RESEARCH ARTICLE

# Application of coastal reservoirs in China and its feasibility

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**Abstract:** China is a water-rich country in terms of rainfall and rivers' size, but its urbanization mainly occurs in the eastern coastal cities. The densely populated coastal cities intensify the water stress. To seal the gap between water demand and supply, many ways have been tested like water diversion projects, desalination plants and wastewater recycling plants etc. Different from these solutions, this paper discusses the strategy of coastal reservoirs in China's coastal cities. Its feasibility of using the available water is investigated and its water quality can be ensured if the second generation coastal reservoirs are applied. The results show that the water shortage problems in China coastal cities can be well solved if CRs are applied.
**Keywords:** urban water supply, coastal reservoir, inter-basin water diversion, inland dams, water quality

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## 1 Introduction

Since 1900, there has been a nearly 16-time increase in population under water scarcity, but the total population has increased only 4-fold. Currently, 80 countries have water shortages, and 2 billion people do not have sufficient clean water, with at least 1 billion people's basic water needs can't be met. In the next decades, the world population may increase by 1 billion every 12 years. Most people will live in coastal cities due to urbanization. An example of global water crisis can be seen in China. Its water availability per capita is similar to Iran, the country's water shortage is about 50 km$^3$/year. Many expensive attempts have been made to quench China's water crisis, but none of them has been proven successfully. China's total runoff to the sea is about 1,724 km$^3$/year, the storage is only 2.9% of runoff lost to the sea. So China is not short of water, but its storage; China is not running out of water, but water is running out of China. By decreasing runoff lost to the sea using coastal reservoirs, China's water shortage can be effectively eliminated.

In China, 60% of 1.3 billion people live in 12 coastal provinces. China's per capita availability of water is just 25% of the world's average, and more than 400 Chinese cities are short of water among total 600 cities. This is a paradoxical situation since China is one of the countries that have rich water resources. However, most of the water resources are unevenly distributed. This paper examines the feasibility of coastal reservoirs in large river mouths, and the research outcome shows that China's water thirst can be quenched, water quality of its coastal cities can be improved significantly. China's inland cities' water supply can be also improved once these coastal reservoirs are constructed. It is certain that coastal reservoirs can solve coastal cities' water shortage in China. The following sections show the proposed coastal reservoirs (CRs), where the red lines represent CR's dike, yellow lines are gates to regulate in/out flows, and the shaded areas are the freshwater bodies, long white lines with arrows are clean water paths, black lines are unwanted water.


**Figure 1.** Potential coastal reservoirs for Qingdao, China.

## 2 Possible Coastal Reservoirs in Yellow Sea

Yantai is a city on the Bohai Strait, it borders Qingdao on the southwest and Weihai on the east. Its population was 7 million in 2010. Qingdao's area covers 10,654 km$^2$ which receives 775.6 mm/year rainfall. Dagu River is Qingdao's mother river with 180 km long and 6,131 km$^2$ catchment, its annual runoff is 0.66 km$^3$. Yantai's coastline is about 909 km where 121 rivers drain its water to the sea, the top ones are the Daguji-a River, Wulong River etc. Their catchment areas and annual runoff are 2,295 km$^2$/ 0.65 km$^3$, and 2,806 km$^2$/ 0.72 km$^3$,

respectively. The annual rainfall is about 680 mm in this region. To solve Qingdao and Yantai's water shortage problem, the coastal reservoirs are proposed as shown in Figure 1 and 2.


**Figure 2.** Potential coastal reservoirs for Yantai, China.

## 3 Possible Coastal Reservoirs in the East China Sea

Ningpo is a coastal city in the northeast of Zhejiang Province in China. Its port is one of the busiest in the world. In 2010, its total population was 7.6 million over 9,365 km$^2$. The Hangzhou Bay divides Shanghai and Ningbo whose total coastline is 1,562 km including 788 km of mainland coastline and 774 km of island coastline. The city receives an average annual rainfall of 1,440 mm mainly by typhoons and monsoons. The Yong River is Ningbo's mother river, formed by the Fenghua River and the Yao River. The catchment of Yong River is 4,572 km$^2$ and its annual flow is 3.5 km$^3$. There are 9 reservoirs to supply water to Ningbo. In May 2015, the water storage dropped to 30.95%. As signs of water supply shortage appeared, the city launched a drought emergency response to ease the water shortage. To increase its water supply, a coastal reservoir is proposed as shown in Figure 3.

