An overview of water resources management of the Pearl River

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Abstract This paper summarizes the main features of water resources management of the Pearl River basin in southern China. A regulation over the basin through integrating various regions was first established for enhancing the water resources management. Based on such a regulation, a public policy frame was then constructed aiming for the harmony between human activities and nature. It is hoped that, as a result, the basin's socio-economic sustainable development could be achieved. In practice, the Pearl River Water Resources Commission (PRWRC), which is the basin regulatory authority, has been focusing on various aspects of regulating water basin and conserving water resources. These aspects include the development of innovative regulations of treating water, exploration of compensation schemes for water resources prevention, investigation of the hydraulic engineering project impacts on region relocation and ecology, and establishment of marketing schemes for sustainable application of water resources. It is expected that these regulating water resources aspects would result in enhancing public participation and negotiation in the Pearl River basin management. A case study is presented on the PRWRC's effort in coordinating water discharges from a number of reservoirs to protect the safe water supply in the Pearl River basin from seawater intrusion during the dry season.

Keywords Pearl River; PRWRC; seawater intrusion; water market; water resources

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Introduction

Each river system from its headwater to its mouth is an integrated system and should be treated as a whole for watershed management. A holistic approach called Watershed Protection Approach presented by USEPA (United States Environmental Protection Agency) integrates surface and ground water quality, water quantity and human health issues, and recognizes that environmental success will be achieved if goals and objectives are formulated in ecological rather than programmatic or administrative terms (Brady, 1996). Since watershed management is dedicated to solving watershed problems on a sustainable basis, integrated watershed management should be designed to achieve physical sustainability utilizing, to the greatest extent possible, public participation in an economically viable manner (Said *et al.*, 2006). The question then asked is: What kind of tools can be taken to implement watershed management? Integrated assessments of water supply and demand, sustainability assessments of proposed basin improvements, as well as state-of-the-art geographic information systems are critically important tools for basin management (Schmandt, 2006). Moreover, modelling is a critical tool in integrated assessment of water resource management whose success and adoption requires participation of stakeholders or various interest groups (Croke *et al.*, 2007). In addition, at the broadest level, the identification of regional patterns or organizational similarities is likely to facilitate the linkage among organizations to coordinate their actions at the (larger) river basin or ecosystem scale (Clark *et al.*, 2005).

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Among a whole basin, usually, an estuary is a river's mouth for delivering water from lands to oceans. Mostly, there is major water demand in estuary areas due to domestic, agricultural and industrial water consumptions in coastlines. In return, the discharge of industrial and municipal wastewater into estuaries is a critical cause of degrading regional environment. In addition, seawater intrusion into estuaries also decreases water quality, which will become more severe with high tides (Ghafouri and Parsa, 2003). Seawater intrusion, which was noted in all coastal areas in the 1940s (Poland *et al.*, 1959), is still a widespread problem. Moreover, the possible progressive rise of sea level due to global warming could cause seawater intrusion further inland, resulting in salinization of fresh groundwater (Momii *et al.*, 2005). Also, it may intrude into the stream water along river channels in the estuaries once the streamflow is too low to arrest the seawater intrusion, as found in the Pearl River Delta (PRD) (PRWRC and PRWRCA, 2004).

In evaluating the measures of controlling seawater intrusion (such as in lieu delivery of surface water to replace groundwater pumpage and injection into barrier walls), Reichard and Johnson (2005) stated that simulation-optimization methods, applied with adequate sensitivity tests, can provide useful quantitative guidance for controlling seawater intrusion into aquifers. Ghafouri and Parsa (2003) applied the finite element model into well-mixed estuaries to recognize the influential mechanisms and predict the impacts of seawater intrusion. However, practically, there is a lag of applying the integrated watershed management at a basin scale to combat the problem. This paper provides such a case of regulating water from a series of reservoirs in the Pearl River Basin (PRB) to resolve the seawater intrusion. Also, the frameworks and methods being used for integrated basin management through the Pearl River Water Resources Commission (PRWRC) in China are presented.

