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COASTAL RESERVOIR - A TECHNOLOGY THAT CAN DEVELOP FRESHWATER FROM THE SEA WITHOUT DESALINATION

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DISCUSSION ON COASTAL ENGIEERING RELATED TO COASTAL RESERVOIR

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ABSTRACT

It is more difficult to construct ocean reservoirs due to the complexity of ocean environment such as meteorology, tide, current, wave, topographic landforms and geologic conditions. Those reservoirs are influenced by stormy surge and other extreme climates, even attacked easily by stormy waves. In the case of sea water environment, the difficulty of seepage resistance and construction cost of ocean reservoir have to be increased to a high extent so as to guarantee the quality of water in the reservoirs. In general, an ocean reservoir consists of the embankment around the reservoir, water intake and pumping gate, water pumping station, water pumping gate well and control center etc. CCCC First Harbor Consultants Co., Ltd. (FHC) has successfully completed a great amount of ocean engineering design with respect to complex meteorology, tide, current, wave, topographic landforms and geologic conditions. The above engineering practices involve waterway, ship gate, sand-retaining breakwater, artificial island, sea reclamation, revetment etc. Thus, a complete set of techniques and theory can be followed to carry out the construction of ocean reservoirs.

Keywords: Coastal reservoir; First Harbor Consultants Co., Ltd. (FHC); coastal engineering; similar engineering case; landscape and ecological engineering.

1 INTRODUCTION

Water resources are irreplaceable basic natural resources, public resources and economic resources on earth. Quality, abundant, safe and reasonable water supply has a far-reaching decisive impact on coordinated development of economy, society and environment and continued improvement of people's life quality.

Water shortage is a worldwide problem. 1.5 billion people, according to a survey conducted by the National and World Banks, are affected by water shortage on a global scale. They estimated that the population affected by water shortages in 2050 will be 2/3 of the total population, or 2.7 billion. However, the fresh water utilized by human beings is less than 1/6 of the total water resources, and remaining 5/6 flows into the sea for nothing.

Reservoirs are water bodies formed by dams built at a valley or an estuary of a river. Their previous functions were mainly flood control, power generation, irrigation and shipping. However, water supply from reservoirs has become the most important source in handling water supply pressure. From a global perspective, the reservoir is a water storage body with a capacity of more than 100,000 m^3 and characteristic of water supply from rivers. The reservoir is a semi-artificial semi-natural water body between rivers and lakes.

Coastal areas are most habitable for human beings. At present, coastal areas is becoming more and more heavily populated, resulting in increasing water supply pressure.

The marine reservoir is a comprehensively utilized water conservancy project which involves building dams, reservoirs at the estuary or intertidal zone or damming a river at the bay to reserve fresh water. There are now two main types of marine reservoirs: one is water storage works that necessitates the construction of an ocean dam to intercept and collect land water or to draw water from river networks in wet seasons, and they are often referred to as polder reservoirs for storage of freshwater; and the other is a reservoir formed by damming on the sea beach of an estuary. Known as reservoirs for avoidance of saltwater and storage of freshwater, they draw the abundant water resource from the estuary by building a water pump house, regulate water flow in dry seasons, and satisfy water supply demand.

Ocean reservoirs are generally composed of a reservoir dam, a water pump gate, a water pump station, a water gate shaft, a control center and other components. The traditional marine reservoir stabilizes fresh water surface by building a dam and acquires the dynamic reservoir capacity with a change of water depth of the reservoir. In 1957, the Americans invented and built the soft dam marine reservoir, used a soft to fix water depth (same depth with seawater), and acquired the dynamic reservoir capacity with flat expansion and contraction.

Many countries have carried out a number of studies and engineering practices on the theories, methods and engineering technologies for development and utilization of water resource. As marine reservoir research covers a multitude of disciplines, involving marine environment meteorology, tides, currents, waves, sediments, topography, geology, water quality ecological environment, and materials, etc., showing a trend of enhanced communications among various disciplines.

The company has successfully designed and implemented a large number of marine engineering cases, such as waterway projects, ship lock projects, anti-wave embankment projects, artificial island projects, reclamation projects, and bank revetment projects in varied and complicated weather, tide, ocean current, wave, topographical and geological conditions for coastal engineering both at home and abroad. A large number of marine hydrodynamics, sediment, marine structural engineering theories and practical cases can be applied to the construction of marine reservoirs and contribute to their development.

2 HUMAN NEEDS AND COGNITION OF MARINE RESERVOIRS

2.1 Human needs of marine reservoirs

The main renewable freshwater resources on the planet come from continental precipitation, which is 40000-45000 km3 per year. This is also the basic supply for the global population, however, the global population increases by about 85 million a year, resulting in a rapid decline in per capita freshwater supply. About 80 countries and regions accounting for 40% of the world's population are facing the pressure of water supply. The shortage of water resources is caused by population growth, while water shortage in water-rich areas is a result of water pollution.

China is one of the 13 countries that is most in urgent need of water in the world.