**Figure 3.** A proposed coastal reservoir for Ningbo and a 10 km long canal to be built to divert water with good quality to the coastal reservoir in flood periods.

Taizhou is a coastal city of China's Zhejiang Province, facing the East China Sea. Along its coastline, it is bordered by Ningbo to the north, Wenzhou to the south. In 2010, its population was 5.9 million over 9,413 km$^2$. Its coastline length is about 651 km including islands' coastline. The largest island is Yuhuan Island where a coastal reservoir was constructed (Figure 4). The original design purpose of coastal reservoir was to supply freshwater, which is located in the Yueqing Bay. The construction started in 1998, and completed in 2004. The reservoir's water surface area is 11 km$^2$, storage capacity is 59 million m$^3$. The reservoir's catchment area is 166 km$^2$ where the annual rainfall is 1,430 mm. Thus the estimated runoff to the reservoir is about 120 million m$^3$, double the storage capacity. In 2008, it was found that the reservoir was in hypereutrophicated state[1]. This is an example of reservoir failure for water supply without bypass channels. The 198 km long Jiao River is the largest river in Taizhou, it drains water from 6,519 km$^2$ catchment to the Taizhou Bay. A coastal reservoir for Taizhou is shown in Figure 5.

**Figure 4.** Failed coastal reservoir in Yuhuan constructed in 2004 without SPP scheme.

**Figure 5.** A proposed coastal reservoir for Taizhou's water supply.

Wenzhou is a city located in the southeast of Zhejiang Province, which shares its borders with Taizhou on the north, and Fujian Province to the south. Its population is about 9.1 million in 2010 and 3 million people live in the city. Its area is 11,784 km$^2$ and its coastline is nearly 355 km long which gives the city abundant marine resources and many beautiful islands. The Ou River is the largest river in Wenzhou prefecture. Most flood disasters are caused by typhoons. For example, the typhoons "9417" and "9994" caused huge loss by floodwater in

the 1990s. After September, the long dry period causes the water shortage crisis. The total runoff in Wenzhou is about 13.9 $km^3$, some places like its Dongtou County suffers severe water stress. There are some reservoirs to supply water to this city. The total storage capacity is about 2.3 $km^3$, about 15% of its annual runoff. To solve water shortage in Wenzhou, a coastal reservoir is proposed at the mouth of River Ou as shown in Figure 6.

**Figure 6.** A proposed coastal reservoir for Wenzhou's water supply.

Fuzhou is the capital city in Fujian Province, China. Its population was 7.11 million in 2010 over 11,968 $km^2$, 4.4 million people live in urban and rural area was 2.7 million. Its coastline length is 1,137 km. The 562km long Min River is the longest river in Fujian Province, it drains water from 60,992 $km^2$ catchment into the sea in Fuzhou at the flowrate of 62.9 $km^3$/year. There are two passages at its estuary, i.e., the Changmen channel and Meihuagang channel. Similar to other Chinese rivers, the flowrate in January is very small around 619 $m^3$/s, but the highest flowrate of 4,706 $m^3$/s occurs in June. Runoff during April-September is about 74.4% of the annual total. The dry period appears from October every year. The proposed coastal reservoir for Fuzhou is shown in Figure 7.

**Figure 7.** A proposed coastal reservoir for Fuzhou's water supply.

Quanzhou is one of the largest cities in Fujian Province. There were 8.13 million people in 2010 over an area of 11,245 $km^2$. The 541 km long coastline is separated with Taiwan by a 200 km wide strait. There are in total 207 islands in Quanzhou, where 34 rivers run 8.7 $km^3$/year water to the sea. Among them, Jinjiang River is the largest one. It is a 182 km long river where water comes from 5,629 $km^2$ of catchment. Another large river is the Luoyang River which has 229 $km^3$ of catchment and 39 km of river course. Its annual runoff is about 16.2 $km^3$. The proposed coastal reservoir is shown in Figure 8.

