

Coastal Reservoir-a Technology That May Dominate Future Water Supply

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Abstract-New large dam construction is a worldwide problem due to its negative impacts on the ecosystem, and as a result, it is crucial to investigate the future water supply infrastructures. After comparison with the existing solutions for water supply, such as inland reservoirs, desalination plants and wastewater reuse facilities, we conclude that coastal reservoir will be the dominant solution in the future because: a) increasing numbers of people migrate towards coastal/deltaic regions and more megacities are emerging along the coastline; consequently the water shortage on the coastline is the most severe; b) the future water deficit is huge (about 10 times the flow of the Nile river), with no solution other than the implementations of coastal reservoirs, freshwater reservoirs in the seawater to develop runoff from rivers, able to provide so much water. Now the world only uses 1/6 of total runoff, with the remaining 5/6 of runoff lost to the sea; c) all solutions for water supply have significant impacts on the environment, and only the strategy of using coastal reservoirs is sustainable, as it is without brine as a by-product or high carbon emissions. This paper discusses the supply of water to Beijing and Tianjin, the most notorious region in the world for its thirst. It is found that the water shortage problem in the region can be solved, the efficiency of South-North Water Diversion Project can be improved significantly, and carbon emission can be reduced in the region if this new solution is applied.

Keywords- Coastal Reservoir; Inland Reservoir; Water Supply; South-North Water Diversion Project

I. INTRODUCTION

Water is the essence of life and it is through water that we experience the impact of climate change directly (Postel, 2010). The United Nations predict that by 2025, about 1.8 billion people may be living in countries or regions with absolute water scarcity, and 2/3 of the world's population will be under water stress conditions (UN Water 2013). Water shortage can be caused by population growth, which drives the growth of water demand for domestic, agricultural and industrial purposes. Water shortage in water-rich areas can be also caused by water pollution. The water problem caused by poor quality and insufficient quantity has been widely noted and researchers, decision makers and ordinary citizens are well informed about the issue, however few studies consider the following facts: 1) more and more people migrate to coastal areas, increasing the pressure on water resources in these areas; 2) sedimentation by soil erosion reduces the storage capacity of existing reservoirs by 1% annually, which will result in almost all existing reservoirs being silted completely in the following 50-100 years; 3) for many countries like Australia, it is almost impossible to build new dams to replace the lost storage. The key question to ask is: "where will the people find their drinking water in the future?" Gleick (2001) estimated that to meet the world crop demand projected for 2025, an additional 800 km³ of water per year could be required; a volume nearly equivalent to 10 times the annual flow of the Nile River. This is why the US National Academy of Engineering (NAE) lists clean water supply as one of the 21st century's "Grand Challenges" that must be addressed and solved for a high quality of life to be sustainable in the future. Whilst there is plenty of water in the world, the problem is that it is either not where it is needed or not clean and fit for human use.

Apart from the natural scarcity of freshwater, the quality of available freshwater is also deteriorating due to pollution, further intensifying worldwide water shortage. Every day, 2 million tons (1,500 km³/year) of sewage and other effluents drain into the world's waterways, which is six times more water than already exists in all the rivers of the world (UN WWAP 2003). As a result of population growth and economic development, global water resources are grossly polluted by human, industrial and agricultural wastes to the point that vast stretches of rivers are dead or dying, and many lakes are cesspools of waste. Consequently, the World Commission on Dams proposed that re-inventing the management of freshwater resources is one of the greatest challenges in the next decades (WCD, 2000).

Overall, the world population will keep increasing steadily by 57% in the next 50 years if the growth rate remains unchanged. It is interesting to note that coastal areas have the highest population growth rate, because coastal and deltaic regions are areas that are the most productive and valuable in terms of agricultural production and fishery resources, are where the natural waterways are suitable for navigation, and where the relatively flat topography also offers the best potential for industrial development.

Most importantly, people move to coastal areas for a "sea change" as the coastal and marine environment provides an aesthetically pleasing landscape and the opportunity for a multitude of recreational activities. Hence more and more people are migrating to coastal areas. This can be seen in Australia where in the 1950s only 70% of people lived in the coastal areas, but this percentage has now increased to 92%. Similar patterns have been observed around the world. In 1950 only 30% of world's total population lived in coastal regions, but presently about 70% of people live there (Yang 2013). Consequently, more and

more megacities are developing in the coastal zones such as New York, Tokyo, Shanghai, Mumbai, Beijing, and Tianjin etc., which leads to a worsening water deficit (Sekovski et al. 2012). Governments and water utilities around the world are confronted by a significant and perplexing question: where can sufficient high quality water to meet the future water demand, with low energy and environmental costs, be found? Hence, urgent attention is needed to develop innovative water supply strategies for coastal communities as they are the economic powerhouses of the global economy.

II. EXISTING SOLUTIONS TO WATER CRISIS AND THEIR EFFECTIVENESS

To meet the gap between water demand and supply in the coastal regions, many strategies have been proposed and applied, such as desalination plants, wastewater reuse, water transfers and water saving technologies, etc. Clearly, there is no single answer to solving this problem. In this study, a new approach will be explored, based on using coastal reservoirs for freshwater storage. The excess freshwater from river runoff during the wet season is stored in those reservoirs and is then pumped back to land during the dry season. Here we take Beijing as an example to discuss their effectiveness and sustainability.

