Water Resources Sustainability in the East River in South China Using Water Rights Analysis Package

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EXTENDED ABSTRACT

The East River in southern China is the vital water source for the cities outside, such as Hong Kong, Shenzhen, and inside, such as Heyuan, Huizhou and Dongguan, of the region. For studying the regional water resources sustainability, it is necessary to evaluate the balance between the water supply capacity from the River and the water demand potential from those cities. The understanding of water resources sustainability would benefit the River basin management and the regional socio-economic sustainable development.

This study investigates the water supply capacity of the East River in according to the projected water demands in various water consumption sectors in 2010, with water rights priorities assigned to different water users inside and outside of the East River basin. With the application of Water Rights Analysis Package (WRAP) and the streamflow conditions in 1963 that was the driest year in the records since 1951, the water resources security of the River is analyzed. Meanwhile, for evaluating the attenuation of the water shortage, the effects of releasing water from the Xinfengjiang Reservoir, which is the largest reservoir in the basin, is studied.

The simulation results reveal that the water shortage can be significantly reduced with adjusting the operation of the Xinfengjiang Reservoir. However, the storage of the reservoir at the beginning of the drought is of great importance. Only with normal full storage, all the projected 2010 water demands from various water users in the region can be satisfied. Figure 1 shows the results of releasing water from Xinfengjiang Reservoir, and the simulation is started at the beginning of 1962. For reducing the water shortage, using the projected 2010 water demand inside and outside of the East River basin, the Reservoir water storage may reach its inactive capacity.

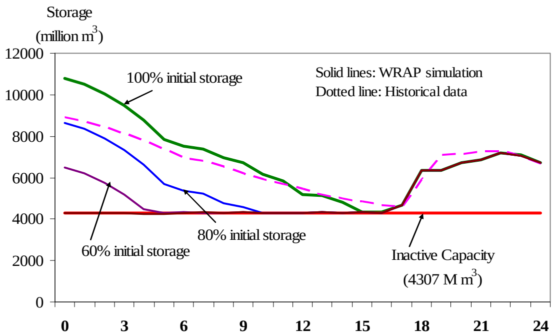


Figure 1. Variation of Xinfengjiang Reservoir storage along time for different initial water storage in the reservoir.

1. INTRODUCTION

The East River is located in the Guangdong Province in southern China (Figure 2). It is one of the four major river systems in the Pearl River Basin. The length of its mainstem is 562 km and the area of the River Basin is 35,340 km^2 (Chen and Wu 2007).

Water resources in the East River are multifunctional. The river serves as the major water supply to the cities and regions both inside (Heyuan, Huizhou and Dongguan) and outside (Hong Kong, Shenzhen and Guangzhou) of the basin. Also its water serves for the purposes of navigation, ecology and environment in the river. Moreover, the reservoirs in the basin are functioned for flood control and hydropower generation. Therefore, integrated water resources management in the East River is vital and necessary.

In addition, due to the rapid economic growth and socio-development of the region since the 1980s, the water demand has being increasing drastically. Meanwhile the increasing water pollution tends to decrease the available water resources. The water shortage problem might be a major crisis affecting the whole region especially during severe drought periods in the near future.

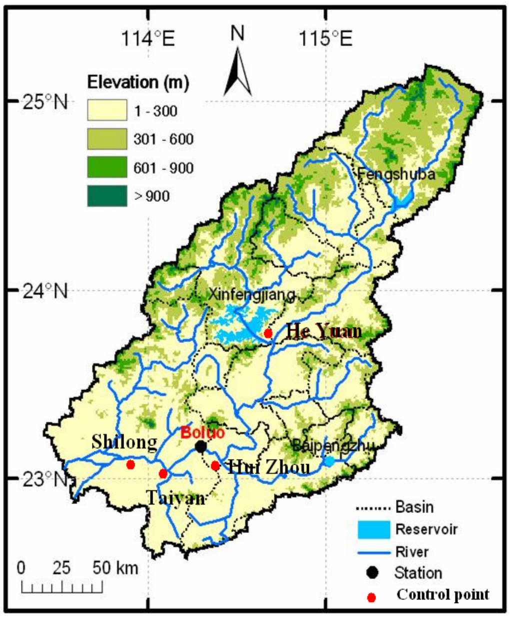


Figure 2. The East River Basin (adapted from Chen and Wu 2007).