Background of the Pearl River Basin

The PRB (see Figure 1) lies between latitudes 21°31′N and 26°49′N and longitudes 102°14′E and 115°53′E, which is a major source of water supply in southern China for agriculture, hydropower generation, navigation, and drinking water. The basin consists of four parts – the West River basin, the North River basin, the East River basin and the PRD (Figure 1), accounting for 77.83%, 10.30%, 5.96% and 5.91% of the total basin area, respectively (Table 1). The structure of the Pearl River is converged of three main rivers, namely the West River, the North River and the East River, at the PRD, then flowing into the South China Sea through 8 river mouths, such as Hu Men, Jiao Men, Hongqi Men, Heng Men, Modao Men, Jiti Men, Hutiao Men, and Moya Men. The total

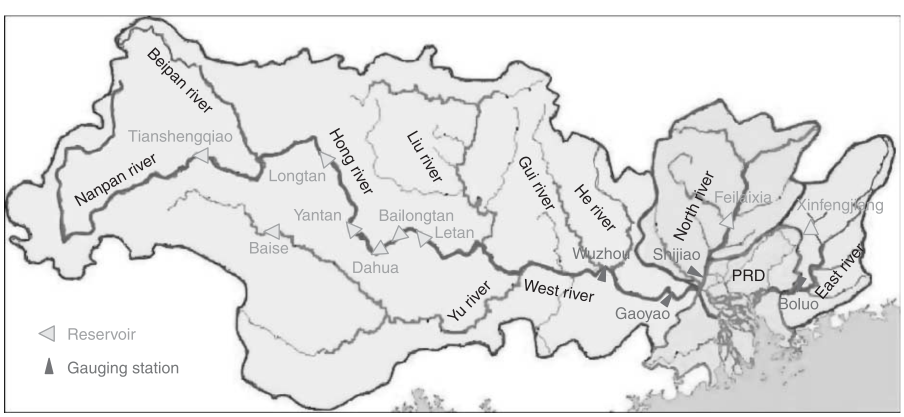

Figure 1 Pearl River Basin

Table 1 Areas and properties of the river subbasins in the Pearl River Basin (PRB)

Basins	Area (km^2)	Percentage accounting for the total basin area (%)	Length of the main reach (km)	Average slope of the main reach (%)
West River	353,120	77.83	2,075 (above Sixianjiao)	0.058
North River	46,710	10.30	468 (above Sixianjiao)	0.026
East River	27,040	5.96	520 (above Shilong)	0.0388
PRD	26,820	5.91	139	−0.0048
PRB	453,690	100	2,214	0.0453

drainage area of the basin, covering two countries, China and Vietnam, is about 453,690 km^2 and 97.44% (equivalent to 442,100 km^2) of which lies in China (Xue, 1995).

In southern China, the Pearl River flows through six provinces, i.e. Yunnan, Guizhou, Guangxi, Guangdong, Hunan, and Jiangxi. It is necessary for the PRWRC, which is responsible for the unified management of the whole basin, to allocate and regulate the water resources, and to coordinate among various groups of interests.

Characteristics of water resources in the Pearl River Basin

Precipitation and runoff

Figure 2 shows the monthly annual average precipitation and streamflow, respectively. Annual average streamflow in the Pearl River basin is $336 \times 10^9\,m^3$/yr, next to that of the Yangtze River in China, and the per capita water resource in the basin is 3,450 m^3/yr/capita, 1.6 times the averaged per capita water resource in China (Xue, 1995). However, the precipitation and runoff are distributed with high temporal and spatial heterogeneities. About 80% of annual precipitation and runoff occurred in the wet season from April to September and about 90.9% of annual runoff (equivalent to $294.1 \times 10^9\,m^3$/yr) passing through the PRD is from the outside of the PRD. It is obvious that the high heterogeneities of the precipitation and runoff may easily trigger regional floods and droughts.