**Figure 8.** A proposed coastal reservoir for Fuzhou's water supply.

The second largest river in Fujian is the 1,923 km long Jiulong River, water from 14,700 $km^2$ of catchment containing cities like Longyan, Zhangzhou and Xiamen cities. The flowrate at Fuhe station is 12.6 $km^3$/year. Its downstream reach receives another tributary, the Nanxi River. In total, the river drains 26.3 $km^3$/year of water to the sea at Xiamen. Typhoons often cause floods in this region. The Jiulong River is the water source of Xiamen by a pipeline at 12 $m^3$/s. In Fujian Province, Xiamen is facing the most severe water shortage problem. Xiamen covers 1,699 $km^2$ with 3.5 million people in 2010. The total resident population was increased to 4.2 million in December 2014. Xiamen Island was considered to possess one of the world's great natural harbors. A 2.2 km long causeway links the Xiamen Island with the mainland. Xiamen's coastline length is about 234 km, water depth is over 12 m. Its annual rainfall is about 1,200 mm. To solve its water shortage problem, a coastal reservoir is proposed as shown in Figure 9.

**Figure 9.** A proposed coastal reservoir for Xiamen in the Jiulong Estuary.

## 4 Possible Coastal Reservoirs in the South China sea

Shantou is a large coastal city on the coast of Guangdong Province, China. Its total population is 5.4 million in 2010 over an area of 2,064 $km^2$. Shantou was a city significant in Chinese history because it was an important port established for international trade. Shantou is a monsoon-dominated subtropical region. The annual rainfall is around 1,630 mm, about

60% of which occurs from May to August and its runoff depth is about 790 mm. The remaining 8 months only receive 40% of its rainfall. In 2010, the drought caused 55,000 people short of drinking water. The island county Nan'ao in Shantou had more than 42,000 people short of drinking water. There are many rivers in Shantou, the major rivers are Han, Rong, Lian, Hao and Leiling River. The catchments of Han, Rong and Lian Rivers are 30,112 $km^2$, 4,408 $km^2$ and 1,353 $km^2$, respectively. The river lengths are 470 km, 175 km and 72 km, respectively. The average runoffs are 25.4 $km^3$/year, 3.56 $km^3$/year and 1.04 $km^3$/year respectively. In 2014, the total water supply was 1.05 $km^3$/year. The proposed coastal reservoir at Rong Estuary for Shantou is shown in Figure 10.


**Figure 10.** The proposed coastal reservoir at Rong Eestuary for Shantou.

Both Shenzhen and Hong Kong are two major cities on the Pearl River Delta. They are rapidly developing cities which are facing water shortage problems in South China. The total area of Shenzhen is 1,997 $km^2$, and the area of Hong Kong is 1,106 $km^2$. They are separated by a river called Shenzhen River, thus both of them can be treated as a single city in terms of water supply. The population of Shenzhen and Hong Kong are 11.4 million and 7.33 million in 2015, respectively. Shenzhen is the third largest city next to Shanghai and Beijing in China. Its water supply per capita is only 200 $m^3$, which is about 1/12 of the national average water supply. Its water consumption was 1.955 $km^3$ in 2011 and 1.14 billion $m^3$ was imported from Dong River or East Pearl River. Hong Kong's water consumption in 2012 was 0.935 billion $m^3$, 80% of it is imported from Dong River and the remaining 20% from local water catchments. Hence Shenzhen and Hong Kong both have a high dependence on importing water. However, The water development of Dong River is already saturated and it is impossible to increase the supply. The reservoir capacity in Shenzhen and Hong Kong are only 0.611 and 0.586 $km^3$, respectively. The current city reservoirs of water resources can only meet about 20 days of emergency use.

Annual average rainfall and amount of water resources in Shenzhen are about 1,966 mm and 1.872 $km^3$, respectively. However, the average utilization during 1998 to 2005 was only 0.499 $km^3$, this is only 14.6% of annual average rainwater. Around 1.8 to 3.0 $km^2$ of freshwater runs into the ocean every year. Hong Kong also has 0.5 $km^3$ of freshwater discharged into ocean via Shenzhen River. Apparently, insufficient capacity of reservoirs is the main cause of water shortage. A large reservoir is required to store a large amount of fresh water during the rainy season. However, due to special geographical condition, there are no large natural lakes, rivers and reservoirs in both Hong Kong and Shenzhen. Since Hong Kong and Shenzhen are urbanized areas which have high dense population, the cost of inland reservoirs is very high and the quality of storm water is poor, we have to find suitable locations for this region's coastal reservoirs.