To solve the water shortage problem in Beijing, there are many existing proposals and a lots of research work already done; thus it is worthwhile to compare these proposals in terms of sustainability, energy usage, gas emission, environmental impacts on the ecosystem, life span and cost etc. The current water deficit in Beijing is 1.5 billion m³ and the existing proposals for solving this water deficit include water transfers, inland dams, wastewater recycling and reuse, desalination plants, and the proposal in this paper, the so-called coastal reservoir that aims to capture available runoff to the sea. The rainfall in the Beijing region (630mm/a) that generates this runoff is comparable with other metropolises, e.g., London (581mm/a), Paris (566 mm/a), and Moscow (522mm/a).

Inland reservoirs: The life span for concrete dam is about 100-200 years, but this is dependent on its sedimentation rate. For reservoirs, the worst enemy of its long term sustainable use is sedimentation (USBR, 2006). The total sediment loss in the world is estimated to be 13.5×10^9 tonnes/annum or 150 tonnes/km²/year. About 25% of this sediment is transported into the seas and oceans and the remaining 75% is trapped, retained and stored in lakes, reservoirs and river systems (Batuca and Jordaan, 2000). Consequently the silting process is reducing the storage capacity of the world's reservoirs by more than 1% per year. In the world there are around 45,000 large reservoirs used for water supply, power generation, flood control, etc., and their construction peak time appeared between 1950 and 1990 as shown in Fig. 1. About 1~1.5% of the total storage volume is lost annually as a result of sedimentation, and about 300-400 new dams would need to be constructed worldwide every year to maintain current total storage (White, 2001). The worldwide reservoir sedimentation rates are shown in Table 1. This means that we are losing our existing reservoir capacity rapidly, and not enough new capacity is being developed to replace this lost capacity. UN Experts have warned that in the future, soil erosion and reservoir sedimentation rates would be accelerated due to the severity of storms and rains as a result of global warming (UNEP, 2001). A serious question to ask is: when all existing reservoirs have lost their storage capacity in 100-200 years after their construction, without replacement, where can drinking water be obtained? During the 19th Congress of the International Commission on Large Dams (ICOLD), the Sedimentation Committee passed a resolution encouraging all member countries to simulate and predict the process of reservoir sedimentation. Many countries have developed innovative methods to meet the goals of this ICOLD resolution.

TABLE 1 ESTIMATED AVERAGE RATES OF RESERVOIR SEDIMENTATION AND ITS EXPECTED HALF-LIFE (DATA FROM SHEN 2010 AND WHITE 2001)

Location	Estimated annual loss of storage due to sedimentation	Estimated reservoirs half-life (yrs)	Location	Estimated annual loss of storage due to sedimentation	Estimated reservoirs half-life (yrs)
World	1%	50	Northern America	0.2%	250
Tunisia	2.3%	22	Northern Europe	0.2%	250
China	2.3%	22	Saharan Africa	0.23%	217
Turkey	1.2%	42	Middle East	1.5%	33
Morocco	0.7%	71	South-east Asia	0.3%	167
India	0.5%	100	Central Asia	1.0%	50
USA	0.22%	210	Australia	0.27%	185

Fig. 1 shows that after 2000, the world has completed almost no new large dams; this is because:

1) The existing inland reservoirs have had significant negative impacts on ecosystems and biodiversity. These impacts are typically more negative than positive, and have resulted in the irreversible loss of many species and ecosystems. Global estimates of the magnitudes of the social and environmental impacts of dams include 40-80 million people displaced, including uprooting of vulnerable native communities, and 60% of the world's rivers being fragmented by these dams (WCD, 2000). Therefore, the construction of dams has resulted in significant public opposition, and all governments and their water authorities have had to cancel or postpone their plans for any new dam development.

2) The dam site is a non-renewable resource which needs an ideal combination of hydrological and geomorphological conditions. Normally, large inland reservoirs are constructed in the mountainous areas where the dam foundation has sufficient strength and durability to support the dam constructed, and the storage is sufficient. Obviously, after so many years development, the ideal dam sites have already been developed, further contributing to the diminishment of new dam construction shown in Fig. 1.

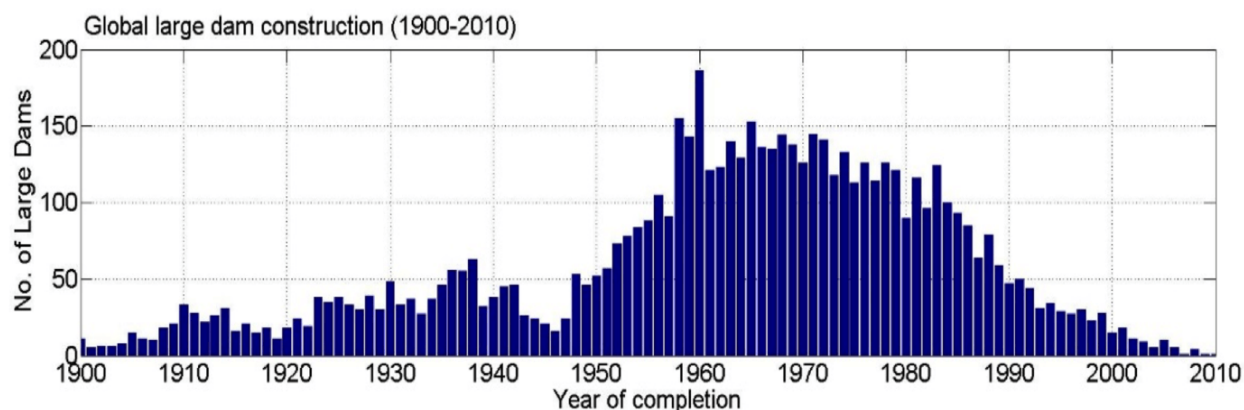


Fig. 1 Number of inland dams constructed by year. Source: Global Reservoir and Dam (GRanD) Database