Reservoirs

For the purposes of flood preventing, hydropower generation, irrigation, and so on, about 18,000 reservoirs with a combined storage capacity of 57 m^3, among which 53 belong to the category of large-scale reservoirs with a total storage capacity of $52 \times 10^9\,m^3$, were existed in the PRB by 1998. Table 2 listed the reservoirs with large and middle scale of storage capacity in the Pearl River basin. The operation of the reservoirs is conducive to relieving the heterogeneities of temporal distribution of water resources.

Main functions of the PRWRC

The PRWRC is the only authority for the basin with the responsibility of regulating water resources as a basin whole. The Commission was established in October 1979 and

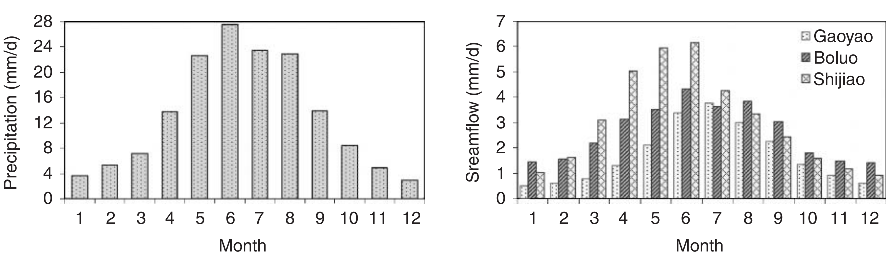

Figure 2 (a) Monthly annual average precipitation over the whole Pearl River basin, and (b) monthly annual average streamflow for the main three tributaries of the Pearl River. The gauge stations for the three tributaries are given in Figure 1

Table 2 List of reservoirs with large or middle scale of storage capacity in the PRB

Basins	Large scale			Middle scale			Total		
	No.	Total storage (10^9 m^3)	Flood control storage (10^9 m^3)	No.	Total storage (10^9 m^3)	Flood control storage (10^9 m^3)	No.	Total storage (10^9 m^3)	Flood control storage (10^9 m^3)
West River	24	14.649	5.708	212	5.953	1.847	236	20.602	7.555
North River	6	3.812	1.666	41	1.193	0.353	47	5.005	2.019
East River	4	17.240	4.207	35	0.804	0.166	39	18.044	4.373
PRD	5	1.450	0.351	60	1.601	0.517	65	3.051	0.868
PRB	39	37.151	11.932	348	9.551	2.883	387	46.702	14.815

is regulated by the Ministry of Water Resources of China. Due to the rapid socio-economic development of the basin since the early 1980s, the shortage of water resources has been constraining many parts of the region for further development, and the optimal allocation and sustainable utilization of water resources are playing a critical role in successful water resources management. In response, since then, the PRWRC has been continuously developing and revising the basin regulation schemes for meeting various demands and concerns in the basin management. The main functions conducted in the PRWRC are listed as follows:

1. *Setting up the Pearl River basin regulations*: to design the basin regulations according to China Water Law, to monitor the execution of water policies over the region.
2. *Planning the regional-related hydro-engineering projects*: to draft hydro-related basin engineering development plans, to organize prophase works of the projects, to prepare and implement the annual investment plans of engineering projects from the central government, and to censor technically regional large or middle scale hydro-engineering projects.
3. *Regulating the basin water resources*: to assess the basin water resources, to allocate and regulate water resources, to design the inter-provincial water resources allocation and drought mitigation plans, to survey feasibility study for large water-related projects, to advise water-saving projects, to coordinate the hydrologic works, and to publish the basin water resources bulletins.
4. *Conserving the water quality*: to partition the basin into different water-function regions, to assess the capacity of diluting and purifying the pollutants, to present the maximum amount of discharge for specific receiving water body, and to monitor the water quantity and quality for inter-provincial or important water bodies.
5. *Preventing flood and drought damages*: to prepare and implement the flood prevention and drought mitigation plans, to manage the region for holding flood water by exploring compensation schemes, to perform the feasibility study of important engineering projects for flood controlling and drought mitigation, and to organize and lead the general flood prevention office.
6. *Managing the basin water bodies*: to advise the regulation and development of the river channels, lakes, banks, estuaries and coastal areas, to supervise the construction of regional-scale hydro-engineering projects, and to ensure the security of the project operation.
7. *Regulating the water price and the hydropower price*: to manage the operation of the state-owned assets, and to present the water rice and the hydropower price.