The Pearl River or Zhujiang River is an extensive river system in southern China. The Xi River ("West River"), Bei River ("North River"), and Dong River ("East River") are all considered tributaries of the Pearl River, because they share a common delta, the Pearl River Delta. And the details of these tributaries are listed in Table 1. The 2,400 km long river is the third-longest river in China, after the Yangtze River and the Yellow River, and the second largest by runoff volume, after the Yangtze. Its catchment is about 409,480 $km^2$ as shown in Figure 11 and its annual rainfall is about 1,470 mm.


**Figure 11.** The catchment of the Pearl River system (409,480 $km^2$).

The Pearl River's estuary is regularly dredged to keep it open for navigation. The estuary separates Shiziyang in the north, Lingdingyang in the south, and Jiuzhouyang at the southern tip of the estuary. This bay separates Macau and Zhuhai on the west from Hong Kong and Shenzhen on the east. A capital city of Guangzhou lies on the north. The Dong River provides freshwater for 40 million people living in six cities which are Heyuan, Huizhou, Dongguan, Guangzhou, Shenzhen and Hong Kong. There are three main reservoirs located in the upper, middle and lower reaches of Dong River. They are Fengshu dam, Xinfengjiang dam and Baipenzhu dam (Figure 12). These three large reservoirs which have a large volume of approximately 17 $km^3$. As small reservoirs such as Shenzhen reservoir (46.1 million $m^3$) have a limited potential for further enhancement of their water storage capacity in the future, the large reservoirs have potential to regulate their water storage for annual use.

The 562 km long Dong River catches rainwater from 35,340 $km^2$ drainage area, over which the rainfall is about 1,500-2,400

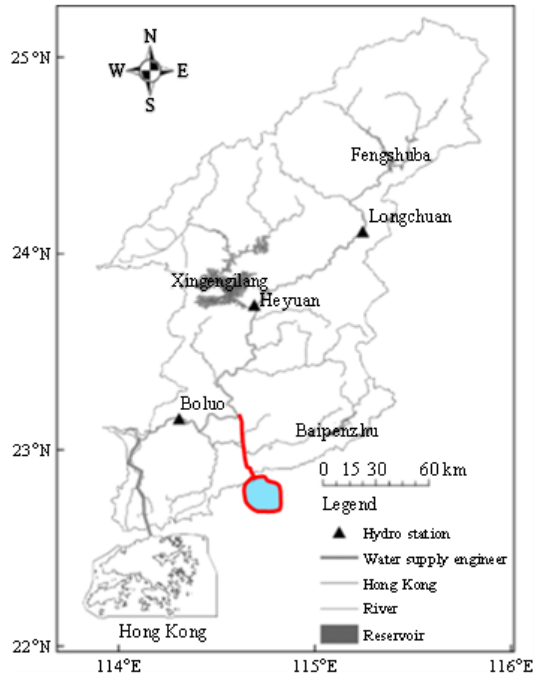


**Figure 12.** Dong River Basin and water diversion from Dong River to the proposed coastal reservoir (red line and oval).

mm/year and runoff depth is 950.4 mm/year, the annual runoff is about 25.7 km$^3$. About 80% of rainfall occurs during April-September, thus flood disasters appear in this period, the maximum measured flood discharge was 14,100 m$^3$/s at Boro station (catchment area is 25,300 km$^2$) in 1959. But droughts occur in the remaining 7 months with only 20% of rainfall. The recorded minimum flow in Boro station was only 31.4 m$^3$/s on May 5, 1955. The total water consumption in Guangdong Province is 10.7 km$^3$/year as shown in Table 1. It is 31.8% of Dong River's runoff or 3.2% of the Pearl River in total.

In 1964, Guangdong constructed the water diversion project from Dong River to Shenzhen and Hong Kong. The water allocation agreement was signed in 2015 under which Guangdong providesabout 70∼80% of water demand from Dong River to Hong Kong. The agreement also allows Hong Kong the flexibility to raise the annual supply ceiling from 0.88 to 1.10 km$^3$. This ultimate annual supply ceiling was first set out in the water supply agreement signed in 1989, promulgated by the Guangdong authorities in 2008. The Distribution Plan sets out the maximum amount of water which Hong Kong and other seven cities in Guangdong Province can draw from Dong River (Table 2).