Water-transfer: Currently, the water supply in Beijing mainly relies on infrastructures such as mountainous reservoirs, which have provided, and will continue to provide a large portion of water to consumers. However it is unrealistic to construct new dams to supply Beijing with 1.5 billion m³ of water using the old-fashion technology of inland-reservoirs. The South-North Water Diversion Project (SNWDP) was initiated by Chairman Mao in 1952, started its construction in 2002, and from 2015 has supplied about 1.05 billion m³/year to Beijing via a 1,432km artificial channel, with a cost of 300billion Yuan RMB (about US\$50 billion). The source is located at an elevation of 170m above-sea-level (ASL), and provides a flowrate of 9.5billion m³/year, with the excess water being pumped to Miyun reservoir where the normal water level is 157.5m ASL. Beijing's elevation is about 50m ASL. The distance from Beijing to Miyun reservoir is about 103km, with a hydraulic head of about 133m. Pumping capacity from Miyun Reservoir to Beijing is currently 20m³/s. It is reasonable to assume that 0.5billion m³/year will be pumped to the reservoir. The water diversion channel is shown in Fig. 2.

With these details, one can estimate the pumping energy from Beijing to the Miyun Reservoir. The energy equation can be written with the following form:

$$Z_1 + \frac{V_1^2}{2g} + h_{pump} = Z_2 + \frac{V_2^2}{2g} + h_{loss} \quad (1)$$

Where: Z = elevation, V = velocity, g = gravitational acceleration, h = energy head, the subscripts 1 and 2 represent the source and destination of pipeline. $Z_2 - Z_1 = 133\text{m}$, the mean velocity at the reservoirs is very small, i.e., $V_1 = V_2 = 0$. The energy loss can be expressed by the Darcy-Weisbach Equation:

$$h_{loss} = \left(f \frac{L}{D} + \sum K_i \right) \frac{V^2}{2g} \quad (2)$$

Where: h_{loss} = head loss, f = friction factor, L = pipe length = 103km, D = pipe diameter = 2.6m, V = flow velocity in the pipe ($=Q/A$, for Q = discharge, A = cross section area), K = co-efficient for minor energy loss that is negligible relative to the friction loss.

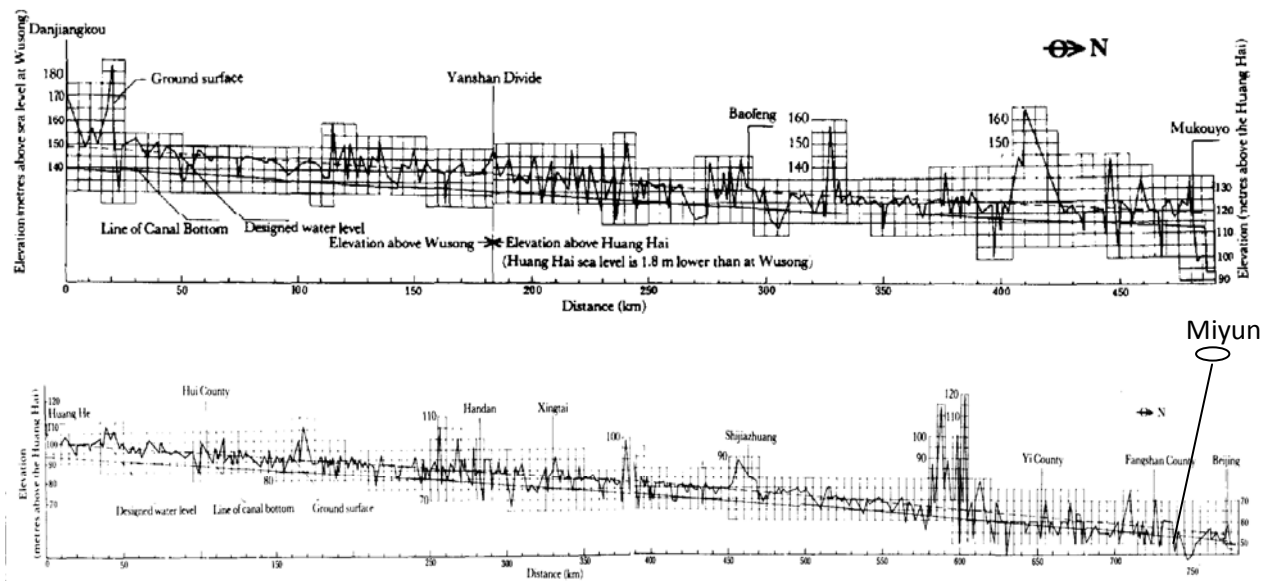


Fig. 2 Longitudinal profile of the Middle Beijing Route Canal from Head works to Yellow River (upper) and from Yellow River to Beijing (bottom)