The above PRWRC functions were developed mainly based on the principle of harmonious coexistence between human beings and nature. The next session will present an example about regulating a group of reservoirs for diverting water to combat seawater intrusion in the PRD coordinated by the Commission.

A case study of combating seawater intrusion in the PRD

To illustrate various aspects of the water resources management and to express the PRWRC functions of regulating the basin further, a case study related seawater intrusion along the river channels is given in the paper. In winter and dry season, from December to the next year February, seawater intrusion severely influences the people's living in the PRD, especially in cities of Zhuhai and Macao (see Figure 3). To solve the problem is a challenge to the PRWRC.

The situation of the seawater intrusion

In the PRD, due to the low flow caused by the climate variation (e.g. less precipitation in the dry seasons in 2003, 2004, and 2005), the seawater intrusion in the estuaries occurred frequently (see Figure 3). This impaired the freshwater quality of the river channels where are the main water source for the region.

Table 3 listed the streamflow near the outlets of the West River (Wuzhou), the North River (Shijiao) and the East River (Boluo) in September and October in 2004 and 2005. Table 3 also shows that in 2004 both the North River and the East River streamflow discharges were in 50 year drought, and the West River was in 20 year drought. In 2005, both the West River and the North River were in 10 to 20 year return period drought.

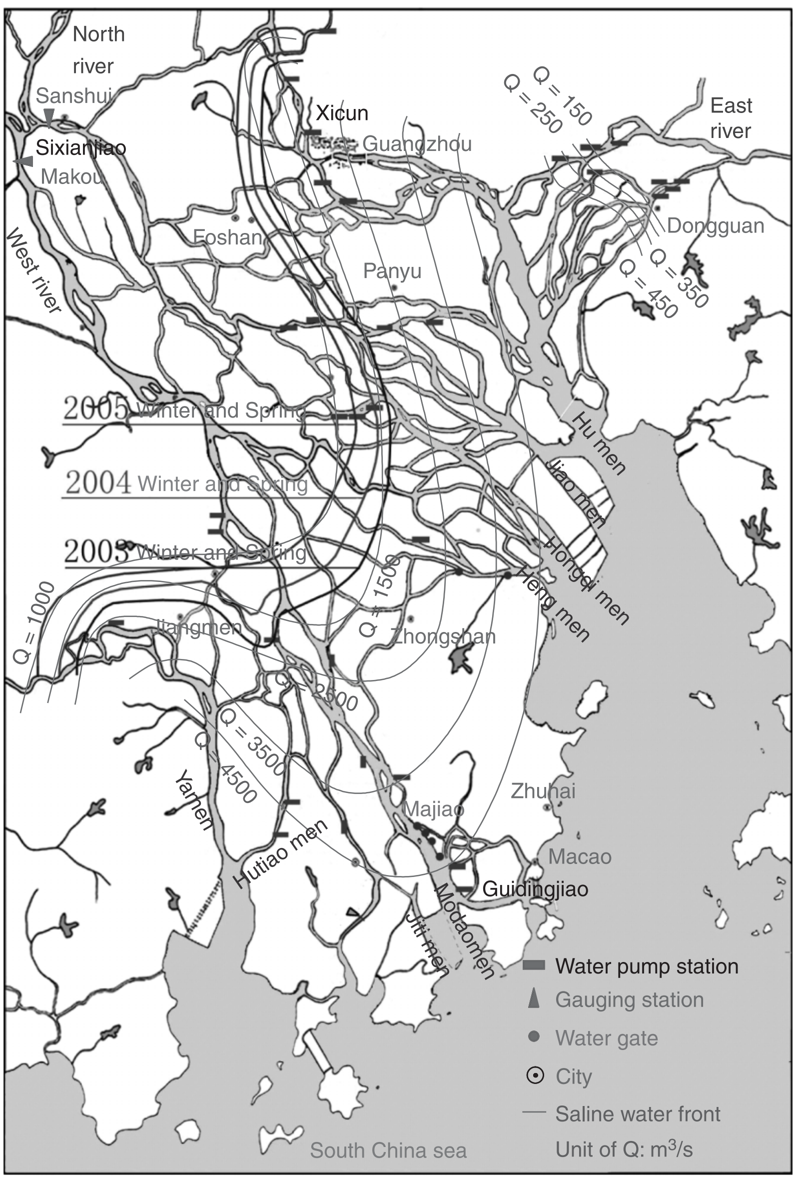

Figure 3 Fronts of saline water (chlorine content > 250 mg/L) under different amounts of streamflow (adopted from PRWRC and PRWRCA (2004))

Table 3 Streamflow in September and October at Wuzhou, Shijiao and Boluo and the category of return period of drought, and the number of days with chlorine content at water extraction point larger than 250 ppm

Year	Percentage of normal streamflow (%)						Return period dry year			The number of days (Chlorine content > 250 mg/L)
	September			October			West River	North River	East River	
	Wuzhou	Shijiao	Boluo	Wuzhou	Shijiao	Boluo				
2004	67	36	58	55	35	37	20	50	50	33
2005	47.3	47.2	–	62.8	46.8	–	10–20	10–20	–	123
2006	–	–	–	–	–	–	–	–	–	88

The lower streamflow aggravated the seawater intrusion in the PRD in 2004, 2005 and 2006. Table 3 also listed the number of days when chlorine content at some water extraction points larger than 250 ppm. So, the seawater intrusion would pose a direct threat to the safety of water supply from the river channels in the PRD. It is difficult for water treatment plant and impounding water body (e.g. reservoirs) to continue supplying water for more than one month.

