Case Study 29

Securing the Drinking Water Supply for the Growing Population of Xiamen City, PR China

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Key Message

- Effective management of freshwater resources across local (subnational) administrative boundaries requires not only close cooperation and collaboration of concerned local governments and line agencies but also the support of academic and research institutions. Such institutions can provide needed scientific data and water quality monitoring information for appropriate public investments and interventions in terms of water supply policy and management measures.

- In securing continuous freshwater supply to meet the growing population demand, scientists in Xiamen collectively demonstrated their indispensable role in water resource management decisions.

Abstract

This case study is aimed at demonstrating an ongoing comprehensive and science-based water supply management initiative to determine the amount and quality of safe drinking water for the growing population of Xiamen City and other sub-urban areas. Also highlighted are the integrative approaches in water management of the Jiulong River system especially in coordinating the relevant cross-boundary municipalities, agencies, and users. The case study underscores the importance of science in assisting management decisions particularly in water quality monitoring, water safety and allocation across boundaries, as well as in information management. It also elaborates the need to improve the existing methodological approach to increase scientific reliability in prediction modeling. Lessons learned from water supply management initiatives are also presented.

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Background

Main issues of drinking water supply for coastal cities

Global population is set to increase dramatically within the next 30 years, up to a staggering 9.6 billion by 2050 (UN, 2013). With a great majority of the population residing in coastal cities, particularly in developing countries (Lutz and Samir, 2010), the demand for clean and safe drinking water supply would be a key challenge to sustaining the urban population. Most developed coastal cities lack freshwater resources largely due to relatively limited water catchment areas. In China, many cities have to rely on water supply from adjacent inland watersheds. Such a situation often gives rise to transboundary distributional challenges, affecting both quantity and quality of water.

Unregulated human settlements and economic activities within a watershed area are often found to degrade the quality of freshwater resources. Overfertilization of agriculture farms and discharges from animal and domestic wastes, which are often inadequately treated, lead to nutrient (mainly nitrogen [N] and phosphorus [P]) enrichment in receiving waters; often resulting in eutrophication and algal blooms. In addition, persistent organic pollutants (POPs), heavy metals, and other pollutants from both point and diffused sources, threaten water security for coastal city populations.