TABLE 2 COMPARISON OF DIFFERENT PROPOSALS TO SECURE 1.5 BILLION M³/YEAR WATER SUPPLY FOR BEIJING IN TERMS OF SUSTAINABILITY, COST AND CARBON EMISSION

	Inland dams	Water transfer	Desalination	Recycled wastewater	Coastal reservoir
Energy used ($\times 10^9$ kWh)	0	0.38	6.0	1.71	0
Estimated water price (Yuan RMB/m ³)	4	6.75	7.7	5	1~2
Green-house emission (carbon dioxide) in million ton	0	0.38	10	5	0
Construction cost (in billion Yuan)	Very high	300	66.5	187	17
Maintenance/operation cost	Low	Low	High	High	low
Impacts on ecosystem	Loss of biodiversity	0.35 m people relocated	Brineon marine biodiversity	low	No negative impacts on ecosystem
Life span (years)	100-200	100	20	20	Infinite
Sustainability	unsustainable	unsustainable	medium	sustainable	sustainable

If we assume that four concrete pipelines (absolute roughness $\varepsilon = 3\text{mm}$) each with a diameter of 2.6 m are used to pump the water, the Moody chart shows that the friction factor $f = 0.02$. The discharge Q is 0.5 billion m³/year (assuming 290 days operation in a year) or 20 m³/s, and velocity $V = 1.88\text{m/s}$ with two pipelines in operation at a time. The required power E can be estimated from:

$$E = \rho g Q h_{\text{pump}} \quad (3)$$

Where: ρ is density of water ($=1000\text{kg/m}^3$).

The results calculated using Eq.3 show that $h_{\text{pump}} = 276\text{m}$, the required pumping energy, $E = 376 \times 10^6\text{kWh}$, and the cost is about 376×10^6 Yuan RMB. Currently, the water price announced by the government for the SNWDP is about 6 Yuan RMB/m³ without pumping cost, environmental cost and other costs. So if the pumping cost is included, the total cost is about 6.75 Yuan RMB/m³ ($376 \times 10^6 / 500 \times 10^6 = 0.75$ Yuan/m³). The required gas emission is about 0.376 million tons, as generating 1 kWh releases 0.997 kg carbon dioxide. In total, 0.345 million people were relocated and the SNWDP intersects 701 rivers and creeks. The design life span is about 100 years for its concrete structures.

Desalination plants: Beijing also has begun building a massive coastal desalination plant in the Caofeidian district of Tangshan, in Hebei Province. When completed in 2019, the plant should be capable of supplying 0.365 billion m³ of water per year; as much as a third of the potable drinking water consumed by Beijing's residents. The 6.6 billion Yuan plant will use reverse osmosis technology to supply 0.66 billion m³/year and utilise a 9.6 billion Yuan network of 290km long pipes to deliver it to the city. The water delivered to Beijing costs 7.7 Yuan/m³. But desalination's high-energy demand and steep capital expenditure and operational cost challenge the idea that it can operate as an environmentally and economically sustainable water supply alternative. On average, desalination plants consume 4 kWh/m³ of freshwater produced (Stamatov and

Stamatov, 2010), while wastewater reuse requires less than 1 kWh of power to process the same volume of water to the same quality. Therefore, it can be estimated that if Beijing used only desalination technology to meet its water demand of 1.5 billion m³/year, the total construction cost would be 66.5 billion Yuan for its pipelines and plants ($= [6.6 + 9.6] / 0.365 * 1.5$). The total energy required will be 6 billion kWh ($= 4 * 1.5$). For a desalination plant with the capacity of 0.15 billion m³/year, Stamatov and Stamatov (2010) estimated that the extra annual carbon dioxide emission would amount to around 1 million tonnes per year; thus a 1.5 billion m³/year desalination plant will produce 10 million tons of carbon dioxide, 2.5 times more than the CO₂ from all cars in Beijing in 2009, based on the data from Wang et al. (2014). Recently, in Australia, the politicians describe the newly constructed desalination plants as “white elephants”. The desalination plants also produce brine as a by-product which may pollute the environment, potentially affecting its sustainable operation.

Wastewater recycling: The Western Corridor Recycled Water Project is the largest advanced water recycling project in the Southern Hemisphere, with an estimated total cost of about 16.2 billion Yuan and a capacity of 0.13 billion m³ of water per year; thus for a 1.5 billion m³/year project, the construction cost would be around 187 billion Yuan. The treatment process consumes 1.14 kWh/m³ of electricity and generates carbon dioxide equal to half of that which is generated by the desalination process (Poussade et al. 2011). Then the required energy and associated greenhouse emissions are 1.71 billion kWh/year ($= 1.14 * 1.5$) and 5 million tonnes of carbon dioxide respectively. Similar to the desalination process, the maintenance and operation costs of water recycling are also very high. There are no significant impacts of wastewater treatment on the ecosystem. Its life span can be assumed to be the same as the desalination plant, i.e. 20 years.

Coastal Reservoir: Because the combined freshwater from all the rivers into the ocean globally in on average 42,000 km³ per year (UNESCO, 1978), it is conceivable that this portion of freshwater will be innovatively developed in the next several decades. The central challenge for the development of this runoff is to keep river water from mixing with seawater, as the saline water tends to mix with the freshwater in estuaries under influence of waves and tides. Recently coastal reservoirs, freshwater reservoirs in the sea, have emerged as a technology to store the runoff lost to the sea, as shown in Table 3, with its barriers or embankments separating the freshwater from the seawater.