For example, in Zhuhai and Macao, in winter 2004, it could not extract fresh water from the river channel for as long as 32 consecutive days due to the high chlorine content (from late December 2004 to 27 January 2005). On 11 January 2005, the seawater tide had intruded to water extraction point of the Guangzhou Xicun Water Treatment Plant (see Figure 3), the chlorine content at its extraction point reached 8,750 mg/L, which was 35 times the China's Drinking Water Standard of chlorine content ($\leq$250 mg/L). In winter 2005, the seawater intrusion hit the PRD about 15 days earlier than in 2004. Zhuhai and Macao could not extract fresh water from the river channel for as long as 48 consecutive days due to the high chlorine content (from 26 November 2005 to 15 January 2006).

It is reported that people who drink water with high chlorine content may get some diseases (e.g. diarrhea) and may induce high occurrence of disease on circulation system of body. Therefore, salinity problem has been regarded as another natural disaster apart from floods, droughts, and typhoons in the PRD (PRWRC and PRWRCA, 2004).

Solutions

Due to the increasingly serious salinity problem in the PRD, in November 2004, PRWRC and PRWRCA (Pearl River Water Resources Conservation Agency) jointly presented a report – *Analysis and Early-warning Report of Seawater Intrusion and Water Supply from Winter 2004 to Spring 2005 in the PRD* – based on substantial field work. The report displayed a detailed study on the hydrology literature and records of activities of sea tides, and communication with groups concerned (e.g. some large reservoirs' operators – electricity corporations, local government agencies, etc.). In the report, the area affected by salinity (i.e. the distance of seawater intrusion along the river channels) under different amounts of streamflow in the PRD was given through field survey and numerical study (see Figure 3). The larger the streamflow, the smaller area will be affected. For example, if the sum of the flowrate at Makou and Sanshui reaches 4,500 m^3/s, only Guidingjiao pumping station and Guangchang pumping station are influenced.

Therefore, a feasible scheme – generating artificial flood waves by unified water regulation from the reservoirs in the basin to combat the seawater intrusion – was proposed in the report. However, the problem is that the larger the streamflow needed, the larger amount of water diverted will be needed. Practically, the sum of the flowrate at Makou and Sanshui should be no less than 2,500 m^3/s, under which the saline water can be acceptable to such an extent that appropriate fresh water can be extracted in the most affected regions.