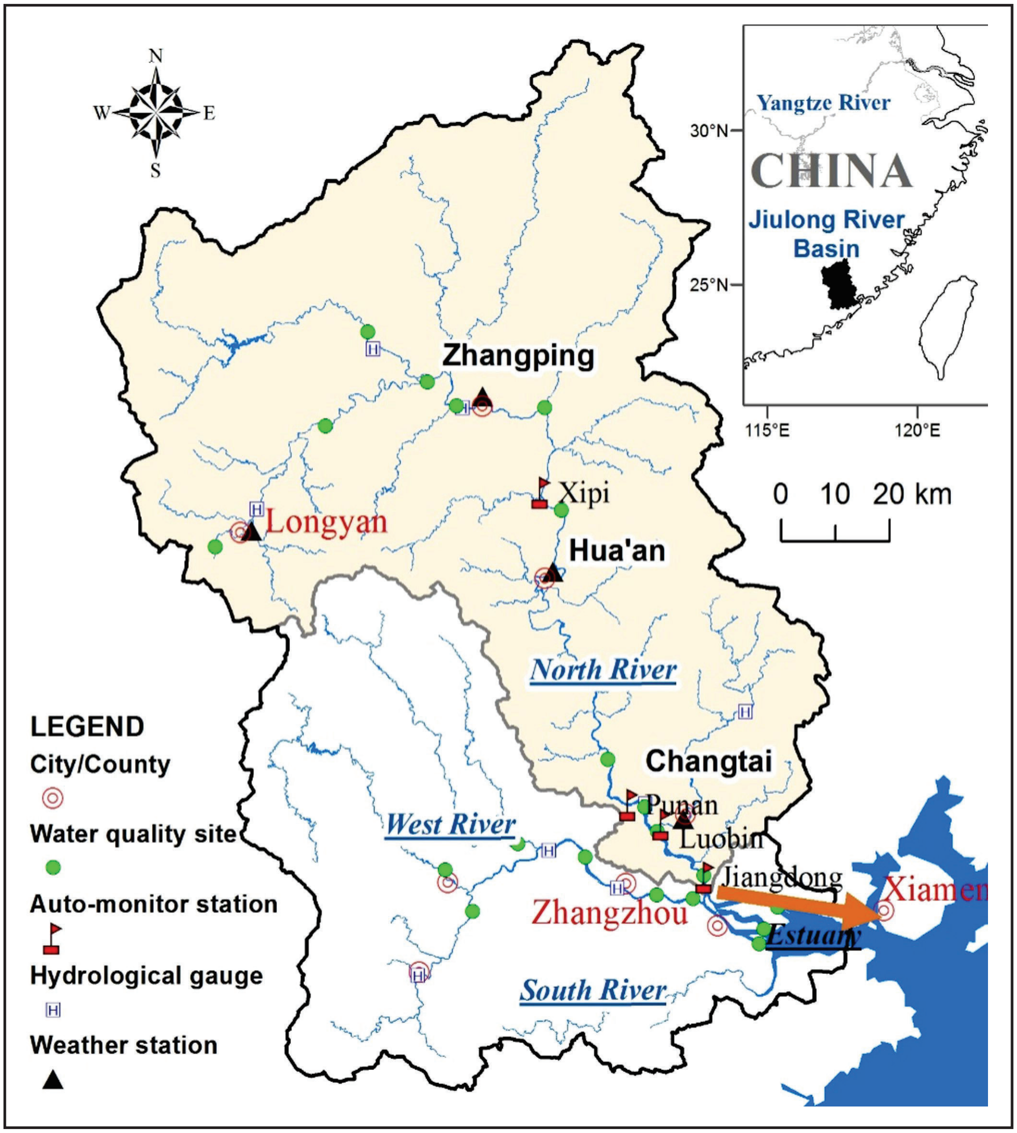
Furthermore, a large number of dams have been constructed worldwide (China included) along river channels for hydropower generation, flood control, irrigation, and to a certain extent, for tourism development (Miao, et al., 2015). However, intensive dam construction can drastically change river hydrology and biogeochemistry and thus create negative impacts on the river ecosystems (Kelly, 2001; Vörömarty, et al., 2003). One of the most direct consequences for cities located downstream is the reduction of freshwater supplies from the upper reaches of major rivers.

In the context of increased human and climatic perturbations, freshwater supply—or the lack thereof—is already an urgent coastal management challenge. The lack of scientific understanding of pollutant emission and transport, limited investment in pollution mitigation, and inadequate monitoring of water quality continues to hinder the sustainable management of water resources (Jia, et al., 2010). The lack of comprehensive data on watershed-river-reservoir and on quantity and quality of receiving waters in urban coastal areas also severely affects the effectiveness of the design and implementation of water resources management programs. For rapidly developed coastal cities like Xiamen, availability of appropriate scientific information and management tools was essential to address freshwater resource management concerns, especially those across administrative boundaries.

Geophysical characteristics of Xiamen and water supply challenges

Xiamen, historically known as Amoy, is a major city on the southeast (Taiwan Strait) coast of Fujian province, the People's Republic of China. Xiamen has an area of 1,699 km^2 and a population of 3.81 million by the end of 2014 (XBOS, 2015). Xiamen comprises Xiamen Island, Gulangyu Island, and part of the rugged mainland coastal region from the

Figure 1. **Jiulong River Basin showing various monitoring sites. Arrow shows water transfer from source (Jiangdong reservoir in the southern part of North River) to Xiamen City.**



left bank of the Jiulong River in the west to the islands of Xiang'an in the northeast. It borders Quanzhou City to the north and Zhangzhou City to the west. The city previously centered on Xiamen Island but expanded to include four other districts: Haicang, Jimei, Tong'an, and Xiang'an on the mainland.