In the East River basin, the challenges of water resources management include the balance between water demand and supply capacity, and the operation of water resources facilities for dealing with possible water pollutions and water shortage besides for flood control. However, studies of the water resources of the East River with a quantitative basis are few. In this study, a river/reservoir system management model, the Water Rights Analysis Package (WRAP) (Wurbs 2004) is used to simulate the management of water resources of the East River basin. This may benefit the water basin management in future.

2. BRIEFING OF THE WRAP MODEL

The WRAP was developed by Ralph A. Wurbs and his colleagues in the Department of Civil Engineering in the Texas A&M University in the United States in the mid-1980s. It is part of the Texas Water Availability Modeling (WAM) System implemented and maintained by the Texas Commission on Environmental Quality (TCEQ), and the package has been used to simulate the management of the water resources of the river basins in Texas (Wurbs 2005). Since then, the WRAP continues to evolve and the June 2006 version is adopted in this study.

The WRAP simulates management of the water resources of river basins under a **priority-based** water allocation system (Wurbs 2006). In the WRAP, water management and use requirements, policies, practices and facilities are expressed in terms of **water rights**. In general, a water right in WRAP represents a water user, which refers to either a water diversion target, streamflow requirement, storage target of reservoirs or hydropower generation target. The availability of water resources are simulated using the basin hydrology information represented by sets of historical naturalized monthly streamflow sequences.

A fundamental concept used in the WRAP simulation is that the available streamflow is allocated to different water rights in turn in the priority order. This is designed for the conditions in Texas, where the legal rights to the use of streamflow are generally based on the doctrine of prior appropriation. Senior water rights are protected from having their supplies diminished by later water users (Wurbs 2004).

The WRAP model required the input of the following fundamental data:

Control Points: They are set to define the spatial connectivity of a river system. All water rights are associated with control points to specify their locations. At any single control point, the number of water rights is not limited.

Basin Hydrology: They include the naturalized streamflow and the net evaporation from reservoirs. Naturalized streamflow (in million m^3/month) represents sequences of past streamflows adjusted to represent a specified condition of river basin in the absence of any water management activities but with all other aspects of the river basin reflecting constant present conditions. Net evaporation is the difference between monthly evaporation depth and precipitation depth.

Water Rights: The most basic components of a water right are its control point, priority number and the target diversion, hydropower generation or streamflow requirement. However, the WRAP model also provides high flexibility for modelling complex system configurations and operations.

Reservoirs: The input defines the reservoir properties. They include the different storage capacities (dead, conservative and flood control) and storage-area curve. The net evaporation rate is used for determining the net water output from the reservoir surface.

In the WRAP simulation, all input data, including control points, natural streamflow, evaporation rate and water rights are read in by the programme *SIM*. The water rights are then arranged in priority order. Water allocation and management are modelled by accounting procedures within a water right priority loop. As each water right is considered in priority order, the following tasks are performed:

1. The monthly water diversion, streamflow requirements and hydropower generation is set according to the input value
2. The amount of water available to the water right from streamflow is determined based on the available streamflow, after the appropriation to more senior water rights considering its control point and all downstream control points.
3. Water use requirements are met subject to water availability following specified system operating rules. Water accounting computations are performed to determine the diversion, diversion shortage, end-of-month storage, and related quantities. Necessary releases are made from reservoirs.
4. The available streamflow is adjusted for the control point of the water right and all downstream control points to reflect the effects of the water right. Simulation results are recorded.
5. The programme moves to the next water right and repeat the above simulation process until the simulation for all water rights have been finished. The actual streamflow for all control points is calculated for the effects of water diversions and reservoir release.

The simulation algorithms of WRAP are summarized in Figure 3.