TABLE 3 EXISTING COASTAL RESERVOIRS WORLDWIDE

Name	Catchment (km ²)	Dam length (m)	Capacity (million m ³)	Year completed	Country/ location
Qingcaosha	66.26	48786	435	2011	China/Yangtze
Saemanguem		33900	530	2010	South Korea
Sihwa	56.5	12400	323	1994	South Korea
Marina Barrage		350	42.5	2008	Singapore
Chenhang	1.4		9.14	1992	China/Shanghai
Yuhuan	166	1080	64.1	1998	China/Zhejiang
Baogang			12	1985	China/Shanghai
Plover Cove	45.9	2000	230	1968	Hong Kong
WestSea Barrage		8000		1986	North Korea

To estimate the cost of a coastal reservoir, the coastal reservoir in Shanghai, China is analysed here; its total construction cost was 17 billion Yuan, including a 45km long dam, a pumping system with the capacity of 200m³/s and 2.6 billion m³/year, a 114km long pipeline system with 7.2km of underground tunnels (about 6m in diameter), and two sluice gates with the widths 70m and 20m respectively. If a coastal reservoir is used to supply the water to Beijing, the construction cost should be less than or equal to 17 billion Yuan. Table 2 clearly indicates in comparison with other alternatives, the strategy of employing a coastal reservoir is technically feasible, environment-friendly, sustainable and cost effective. Unlike desalination and wastewater recycling, the coastal reservoir uses the natural stormwater and therefore there is no need to separate the freshwater from salt or waste; as a result the energy cost associated with the treatment is zero and there is no carbon dioxide emission either. When compared with the strategy of inland reservoirs, the method of coastal reservoirs has no cost associated with the inundation of land and relocation of people; normally this is very expensive and could be more than half of a dam's construction cost. The coastal reservoir also has low negative impacts on the ecosystem. After 100 years, the proposed coastal reservoir could be silted due to sedimentation, but another coastal reservoir could be created seaward and the river water can be developed again; thus its life span is infinite. If needed, the barriers shown can be removed and the ecosystem can be returned to its original form. This strategy is sustainable because it can meet the current water needs without compromising the ability of future generations to meet their own needs.

Feasibility of Coastal Reservoirs for Beijing and Tianjin's water supply

The total volume of freshwater in China is 2,810 billion m³, but the distribution of water varies widely among various basins¹¹. For example, the annual runoff of the Yangtze River Basin and the area to its south accounts for 80 per cent of the

national total; North of Yangtze River is where 44.4% of population lives, on 59.2% of the farmland, but it contains only 14.7% of water resources of the whole country (Biswas et al. 1983). Among northern basins, the Haihe River Basin suffers the most sewerwater stress and it is where metropolises Beijing and Tianjin are located, as shown in Fig. 3.

Water Availability: The Bohai Sea receives 4 billion m^3/year of freshwater from the Luanhe and Haihe rivers, and 20 billion m^3/year from the Huanghe (Yellow River), which is one of the longest rivers in the world. Therefore, the total runoff in the region is 24 billion m^3/year , and this number could be increased to 34 billion m^3/year if the SNWDP provides water to the Yellow River. If the river is flushed first, it could then be developed as a water resource in the form of a coastal reservoir. Hence, the water stress in the basin would be greatly alleviated if coastal reservoirs (red circles in Fig. 3) are developed to capture the freshwater that would be otherwise released into the sea. The coastal reservoirs in Huanghe, Haihe and Luanhe river mouths can be connected in series by artificial canals parallel to the shoreline (Green line in Fig. 3); canal construction on the alluvial plain is much simpler and cheaper relative to the proposed routes that are in hilly regions. The freshwater in the coastal reservoirs can then be pumped to the coastal cities like Tianjin, and the water previously used by Tianjin can be diverted to destinations at higher elevations such as Beijing, where the water shortage is only 4.4% ($=1.5/34$) of the runoff lost to the sea. The excess freshwater from river runoff during the wet season would be stored in those reservoirs and is then pumped back to the land during the dry season.

The key challenge for the development of river runoff is keeping river water from mixing with seawater, as saline water tends to mix with the freshwater in estuaries under the influence of waves and tides. This goal can be achieved by building coastal reservoirs located just beyond the river mouths; different from a traditional reservoir. For a coastal reservoir, the solid barriers or embankments separate freshwater from seawater, so that the freshwater can be contained and stored in the sea.