Xiamen has a monsoonal subtropical climate, characterized by long, hot, and humid summers and short, mild, and dry winters. Typhoons normally occur in late summer and early autumn. The annual rainfall is 1,350 mm. However, rapid urbanization, population growth, and climate change in recent years were posing water supply challenges to meeting increasing demand for safe and clean drinking water. Total water supply increased sharply from 295 to 419 million m^3 in 2009–2014 (XBOS, 2010, 2015). Furthermore, the majority of water supply was from the Jiulong River rather than a local source. The Jiulong River is the main river system running through several districts before entering Xiamen coastal seas. It provides Xiamen City 168 million m^3 of water per year through a transport tunnel that was constructed in 1972 (Figure 1), accounting for over 80% of the total water supply. Other major water sources for suburban area are Tingxi reservoir and Bantou reservoir located north of Xiamen Island.

Three tributaries (North River, West River, and South River) discharge water into Xiamen Bay. The North Jiulong River is the main tributary with a drainage area of 9,570 km^2 and a mean annual discharge of 8.23×10^9 m^3. The length of the main tributary to the water intake point at Jiangdong is about 274 km. Land use includes 78% forest (mostly secondary), 16% arable land, 3% urban and residential land, 2% water, and 1% bare or grassland (2007 Landsat Thematic Mapper image). Over 100 hydropower dams were constructed within the Jiulong River Watershed (Wang, et al., 2010).

Four cities/counties (Longyan City, Zhangping County, Hua'an County, and Changtai County) and a part of Zhangzhou City are located in the watershed area. The total population is 1.5 million, 43% of whom live in the urban areas. Longyan City, which is located in the upstream area, recently experienced a rapid increase in animal farming activities. The other counties are predominantly covered with agricultural and forest land, and relatively of low population with the exception of the more densely populated Changtai County and Zhangzhou City in the downstream area.

Current scientific knowledge and management implications

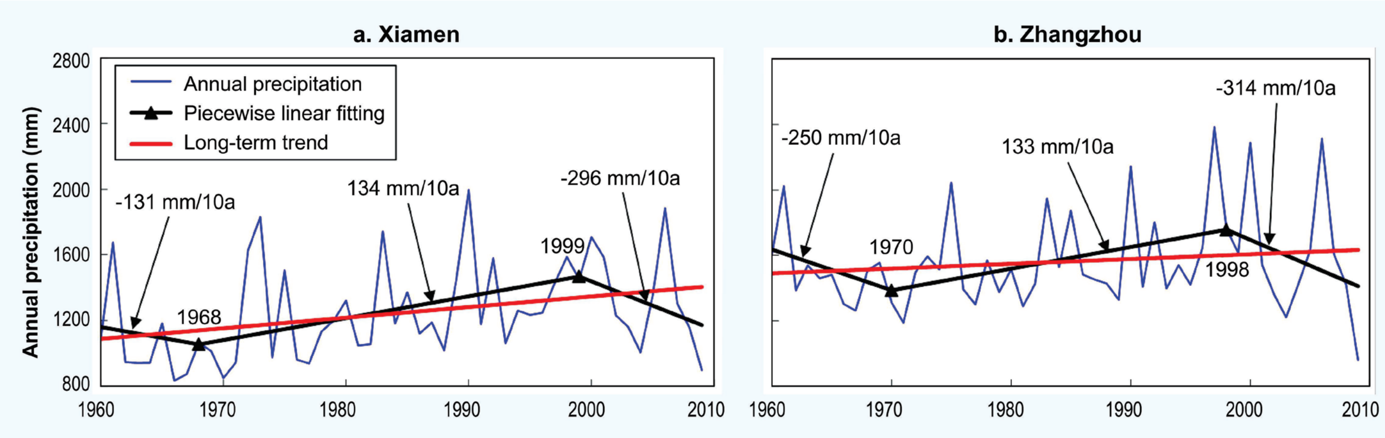
Climate change and its impact on water resource availability

Based on a 50-year (1960–2009) daily dataset of temperature and precipitation at two national meteorological stations (Xiamen and Zhangzhou), the characteristics and long-term trends of climate change were analyzed using the Piecewise Linear Fitting Model (PLFM) (Tomé and Miranda, 2004). The results showed that the annual mean air temperature at Xiamen and Zhangzhou generally increased from 1960 to 2009 by 0.225°C and 1.475°C, respectively. The "warm winter" phenomenon was especially evident in the last 30 years. Precipitation at Xiamen and Zhangzhou showed overall increases during summer. However, precipitation decreased significantly by 20% in the last decade (Figure 2). The occurrence and intensity of extreme climate events such as hot day (>99%), storm day (daily rainfall > 50 mm), and drought day (without any rainfall) significantly increased. The climate in these two areas showed a general trend of "warm and dry" in winter, but with increasing rainstorms in the summer. Given the close link between climate and hydrology, the climate change trends were likely to pose adverse impacts on water resource availability to Xiamen City due to the increased seasonal and interannual variation. Such analysis provided a basis for developing adaptive management strategies in response to climate change in the region.