Hence, following the preliminary scheme, for the first time in the PRB, water diversion from a group of reservoirs to arrest seawater intrusion was executed in January 2005 after the PRWRC negotiated and coordinated among different groups. Due to the lack of relevant experience, the scheme was adjusted during the water diversion. In addition, effective supervision on the execution of the water regulation plan from the reservoirs was also conducted by the PRWRC.

The actual and optimal processes of water diversion from reservoirs both in 2005 and 2006 are listed in the Table 4. From the table, it can be found that about 843 million m^3 water had been diverted from the reservoirs in the West River basin and the North River

Table 4 Description of water diversion for combating the seawater intrusion in 2005 and 2006

Tributary	Year / Reservoir[@]	2005 Time period	2005 Flow rate required (m^3/s)	2005 Amount ($10^6\,m^3$)	2006 Time period	2006 Flow rate required (m^3/s)	2006 Amount ($10^6\,m^3$)
West River	Tianshengqiao	8:00 January 17–8:00 February 1	≥560	465	–	–	200
	Yantan	8:00 January 18–8:00 January 24	≤inflow[+]	220	8:00 January 10–20:00 January 16	≈1350	250
		8:00 January 24–8:00 January 31	≥1700				
	Dahua & Bailong	12:00 January 24–20:00 January 31	≥1900	–	20:00 January 10–8:00 January 17	≈1350	–
	Letan	8:00 January 25–20:00 January 28	≥1950	–	8:00 January 11–20:00 January 17	≈1400	–
	Baise	–	–	–	14:00 January 10–8:00 January 15	≥140	50
	Reservoirs in the Hejiang River	–	–	–	8:00 January 15–8:00 January 17	≈300	50
					After 8:00 January 17	≈150	
North River	Feilaixia	20:00 January 27–20:00 January 30	≥550	158	–	–	–
		20:00 January 30–20:00 February 2	≥250		–	–	–
		20:00 February 2–20:00 February 4	≥450		–	–	–
Total	–	–	–	843	–	–	550
Days ($Q^{\#} \geq 2500\,m^3$/s)		8 days (January 29–February 5)			6 days (January 16–January 21)		

[@]The reservoirs listed in the table can be found in Figure 1;[+]for temporarily storing the extra release from Tianshengqiao reservoir; [#]Q refers to the sum of the flowrate at Makou and Sanshui basin during 19 days (from 17 January to 4 February 2005). In 2006, about 550 million m^3 water had been diverted from those reservoirs in the West River basin during 8 days (from 10 January to 17 January 2006).

Effects of combating the seawater intrusion

Freshwater extraction. During the water diversion from the reservoirs, the flowrate in the PRD increased for 14 days (from 27 January to 9 February) in 2005. The sum of the flowrate at Makou and Sanshui (see Figure 3) larger than 2,500 m^3/s lasted 8 days (see Table 4), with the maximum flowrate of 3,380 m^3/s occurring on January 31 and about 2×10^9 m^3 fresh water entering the PRD. During this period, the cities in the PRD such as Zhongshan, Guangzhou, Zhuhai, and Macao extracted about 54.11 million m^3 of fresh water (see Table 5). Additionally, through controlling the gates at the river channel between Zhuhai and Macao, about 15 million m^3 of fresh water were stored in the reach.

Similarly, in 2006, the flowrate in the PRD increased for 11 days (from 14 January to 24 January), and the sum of the flowrate at Makou and Sanshui larger than 2,500 m^3/s lasted 6 days. The maximum flowrate of 2,810 m^3/s occurred on January 31 in the PRD. During the period, the cities in the PRD extracted about 22.3 million m^3 fresh water (see Table 5). Through controlling the gates at the river channel between Zhuhai and Macao, about 19 million m^3 of fresh water were stored in the reach.

Water quality. Due to the artificial flood wave created by the water diversion both in 2005 and 2006, the quality of the reach water in the PRD was improved considerably. For example, water quality of the main reaches in the PRD changed from VI-V before the water diversion to II-III after that. And the water quality in the inner reaches in Zhuhai, Zhongshan, Panyu, Jiangmen, and Foshan changed from V to III.