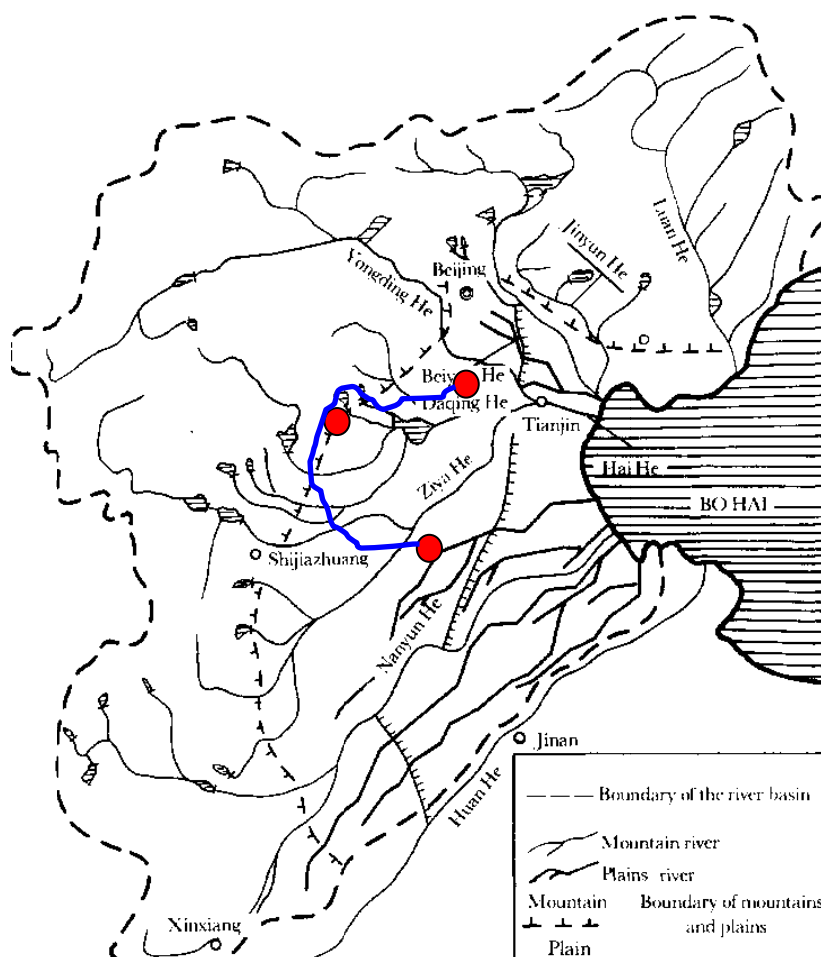


Fig. 3 map of the Haihe catchment and proposed location of coastal reservoirs

Water Quality and Innovative Design: All the coastal reservoirs listed in Table 3 can collect every single drop of rainfall; however they also have potential to collect every single drop of wastewater generated in each catchment. The accumulation of wastewater in a coastal reservoir could lead to algal blooms and subsequently it may become a wastewater reservoir. This happened in Sihwa reservoir, South Korea, which was initially designed for the purpose of water supply; later the government was forced to change the project into an electricity plant for tidal power generation as the water body was heavily polluted (Bae et al., 2010). Northern China is notorious for its water pollution. A traditional method to construct a coastal reservoir in

this region will likely result in the same fate as the Sihwa reservoir, thus an innovative approach to the design and operation is required.

Generally speaking, coastal reservoirs are vulnerable to contamination as coastal areas are rich in pollutants. It is not uncommon that the existing coastal reservoirs that use solid dams tend to fail to provide good quality water, e.g., the Sihwa Lake. In this paper, the proposed coastal reservoirs will not aim to collect every drop of water from the catchment, but only to collect its floodwater. During the flood periods, the water is relatively clean as the wastewater concentration is very low due to dilution. During dry periods, the polluted water is discharged into the sea without being captured. The wet season in this region is from July to August, with very little rainfall occurring in the remaining months. The very long dry period is always accompanied with heavily polluted river water.

This water pollution problem can be solved using a new type of coastal reservoir as shown in Fig. 4. If the incoming water is heavily polluted, the river water will be discharged into the sea as the tidal gates will be opened, and the gates to the coastal reservoirs will be closed; thus the river water will be forced to enter the sea (the Bohai Sea). If the incoming water is very clean (flooding periods), the tidal gates will be closed and the gates towards the coastal reservoirs will be opened so that the clean water will be forced to enter the reservoirs to be stored. In the dry periods, the pumping station will pump the water from the reservoir to consumers. As a result, it is clear that the water quality in the reservoir will be good and no algal blooms, unlike in Sihwa Lake's case, will occur. To optimise such a design and its operation, many factors should be considered: environmental impact, ecosystem services, water demand, hydrological and hydraulic modelling, remote sensing, etc.