Nutrient enrichment and eutrophication (algal bloom) threaten water quality

Increasing human activities and external nutrient loads over the past 30 years were the main causes of water degradation and

Figure 2. Precipitation trends in Xiamen and Zhangzhou (1960–2009).



eutrophication (Chen and Hong, 2012; Chen, et al., 2013). A significant decline of N:P ratio was observed in both river and estuarine waters since the 1990s due to relatively high P loadings, a consequence of waste discharges from the proliferating husbandry of livestock and the application of excessive phosphate fertilizers to cash crops. Continued nutrient enrichment and decline of N:P ratio changed the nutrient stoichiometry and supply ratio in waters, in turn increasing the risk of nutrient-enhanced algal blooms. According to current findings on eutrophication and harmful algal bloom processes, a dual nutrient (N and P) management strategy was necessary to manage the water quality in the Xiamen Bay-Jiulong River Basin. Focus needed to be on reducing animal wastes in the north Jiulong tributary and mitigating overfertilization in the west Jiulong tributary (Chen, et al., 2013).

Three algal bloom events were monitored in the north Jiulong River since 2009, which threatened Xiamen's drinking water supply. The main reason for the algal blooms was the excessive nutrient loading from human and animal wastes, and agricultural runoff accumulated in dam reservoirs with limited removal (Li, et al., 2011; Chen et al., 2014). However, phytoplankton communities change seasonally, associated with river discharge, irradiance, water temperature, and nutrient concentrations (Tian, et al., 2014). The local government was informed by scientists of the perils of nutrient pollution. A number of management initiatives were implemented since the late 1990s with limited success due to the lack of holistic planning and integrative management measures given the complicated socioeconomic and political situation in PR China (Peng, et al., 2013).

Approach and Methodology

Developing a watershed water information system

A water security program was initiated in 2009 and completed in June 2012. It addressed key drinking water issues, including contamination at source. Funded by the Xiamen government, the Jiulong River Watershed Information System (JRWIS) was developed by Xiamen University in collaboration with Fujian Strong Software Company and Xiamen Environmental Monitoring Central Station.

The JRWIS included a multisource database (meteorological data from 10 stations, hydrological data from 7 stations, water quality data from 11 provincial control stations, and 4 automatic water quality stations) based on SQL2005 and ArcSDE, using Web Geographic Information System, remote sensing, and GPS technology. A coupled model (SWAT+EFDC+WASP) was also integrated into JRWIS to simulate river discharge and water quality (e.g., ammonium, total nitrogen [TN], total phosphorus [TP], dissolved organic P, and chemical oxygen demand [COD]). The spatial database included administrative maps, remote imagery, digital elevation model (DEM), soil map, and land use/cover. Monthly water quality monitoring data was easily imported, while in-situ sensor data from buoys and automatic monitoring stations were transferred and imported to the database in real time. Discharge data (flow rate) released by the China Ministry of Water Resources and rainfall/temperature/wind data released by the China Weather Bureau were also linked to JRWIS. In this setup, the database of JRWIS could be easily updated.

The JRWIS provided various function modules, including data acquisition, data management and editing, data query and plotting, map query, water quality assessment, early warning of water quality, and model simulation. The JRWIS was provided with a user-friendly interface and visualization screen, which made it a useful tool for improving water resource management.

Results

The JRWIS was installed in April 2011 and operated and managed by the Xiamen Environmental Information Center. It was a Web-GIS system that enables users to log in and use the system anywhere and anytime provided that there were available Internet access and computer services. The system was also accessible to other related agencies such as the North River Water Transfer Office, the Xiamen Water Affairs Group, and environmental monitoring stations in upstream cities (e.g., Longyan, Zhangzhou), as well as the provincial Environmental Monitoring Central Station in Fuzhou City.