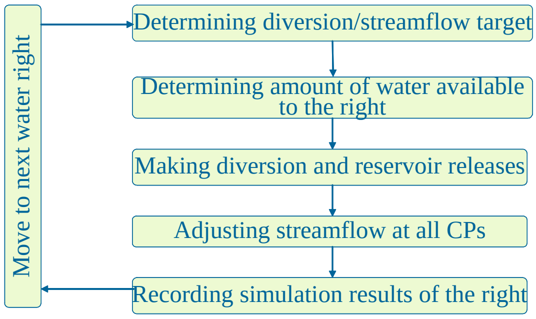


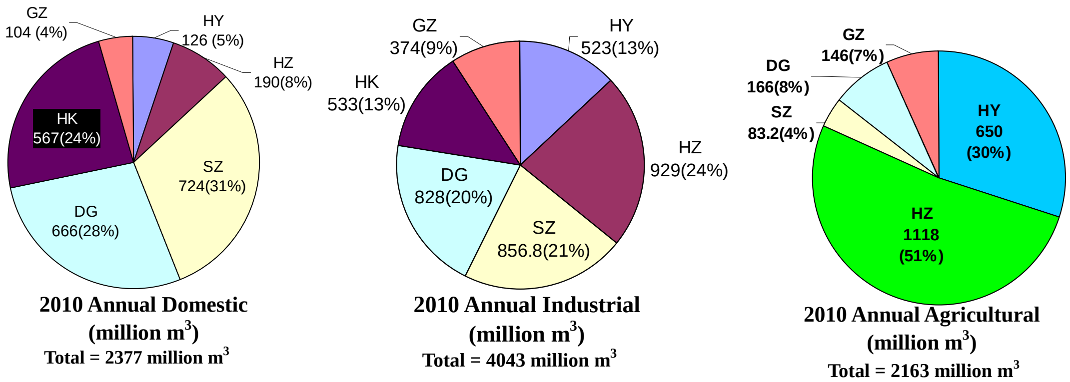
Figure 3. WRAP Simulation Structure.

Simulation results can be extremely voluminous if there are large number of water rights and a long hydrological period of the river. The auxiliary programme *TABLES* can rearrange these outputs and carry out further calculations to present the results in a more useful way. The common outputs are volume of water shortage for each water rights, reservoirs end of period storage and the regulated flows.

3. INPUTS TO THE WRAP MODEL

3.1. Control Points

In this study, control points are set to represent the reservoirs and locations of water intake in the East River. Four control points are set up to represent the six cities which extracts water from the River (Figure 2). Control points are set for Heyuan, Huizhou, Taiyuan and Shilong. Taiyuan is the pumping station where Hong Kong and Shenzhen extract water from the river. Shilong is assumed to be the place where Dongguan and Guangzhou extracting water from. Besides, Boulo is a streamflow gauging station along the River. Lastly, the control point XFJ represents the Xinfengjiang Reservoir where the largest reservoir in the basin is located.



Source: Shenzhen(SZ), Dongguan(DG), Heyuan(HY), Huizhou(HZ) – Sun Yat-sin University, GZ
Hong Kong (HK) – Water Supplied Department (WSD), the industrial part represents the water demands from other sections instead of industrial only.
Guangzhou (GZ) – 2004 Actual data from statistical yearbook

Figure 4. Diversion demands of cities considered and their percentage share.

3.2. Water Diversion Demand

The water consumption data of the region from 1997 to 2004 are collected and the changing trends of those water demands are analyzed. However, in this study, since the potential water consumption will be analyzed, only the projected 2010 water demand provided from Prof. XH Chen in the Sun Yat-Sen University (personal communication) is used (Figure 4). We have observed that the water consumption data from 1997 and 2004 and the projected 2010 data are comparable, and the result will be reported later. The water diversion demand for each cities considered is divided into three sectors according to the type of use: domestic, industrial and agricultural.

In this study, the domestic and industrial diversion demands are assumed to be constant in every month throughout a year. However, for Hong Kong the domestic and industrial (other) supply of Hong Kong is assumed to be evenly distributed among January to November, as the water supply normally temporarily stops in December every year for maintenance of the East River-Shenzhen Water Supply System (WSD 2007).

Variation of the monthly agricultural diversion water demand is significant due to the crop-growing pattern. Crop types in the East River Basin follow the annual tri-harvest-crop pattern, which are two growths of rice in summer and autumn and one growth of dry crop (e.g. wheat or tubers) in winter. The monthly agricultural water demand variation suggested by Guangdong Institution of Water Resources and Hydropower Science (1999) is used in the study.