A coastal reservoir is suggested in the Dayawan, on the south of Huidong as shown in Figure 13 and 14. A water diversion canal is suggested to divert water from the Dong River and its tributary Xizhi River to the reservoir. The canal's length is about 45 km, its reservoir area is about 40 km$^2$, and its barrage length is about 10 km. If the mean water depth is 10 m, then the storage capacity is 0.4 km$^3$. To divert the floodwater into the reservoir, weirs may be needed to be constructed across the Dong River and Xizhi River. This canal mainly diverts the floodwater to the reservoir to supplement water demand of Shenzhen and Hong Kong. The flood disasters in Dong River are expected to be mitigated.


**Figure 13.** A 45 km canal to divert Dong River to a coastal reservoir which is enclosed by 10 km seawall, 40 km$^2$ surface area, about 60 km to Shenzhen and Hong Kong.


**Figure 14.** Proposed small coastal reservoirs for Hong Kong (red shapes).

Water shortage is a historical problem in Hong Kong. The last water rationing occurred in May 1982 when fresh water supply was available on a 16-hour basis for 24 days during the month. Hong Kong is the first city to systematically utilize seawater for toilet flushing in the world. A separate piping system is needed to carry seawater. From the 1950s, the network has been extended to cover about 80% of the total population. In 2015, about 0.75 million m$^3$ of seawater was used for toilet flushing in total, this pipeline costs about 1.3 billion US$ (or 6.5 billion HK$) for the construction of seawater mains, pumping stations, pipes and service reservoirs etc. without the treatment cost like screen and chlorine or hypochlorite, which costs the government 3.4 HK$/m$^3$.

Hong Kong, the coastal city, has the credit for the first coastal reservoir for a city's drinking purpose. Its local catchment provides about 20%-30% of water demand and the remaining 70%-80% of water demand comes from the Dong River. The unit cost of fresh water produced from local coastal reservoirs amounted to about 4.0 HK$/m$^3$ in 2013-2014, while

**Table 1.** The basic information about Pearl River's catchment and runoff.

| Main rivers | Gauge station | Catchment area /km$^2$ | Annual runoff km$^3$/yr | Max. annual runoff | | Minimum annual runoff | |
|---|---|---|---|---|---|---|---|
| | | | | km$^3$/yr | year | km$^3$/yr | year |
| **Xi River** | Wuzhou | 329,705 | 229.0 | 347 | 1915 | 107.0 | 1963 |
| **Bei River** | Shijiao | 38,363 | 43.0 | 73 | 1973 | 17.0 | 1963 |
| **Dong River** | Bolou | 25,325 | 25.7 | 38 | 1975 | 6.1 | 1963 |
| **Pearl River** | | 450,000 | 333.8 | | | | |

in the same period, the water from Dong River costed 8.6 HK$/m$^3$, of which 4.6 HK$ was the cost of raw water and 4.0 HK$ was the processing cost. As the Dong River needs to support 40 million people in the deltaic region including Hong Kong and Shenzhen, and the central government ambitiously wants to develop this delta as a world-class industrial base for advanced manufacturing industries, Hong Kong starts to worry about its reliable water supply from the river. Subsequently, the government attempts to build a desalination plant using advanced reverse osmosis technology which is scheduled for completion in 2020 with an annual capacity of 50 GL/year or 5% of the total fresh water supply. It is also expandable to 100 GL/year similar to Sydney's size. The reverse osmosis technology will be used even it is still energy-intensive, and the estimated cost of desalinated water was 12-13 HK$/m$^3$ in 2013. If the wastewater is reused like the West Corridor Project in Brisbane, the cost will be reduced to 9.8 HK$/m$^3$.