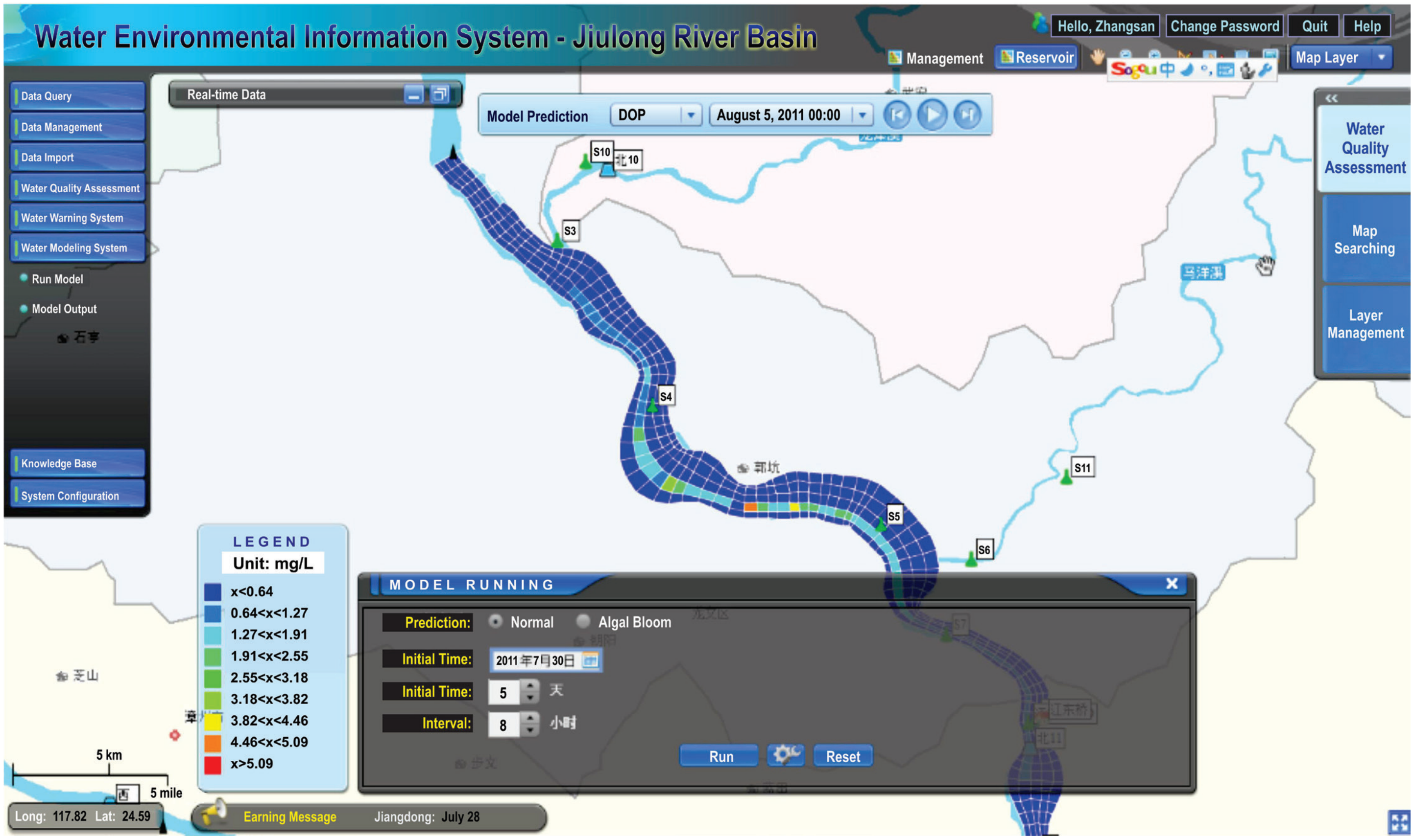
The JRWIS was the first effort in China to develop a robust, comprehensive, and fully coordinated surveillance and monitoring system for water quality. The main applications of JRWIS included:

1. Water quality parameters (e.g., dissolved oxygen, pH, nutrients, chemical oxygen demand, and chlorophyll) could be monitored through data query and plotted. Users easily assessed the water quality situation and spatial and temporal variations. Real-time data over the previous 24 hours were shown at the touch of the screen.