Return flow ratios used in this study are based on the studies of Shiklomanov (2000) and GDRCG (1993a, b). Return flow is applicable to Heyuan, Huizhou and Dongguan only. The diverted water to Hong Kong and Shenzhen would not be returned since they are located outside the basin. For domestic and industrial diversions, 80% of the extracted water is considered to be return to the river, while for agriculture, 40% of the extracted flow is counted to be returned to the river.

3.3. Basic Required Streamflow

Certain streamflow discharge should be maintained in the river channel for serving different purposes, such as arresting sea water intrusion, navigation and environment.

Arresting sea water intrusion: A minimum flow of 150 m^3/s is required to arrest the saline water intrusion at the downstream of the East River (GDRCG 1993a, b, Wu *et al.* 2001); otherwise, water intake of Guangzhou will be affected by sea water intrusion.

Navigation: In the East River, a minimum water depth of a river channel is required for guaranteeing the safety of navigation. The required flow rate is estimated by the Manning's Equation with the channel width, slope, and required navigation depth. Then, the flow at Boluo and Shilong is about 210 m^3/s, and at Heyuan 150 m^3/s.

Environment: Water quality is important for the environment and river ecosystem. Therefore, a certain flow rate in the channel is required to dilute the pollutants and keep the water quality. In the East River, around 300 to 550 m^3/s of flow is required in different months of the year.

It is worth noting that the minimum streamflow requirements of the above three purposes are overlapped, and then the basic streamflow is the maximum of these three.

3.4. Naturalized Streamflow

To estimate the amount of streamflow available to the water diversion demands and analysis the effect of reservoir on the diversion rights and streamflow, naturalized streamflow data are needed for all control points. The Soil & Water Assessment Tool (SWAT) model is used to simulate the required data based on the recorded flow data at Boluo (Chen and Wu 2007). Daily streamflow data were simulated using the SWAT model and the monthly flow data are then aggregated. The naturalized flows are computed from historical streamflow data removing the influences of human activity, such as reservoirs, water diversions, return flows and other factors. The study of Chen and Wu (2007) has shown that the SWAT model can simulate the hydrologic condition of the East River basin with reasonable representation.

In this study, the 1963 streamflow data was the main focus for estimating the balance between water supply and demand. This is due to the fact that the year of 1963 is the driest year of the East River Basin in historical record of 1951 to 2000. Compare to the average annual runoff of the River (22.7 billion m^3), the 1963 annual runoff (8.4 billion m^3) is only 40% to it. Also, the 1963 wet season (April to September) streamflow is less than half the normal streamflow in the same period.

3.5. Xinfengjiang Reservoir

Xinfengjiang Reservoir is the largest reservoir in the East River Basin. Located in the tributary of Xinfeng River (Xinfengjiang), it contains 76% of total reservoir storage capacity in the East River basin. Its conservative capacity is 6.491 billion m^3. The Reservoir started its operation in 1959, serving for flood control and hydropower generation. The required inputs in the WRAP model are the storage capacity versus surface area Relationship and the net water loss over the reservoir water surface in depth.

4. APPLICATION OF THE MODEL

The 1963 streamflow condition is of particular interest in studying the drought effects on the water resources security.

4.1. Priority Order

In the WRAP model, a unique priority number must be specified for each water right. The smaller the priority number, the higher its priority. The water right with the higher priority can obtain the amount it demands when the streamflow is available.

According to the agreements of Hong Kong and Guangdong Province signed since 1960, the Guangdong Province is going to provide enough fresh water from the East River (WSD 2007). Therefore, in order for Hong Kong to obtain enough water, the priority of diverted water to Hong Kong will be set at the highest position in the study.

For the other cities, the priorities are set to be according to the river-flow direction, i.e. upstream cities have higher priorities than downstream cities. Sub-priorities for different demand sectors for each city are set according to the sequence: domestic, industrial then agricultural. The domestic demand has to be satisfied first as it consists of the basic drinking and sanitary need of human beings. According to the definition of damaging level of water shortage used by Chen *et al*. (2002), damage to the human livings would be severe if there is a 5% or more shortage on the domestic supply. On the other hand, industrial water users can tolerate less than 15% of shortage while agricultural users can tolerate up to 60% of shortage.