**Table 2.** Water resources distribution plan for cities in Pearl River Delta.

| | Allocated annual quantity / km$^3$ | | Reliance on Dong River |
|---|---|---|---|
| | Under normal yield | Under drought | |
| **Hong Kong** | 1.100 | 1.10 | 70 ~ 80% |
| **Dongguan** | 2.100 | 1.90 | 90% |
| **Shenzhen** | 1.700 | 1.60 | 70 ~ 80% |
| **Heyuan** | 1.800 | 1.70 | ~ 90% |
| **Huizhou** | 2.500 | 2.40 | 70% |
| **Shaoguan** | 0.122 | 0.10 | |
| **Meizhou** | 0.026 | 0.02 | as a supplementary source of water supply only |
| **Guangzhou** | 1.400 | 1.30 | |
| **Total** | 10.700 | 10.20 | |

Obviously, the basic assumption used by Hong Kong government about their decision of desalination plant is that Hong Kong is short of freshwater. In fact, their shortage is water storage. This can be seen from the simple mass conservation, i.e., the annual runoff depth is 950 mm and Hong Kong's total area is 1,106 km$^2$ or the annual runoff is 1,050 GL/year, about 21 times more than the capacity of proposed desalination plant. This can also be seen from that its local reservoirs release about 20 GL/year over their spillways in typhoon seasons. So it is strange that Hong Kong discharges so large amount of freshwater into the sea, but at the same time, a large amount of energy is used to desalinate seawater. As shown in Figure 13, if every drop of rainwater in Sai Kung East Country Park is collected like Singapore, the 50 GL/year desalination plant can be replaced by small coastal reservoirs whose total catchment area is larger than 53 km$^2$. Of course, the large coastal reservoir shown in Figure 14 is also a long-term solution.

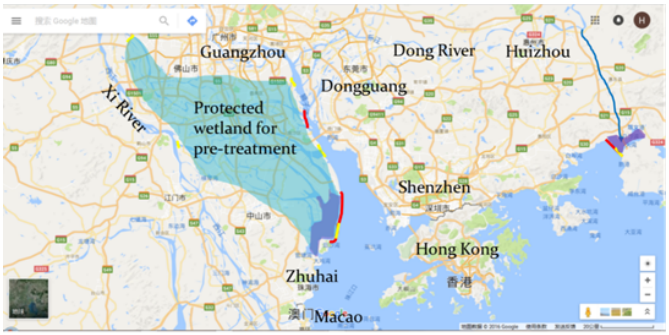


**Figure 15.** Two major coastal reservoirs (dark purpled). One is to develop water from Dong River for Shenzhen and Hong Kong's water supply. the other is to develop water from Bei River and Xi River for water supply to cities like Zhuhai, Macao, Guangzhou, Zhongshan, Dongguang and Fushan. The red lines are barrages, the yellow lines are hydraulic gates, and the blue line is water diversion canal. The shaded area is protected wetland for water purification.

The master plan of water resources development for cities in the Pearl River Delta is shown in Figure 15, where the dark purple areas are coastal reservoirs, one for Shenzhen and Hong Kong's water supply (on the left), the other for cities like Guangzhou, Dongguang, Zhuhai and Macao. The coastal reservoir on the left has high quality water from the reservoirs like Xinfengjiang and Baipengzhu, but the water from Xi River and Bei River has been polluted, thus wetland treatment is needed. The shaded area is the protected eco-area to pre-treat the river water using wetland, where no domestic, industrial and agricultural chemicals are allowed to enter waterways. The red lines are the barrages and the yellow lines are gates to regulate the flow. At its inlets, the gates at the Dongping, Shunde or Donghai waterways will be open when good quality water appears in Xi River in flood seasons. The inlet gates at Lianhuasan, Shawan etc will be open when good quality water appears in the Pearl River (Shiziyang). The gates at outlets of these two coastal reservoirs will be open to improve its water quality or to mitigate flood disasters.

# 5 Conclusions

This paper analyses the water availability and water demand in China and finds that the water shortage occurs in coastal cities can be effectively solved by coastal reservoirs, the conceptual designs of these coastal reservoirs have been conducted. By doing so, the following conclusions can be drawn from this study:

1) Currently, almost all coastal cities have a water shortage and in future, it becomes worsened due to the population growth.

2) The technology of coastal reservoirs is a sustainable, cost-effective and clean way for water supply, it will dominate water supply in future.

3) These coastal reservoirs proposed in this paper are cost-effective, environmental friendly and social acceptable.

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