Discussion

Although an extreme disaster is unwanted, a focusing event, which is a sudden, exceptional experience and may lead to harm or exposes the prospect for great devastation, is perceived as the impetus for policy change and organizational learning (Michaels *et al.*, 2006). The recurrence of seawater intrusion, which became increasingly serious and directly threatens the security of domestic water use in recent years (PRWRC and PRWRCA, 2004), forces the PRWRC to learn what had happened and what the reason is, and to rethink their policies and modify them for meeting the changed situation. This will result in exploring the solutions and pursuing the effective prevention instead of coping with the seawater intrusion after it happens.

Table 5 Water extraction in the PRD during combating the seawater intrusion in 2005 and 2006

Year	2005			2006		
City	Time period	Direct extraction (10^6 m^3)	Water stored in reservoirs (10^6 m^3)	Time period	Direct extraction (10^6 m^3)	Water stored in reservoirs (10^6 m^3)
Zhongshan	January 29–February 14	13.35	0.20	January 16–January 22	4.68	0.244
Guangzhou		18.66	–		9.28	–
Foshan		0.95	–		–	–
Zhuhai & Macao		19.18	11.72		8.34	7.00
Jiangmen		1.96	–		–	–
Total amount		54.10	11.92		22.30	7.244

With the necessary supervision on the execution of unified regulation plan, extensive public participation and cooperation for coping with the natural disaster will be reachable. The active participation of the Ministry of Water Resources of China is a critical factor for the successful execution of the water diversion scheme for combating the seawater intrusion. However, it should be realized that such a measure for combating the seawater intrusion could only temporally relieve the salinity problem to a limited extent. Besides, the seawater intrusion was not only caused by the lower streamflow into the PRB, but also might be due to over extracting water from the river channels in the upper streams, and over-drudging the river bed sand in the middle streams.

Besides solving the seawater intrusion, there are other environmental problems in the PRB, such as flooding, soil erosion in the headwater areas, discharge of untreated wastewater from the urban areas, and environmental and ecological damage caused by the dams. Therefore, conserving the water resources, protecting the environment and restoring the ecology are the basis for sustainable socio-economic development and for the harmonious coexistence of human beings and nature. In turn, the PRWRC will broaden the scope and capacity of managing the river basin. Several suggestions in the basin management are given below:

Maintaining hydrologic function of each component landform. It is known that each watershed has an overall hydrologic function to capture, store and safely release water, which is dependent upon how well each geomorphic component landform is functioning. Therefore, each component landform needs to be considered in the planning process and in setting watershed goals (Peterson, 1999). Therefore, the integrated watershed management need start and execute locally and consider the different situation for different geomorphic component landform. For example, soil erosion in the headwater areas of the PRB need intensive effort to improve and restore the hydrologic and ecological function there.

Regulating law and public administration. To ensure the smooth execution of the unified water regulation for some emergencies, for example flooding prevention and drought mitigation, over the whole basin, it is necessary to build a regulation law which can be applicable by public administration of water resources. Such a law can reach decisions efficient through avoiding redundant negotiations among stakeholders. Then, it would be helpful to structure a system for maintaining the agreement between the public policy frame and the basin regulation scheme.

Balancing the water supply and water demand. Sufficient water supply is the basis for sustainability of socio-economic development. However, the over exploitation of water resources may lead to the breakout of serious problems such as the seawater intrusion, ecological impairment, the degradation of river environment. In return, such the problems will further constrain the sustainable utilization of water resources and the healthy development of river. It is, therefore, significant to balance the relationship between socio-economic development and the assurance of water resources.

Conserving water resource and regulating hydropower generation. Usually the main objectives of building reservoirs are irrigation, flood control, and hydroelectric generation, and dams alter the downstream flow regime of rivers (Batalla *et al.*, 2004). Therefore, the present relocation policy from developing water conservancy and hydropower generation for emphasizing the effects of engineering projects on environment and ecology is reserved for further development. Moreover, the coordination between hydropower generation and natural hazard mitigation is a challenge, and demands more innovative regulation policies.