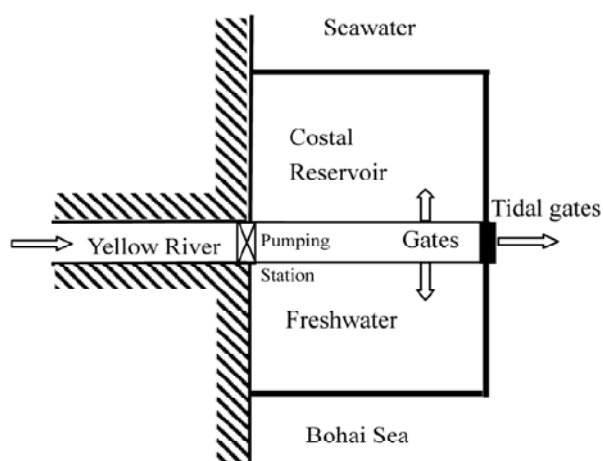


Fig. 4. A novel design for coastal reservoir

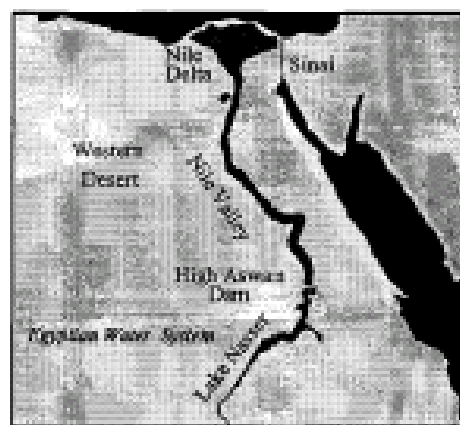


Fig. 5 Nile River in Egypt and its coastal reservoir

Application of Coastal Reservoirs in Other Locations Worldwide

We believe that coastal reservoir will dominate the future water supply rather than alternatives such as the existing inland reservoirs, desalination plants, wastewater reuse etc. Depending on its location, water captured in coastal reservoirs will be of varying quality for domestic, agricultural and industrial water uses. Integration with other water schemes is also possible in some cases. A coastal reservoir's water level is almost at the same level as the sea level, which is quite different from the inland reservoirs where the water level generally is higher than 10m above sea level. For a Coastal Reservoir, as the water level difference on both sides of barrier is very small, the seepage caused by the water pressure is negligible. The differences between inland reservoirs and coastal reservoirs are shown in Table 4. If we compare an inland reservoir with a coastal reservoir in depth, we may conclude that they are totally different. With respect to water quantity, the inland reservoir can only collect the water from part of a catchment, and its size generally is small, but a coastal reservoir has the potential to develop every single drop of rain from the catchment as its size is unlimited. The construction cost of an inland reservoir generally is very high, incurred from very high and strong dam walls, but the pressure force on both sides of the dam of a coastal reservoir is generally small; the wave surge instead is the main concern for its design. The most challenging problem for coastal reservoir's design is pollution prevention as the pollutants from the catchment are likely to be collected, potentially resulting in project failure. Our preliminary assessment shows that the strategy can be used worldwide, and some typical results are provided below.

TABLE 4: DIFFERENCE BETWEEN INLAND RESERVOIRS AND COASTAL RESERVOIRS.

	Inland Reservoir	Coastal Reservoir
Dam-site	Limited (mountainous area)	Unlimited (inside/outside river mouth)
Dam design	High pressure	Low pressure but with wave/tidal surge

Seepage	By pressure difference	By density difference
Pollutant	Land based	Land-based + seawater
Population Resettling cost	High	None
Water supply	By gravity	By pump
Water catchment	Small part	Whole catchment

Egypt and Middle East: Few other countries in the world are as dependent upon a single source of water as Egypt, because it has no effective rainfall except in a narrow band along the northern coastal areas. For thousands of years, the Nile River, as shown in Fig. 5, has allowed the Egyptian civilization to prosper only in the Nile Valley and Delta. The annual Nile flood varies considerably from one year to the other, historically, with severe Nile flooding resulting in the sinking of two ancient cities (Stanley et al., 2001). Its yield of freshwater may reach as high as 151 km^3 as it did in 1978, or may drop to 42 km^3 as it did in 1913. The amount of freshwater discharged to the sea was about 1.8 km^3 in 1990-1991, 3.8 km^3 in 1991-1992, 2.08 km^3 in 1992-1993, and 1.15 km^3 in 1993-1994. To conserve freshwater annually lost to the sea, especially significant flood water, a coastal reservoir may be one of alternatives for the water resources development in Egypt.

The Middle East is the part of the world where water scarcity is the most severe and precarious. Countries in the region have significantly interconnected water resources and some of them rely heavily on desalination technology; however Turkey and Iraq are exceptions, where the Euphrates and Tigris Rivers discharge 46 km^3 of freshwater to Persian Gulf (UNESCO, 1978). Coastal reservoirs at the gulf may provide additional freshwater to countries such as Iraq, Kuwait and Saudi Arabia.

America: One water-imbalanced state in US is California, where the difference between the water demand and supply by 2020 is estimated to be between 2 and 6 million acre-feet per year. Although the actual value of the difference is subject to controversy, almost all agree action must be taken now to avoid increasing differences between supply and demand in the future. In the northern part of the state, it rains more than 80 inches each year, while the southeast corner gets less than 2 inches, and most of the state's precipitation and floods take place during winter and flows into the sea; for example, Klamath River in northern California discharges 1.9 km^3 of river water in to the Pacific annually. Thus, coastal reservoirs could store floodwater during rainy seasons, and release it during summer when most crops grow. The water in coastal reservoirs connected by longshore canals could be diverted to the metropolitan areas of San Francisco, Oakland, Los Angeles and San Diego, which are removed from consistent sources of water; local ocean reservoirs will also store the flood water in rainy seasons and supply additional freshwater to the region.

Islands and Peninsulas: Generally speaking, the catchment area of rivers on islands and peninsulas tends to be small compared with continental rivers. Although the annual precipitation in some islands and peninsulas that are affected by the Monsoon like Japan, Korea and Taiwan varies from 1,200 mm to 2000 mm, distribution of this rainfall is not uniform and has large yearly or seasonal fluctuations. A large amount of flood water has been released into the sea because about two thirds of the annual precipitation occurs during the rainy season. Serious water shortage appears in drought period because only 20% of the total precipitation falls during the other 6 months. Hence, the coastal reservoirs may be very useful especially in regions which lack the suitable locations for the construction of large scale mountainous reservoirs.