2. Timely and accurately prepared evaluation reports of water quality, including monthly, seasonal, and annual variation could be accessed. National or local water quality criteria were also incorporated, and an evaluation could be made based on various templates. According to users from the Xiamen Environmental Monitoring Center Station (XEMCS), JRWIS was much better in terms of data accuracy, time, and efficiency compared to traditional manual approaches.

3. An unhealthy water quality could be detected before reaching the distribution system. This enabled the concerned agency to alert the public and undertake appropriate remedial measures. A case in point was an incident detected by scientists from XEMCS using the information from JRWIS. They noted that values of dissolved

Figure 3. **Model output shown on the JRWIS. A coupled model (SWAT+EFDC+WASP) was integrated into JRWIS to predict water quality.** (This modeling work was completed by Dr. J. Huang of Xiamen University.)



oxygen (DO), pH, and chlorophyll from an automatic monitoring station (Jiangdong reservoir) kept rising from the afternoon of 13 March 2013 until the next morning. Recorded data showed that DO had gone up to 21.22 mg/L, pH rose to 9.96, and chlorophyll content reached 119.6 mg/m^3 (a typical set of conditions for a possible algal bloom). The scientists checked the data from three other automatic monitoring stations (Xipi, Punan, and Luobin) in the upper reaches and found that a nearby station (Luobin, located in a tributary close to Jiangdong) also had a high chlorophyll value of 55 mg/m^3. This important information was delivered to the North River Transfer Office and the Xiamen Water Affairs Group. The manager of the North River Transfer Office decided to increase dam outflow to mitigate an algal bloom. A total of 3 million m^3 of water was discharged on 14 March (1900-2100H), and another 520,000 m^3 on 15 March (1830–1900H). Following these interventions, water quality recovered, meeting the national water criteria. The coupled model (SWAT+EFDC+WASP) simulated river runoff and water quality to verify and assist management in deciding the release of dam water (Figure 3).

Lessons Learned

Given the complex ecological processes occurring in each aquatic ecosystem and the diverse socioeconomic conditions, interdisciplinary research and model prediction have become essential to provide scientific information that will be useful for effective water management. The JRWIS initiative was the first step in the right direction.

The JRWIS was proven to be a useful science-based information system which could serve as an interactive platform available for a variety of users to monitor and manage water quality. It was flexible in configuration so that users could add monitoring station(s) and data, when needed. However, accurate and highly precise measurements, expanded monitoring coverage coupled with high precision modeling were still needed to strengthen more effective assessments.

At present, automatic measurement of water quality is limited to (a) a few monitoring stations (only four stations in such a large catchment); (b) a few parameters (TN, TP, ammonium, COD, etc.); and (c) limited monitoring frequency (every four hours for TN and TP). Current national criteria for water quality do not cover other important contaminants (e.g., pathogenic microorganisms, emerging pesticides, veterinary drugs, and other POPs) that also threaten water quality and human health. There is a lack of precise bathymetry data which are necessary for developing a high-precision hydrodynamic model. In addition, several key coefficients for model input parameters have not been validated because of limited biogeochemical observations. Hence, further work is necessary to ensure that predictive models can contribute more effectively to management decisions. The JRWIS should be further expanded from North River to include other major water sources like the Tingxi, Bantou, and Lianhua Reservoirs in Northern Xiamen. With a growing database, the information system will be further enriched.

The initiative of the Xiamen City government reflected much needed cross-boundary cooperation and collaboration with concerned local governments and line agencies as well as expertise from academic and scientific institutions in developing the database and information system. These efforts helped in the administration of appropriate management measures. The local government has good experience in application of a holistic and integrative management approach in addressing coastal management challenges and the capacity to continue building the information system.

This case study also demonstrated a working model for scientists to contribute to the process of policy and management decisionmaking by providing reliable information and sound scientific advice.

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