Controlling water pollution. The more industrial and domestic water consumption is, the more wastewater discharges. Consequently, it can lead to the decrease of the available water resources. Therefore, it is necessary to control the water pollution and to set the maximum capacity of receiving pollutants for protecting river channels.

Regulating the water right and wastewater discharge right marketing. The water right marketing can be applied to regulate the allocation of the water resources, relieving the conflicts of water demand and water supply. Meanwhile, the marketing of the wastewater discharge right is conducive to protect the clean water in the channel, to encourage the wastewater treatment and to maximize the capability of self-purification of the receiving water body.

Conclusions

This paper surveys the water resources and basin management over the Pearl River basin. The necessity and importance of the unified management of watershed are analyzed through the case study of arresting the seawater intrusion in the PRD. It is also revealed that the unified watershed management decision based on the field investigation and coordination among various stakeholders is critical for coping with natural disasters. This approach should be successfully used to plan watershed management in the Pearl River basin. In addition, the basic principle of regulating water resources and basin should lie in the harmonious existence of human beings in Nature. The PRWRC is following such a principle to balance continuously the utilisation of water resources and the protection of basin environmental health, resulting in further development of the socio-economic sustainability in the Pearl River basin.

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References

Batalla, R.J., Gomez, C.M. and Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River Basin (NE Spain). *J. Hydrol.*, **290**(1–2), 117–136.

Brady, D.J. (1996). The watershed protection approach. *Water Sci. Technol.*, **33**(4–5), 17–21.

Clark, B.T., Burkardt, N. and King, M.D. (2005). Watershed management and organizational dynamics: nationwide findings and regional variation. *Environ. Manage.*, **36**(2), 297–310.

Croke, B.F.W., Ticehurst, J.L., Letcher, R.A., Norton, J.P., Newham, L.T.H. and Jakeman, A.J. (2007). Integrated assessment of water resources: Australian experiences. *Water Resour. Manage.*, **21**(1), 351–373.

Ghafouri, H.R. and Parsa, J. (2003). Finite element modeling of seawater intrusion into well-mixed estuaries. *Environmental Studies, vol. 9, Coastal Engineering VI: Computer Modelling and Experimental Measurements of Seas and Coastal Regions*, ed. C.A. Brebbia *et al*., WIT Press, Southampton UK, pp. 121–130.

Michaels, S., Goucher, N.P. and McCarthy, D. (2006). Policy windows, policy change, organizational learning: watersheds in the evolution of watershed management. *Environ. Manage.*, **38**(6), 983–992.

Momii, K., Shoji, J. and Nakagawa, K. (2005). Observation and Modelling of seawater intrusion for a small limestone island aquifer. *Hydrol. Processes*, **19**(19), 3897–3909.

Peterson, M.M. (1999). A natural approach to watershed planning, restoration and management. *Water Sci. Technol.*, **39**(12), 347–352.

Poland, J.F., Garrett, A.A. and Sinnot, A (1959). Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California. *U.S. Geological Survey Water Supply Paper, Professional Paper*, 1461, Washington, DC.

PRWRC and PRWRCA (Pearl River Water Resources Commission and Pearl River Water Resources Conservation Agency) (2004). *Analysis and Early-warning Report of Seawater Intrusion and Water Supply from Winter 2004 to Spring 2005 in the PRD*. Report for the Ministry of Water Resources of China.

Reichard, E.G. and Johnson, T.A. (2005). Assessment of regional management strategies for controlling seawater intrusion. *J. Water Resour. Plann. Manage.*, **131**(4), 280–291.

Said, A., Sehlke, G., Stevens, D.K., Glover, T., Sorensen, D., Walker, W. and Hardy, T. (2006). Exploring an innovative watershed management approach: from feasibility to sustainability. *Energy*, **31**, 2373–2386.

Schmandt, J. (2006). Bringing sustainability science to water basin management. *Energy*, **31**, 2350–2360.

Xue, J. (1995). *The Pearl River Volume*, Water Resources and Hydroelectricity Press, Beijing, China.