Singapore, a typical island country located between Malaysia and Indonesia, shown in Fig. 6, is one of the most water-deficient countries in the world. The mean annual rainfall recorded is 2.4m, but due to the shortage of mountainous reservoir capacity, every year at least 30% of rainwater in existing catchments has been discharged into the sea (Yang, 2003); this portion of freshwater can be saved if ocean reservoirs are developed.

As shown in Fig. 6, the largest river in Johor, Malaysia, carries 3.75 km^3 of freshwater to the area between the islands of Tekong and Ubin in the Johor Strait. A fully closed reservoir can be easily built by connecting Ubin and Tekong with Malaysia if both Malaysia and Singapore agreed to jointly develop the water resource in the river mouth, then both parties can share the reservoir.

Due to the special case that the river and its mouth belong to different nations, a partially closed ocean reservoir may be more practical for Singapore's water supply; by connecting Ubin and Tekong islands to reduce the seawater into the upper reach of the Johor river during flood tide, the river mouth will then be extended to the sea by about 12 km downstream from existing river mouth. The hydrodynamic model shows that the oscillation zone of saline water intrusion in Johor River's mouth is in the range of 6 to 16.2km; if the river mouth is partially closed, fresh water is then available for 3 hours per day at the border.

It can be concluded from the above examples that by developing coastal reservoirs, global water stress can be greatly alleviated. This alternative is able provide more freshwater to coastal communities in larger quantities and more economically than desalination does. A brief outline of coastal reservoirs in the world is shown in Table 5.

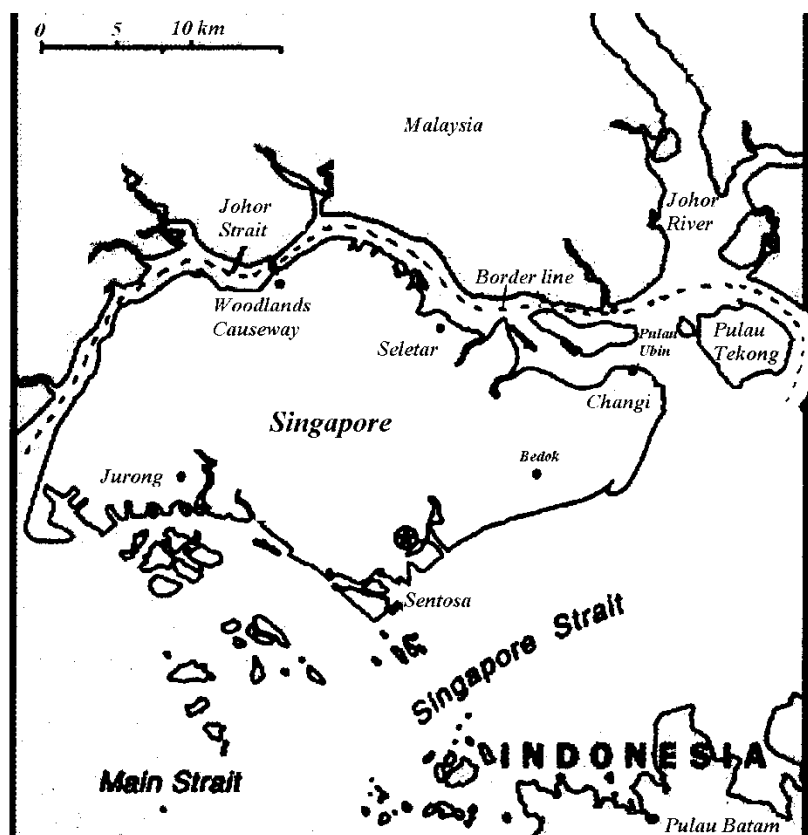


Fig. 6 Map of Singapore

TABLE 5 OUTLINE OF THE PROPOSED COASTAL RESERVOIRS FOR SOME, REGIONS, COUNTRIES AND TYPICAL METROPOLISES IN THE WORLD

Country, region or city	River(s) and captured annual runoff (billion m ³)	Local of coastal reservoirs
West coast in USA	Hood, Klamath, Eel, Sacramento (21)	At these river mouths for San Francisco and Los Angeles etc. link with coastal canal
Egypt	Nile River (11)	Change lagoons into freshwater reservoir (Mariut, Edku, Burullus, Menzleh etc.)
Israel, Iran, Iraq and Kuwait	Kishop, Tigris and Euphrates (55)	To be shared by these countries
Beijing, Tianjin, Shanghai and Guangzhou, China	Yellow, Yangtze and Pearl (2000)	Reservoirs at the outlets of these rivers
Kuala Lumpur and Singapore	Langat, Selangor, Bersama and Johor (total about 150)	Reservoirs at the outlets of these rivers
Brisbane/GoldCoast, Newcastle, Canberra, Adelaide	Richmond River, Hunter River, Shoalhaven River, Murray Darling River	Reservoirs at the outlets of these rivers

III. CONCLUSIONS

This paper has analysed the future population and water demand growth and its distribution, reviewed the existing water supply infrastructures and subsequently the following conclusions can be drawn from this study:

- 1) In the next 100 years, population and water demands may continue to increase significantly;
- 2) Most people in the future will live in coastal and deltaic areas.
- 3) The distribution of existing inland reservoirs will not match the population distribution in the future;
- 4) The majority of the existing inland reservoirs will be out of service due to their structural life span and sedimentation.
- 5) The technology of coastal reservoirs is a sustainable, cost-effective and clean method for water supply, it will dominate the future of water supply.

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