The prerequisite for any water right of Guangzhou to obtain water from the East River is that the minimum flow for arresting saline intrusion (150 m^3/s) at Shilong has to be satisfied. When the flow rate is less than this value, Guangzhou is not able to divert any water as the water intake of Guangzhou is affected by the high saline water.

4.2. Simulation Outputs

The two-year hydrologic period 1963-1964 is used for the simulation. Scenarios have been set up based on different initial storage of the Xinfengjiang Reservoir. Same priority order is used in all scenarios. Once there is shortage in any water rights (including the streamflow requirements), the reservoir will release the amount which the user is short of, provided that it has sufficient storage.

Table 1 shows the overall volume reliability with the influence of Xinfengjiang Reservoir's release for different water diversion users arranged in descending priority order. The overall volume

Table 1. Volume reliability R_V of water rights in different initial reservoir storage

	Region	Water Use Type	Annual Diversion Demand (M m^3)	**Volume Reliabilities R_v (%)**			
				Initial Storage (% of total dead + conservative)			
				100%	80%	60%	40% (Dead)
Descending Priority	HK	D	567	100	100	100	100
	HK	Other	533	100	100	100	100
	HY	D	126	100	100	100	97.38
	HY	I	523	100	100	100	88.80
	HY	A	650	100	100	100	84.45
	HZ	D	190	100	100	100	100
	HZ	I	929	100	100	100	100
	HZ	A	1118	100	100	100	98.11
	SZ	D	724	100	100	100	100
	SZ	I	857	100	100	100	98.19
	SZ	A	83.2	100	100	100	94.75
	DG	D	666	100	100	97.20	96.10
	DG	I	828	100	100	96.71	94.52
	DG	A	166	100	100	98.25	95.89
	GZ	D	104	100	79.17	70.83	58.33
	GZ	I	374	100	79.17	70.83	54.78
	GZ	A	146	100	79.75	71.00	59.90

Note: Water use type: D – Domestic, I – Industrial, A - Agricultural

reliability (R_V) for any water diversion user is defined as

$$R_V = \frac{\sum_{i=1}^{N} v_i}{\sum_{i=1}^{N} V_i} \times 100\% \, , \tag{1}$$

where v_i and V_i are the volume of water diverted and the diversion demand in month i, respectively (in million m^3). N is the total number of simulation month, here N = 24 for two years. For R_v less than 100% it means the water user have shortage. Figure 1 shows the variation in reservoir storage during the simulation period.

4.3. Discussions

The output of the WRAP model confirms that the storage in the Xinfengjiang reservoir is effective in eliminating the water shortage in the diversion demand and streamflow requirement to certain extent. However to attenuate all shortages for the whole drought period (from January of the first year to March of the second year), the conservative storage of the reservoir must be full at the beginning of the year, otherwise the downstream water users may suffer from different severities of shortage.

Historically the Xinfengjiang Reservoir mainly operated according to hydropower demand. A change in the function of the reservoir to sustain water supply during the dry period should be considered. However from the WRAP output, the rate of storage draw-down of the reservoir is much greater than the historical one. Therefore it is important to allocate the water resources in the reservoir to different water users in priority order.

5. CONCLUSION

In this study, the WRAP is used to assess the water supply reliability and water resources sustainability of the East River Basin. Different factors have been considered, like the water diversion demands, streamflow requirements and the Xinfengjiang Reservoir. The historical streamflow of 1963 drought is used to study the possible water shortage situation with the projected 2010 demand and the effect of water release from Xinfengjiang Reservoir using the WRAP.

It can be concluded that Xinfengjiang reservoir storage is sufficient to mitigate the water shortage problem among all water users (diversion and streamflow) for the whole drought period.

However, carefully planned management is required to top up the reservoir storage at the wet season with flood water.

For storage less than the normal full level, shortage in meeting the diversion demands and streamflow requirements is predicted to occur after the reservoir reaches dead storage. Therefore the release of the water has to be carefully controlled in order to provide sufficient for the higher priority water users, like domestic and industrial. For the other water users such as agriculture and navigation their available water has to be curtailed.

To conclude, water resources are vital to human, especially in the rapidly developing areas such as the East River Basin. The water resources in the Xinfengjiang Reservoir are very important for reducing the damages due to serious droughts.

6. ACKNOWLEDGMENT

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