conditional on ecological restoration, authorizing the management institution (the Joint Commission of Watershed Program), improving the incentive mechanism of cross-border compensation and transfer payments considering environmental responsibility, and encouraging multiple-stakeholder involvement.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2018.02.023.

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