China's water resources are unevenly distributed both in terms of time and space. As for time-based distribution, we have a flood season of four consecutive months and 2/3 of the flood is difficult to use; when it comes to spatial distribution, South China is better endowed than North China.

China's most water-poor cities are basically located in the coastal areas. It is not water shortage in the strict sense, but there are indeed lacks of large-capacity reservoirs; by constructing ocean reservoirs to store freshwater in wet seasons, the large amount of floods collected in rainy seasons can be channeled to the river, and thus floods become resources. In addition to water supply for riverside inhabitants, the ecological water demand in the river can also be satisfied, producing very good results for ecological restoration in the drainage basin.

Construction of marine reservoirs and development of fresh water flowing into the sea is a response to the concept the 21st century is the century of the ocean, so water conservancy work must be extended from inland rivers to the ocean for a strategic shift.

2.2 Cognition of marine reservoirs

The marine reservoir is a comprehensively utilized water conservancy project which involves building dams, reservoirs at the estuary or intertidal zone or damming a river at the bay to reserve fresh water.

Many countries have carried out a number of studies and engineering practices on the theories, methods and engineering technologies for development and utilization of water resource. China's West Lake in Hangzhou is a great marine reservoir project in history, and it fully demonstrates the wisdom of the ancients in marine water conservancy. The Netherlands, a traditional maritime power, has developed an ocean-oriented strategy in the beginning of the 20th century for land and water resources development, and the Zuider Zee foreshore reclamation project is one of their typical achievements. Zuider Zee is a large bay in the northwest of the Netherlands surrounded by land, and it is connected to the North Sea in the northwest only. The Dutch built a 30km long embankment to separate Zuider Zee and the North Sea; channeled the freshwater from Rhine and to Zuider Zee, which formed the Lake Eisel. After nearly 20 years, Eisel Lake has become a freshwater lake mainly used for agricultural irrigation and domestic water and a good place for leisure and entertainment.

In China, we have recently built Qingcaosha reservoir and other marine reservoirs, which, to a certain extent, ease the contractions between local economic development and relative shortage of water resources, provide extremely value freshwater resources for the local people's lives and production, and promote the local economic development.

The construction of marine reservoirs is restricted by complicated conditions such as weather, tides, ocean currents, waves, topography and geology, and is affected by extreme weather such as storm tides. These are the topics that the builders need to study.

3 OCEAN ENGINEERING AND OCEAN RESERVOIRS

3.1 Hydrology and sediments related to marine reservoirs

The coast can be divided into three basic types, namely sandy coast, silt sandy coast and silt coast according to the composition of the coastal seabed and the general law of sediment movement. Coastal sediments are mainly from rivers, coastal erosion and adjacent sea beach.

The power of the coastal sediment movement should be attributed to waves, currents and sub-flows caused by local terrain. The role of runoff on coastal sediment movement should be also taken into consideration for a coast with a river flowing into the sea.

The location of marine reservoirs and the layout of maritime buildings should take into account the interaction between marine engineering and sediment movement in the seabed and sea areas to avoid severe siltation, erosion, or drastic changes of coasts or estuaries.

Ocean reservoirs, like other maritime works, should be built on a place where the shoreline is basically stable and the sediment is relatively less.

3.2 Engineering geology related to marine reservoirs

For ocean engineering, the regional basic engineering geological conditions are highly critical.

When selecting a site for marine engineering buildings, the investigation and survey of engineering geology, hydrogeology and seismicity should be carried out according to the requirements, and the comprehensive evaluation of the site should be made according to site soil, geological structure and topography.

A relatively favorable site against seismic damage is suggested for buildings, while unfavorable sites should be avoided. Construction in dangerous areas, if needed, must be fully demonstrated.

The adverse effects on the structure should be taken into account when there is a liquefiable soil layer, a soft soil layer or a serious uneven soil layer in the main holding layer of the foundation, and necessary measures should be taken.

3.3 Structural works related to marine reservoirs

The company has successfully designed and implemented a large number of marine engineering cases, such as waterway projects, ship lock projects, anti-wave embankment projects, artificial island projects, reclamation projects, and bank revetment projects in varied and complicated weather, tide, ocean current, wave, topographical and geological conditions for coastal engineering both at home and abroad. We have established a complete technical theory system in the construction of marine reservoirs.

The main structure of the marine reservoir is a lake dam or a sea dam. A reservoir dam built in the marine environment requires not only the impoundment function but also an ability to resist the waves and the impact of the tide, and that is why the marine reservoirs need to be equipped with anti-penetration breakwater. We have designed and implemented in coastal engineering numerous breakwater works and developed a large number of patents.

The structural styles of breakwaters and embankments for hydraulic structures at a harbor and waterway renovation structures at home and abroad are mainly sloping dikes, vertical dikes and mixed dikes. Most of the sloping dikes are of a diagonal structure. Vertical dikes located on the rubble bed are structured with concrete blocks, reinforced concrete caissons and other construction materials. The mixed dike is a dam structure characteristic of a good loading condition, a good-looking appearance, a small work amount on water and quick construction involves the placement of semi-circular components and prefabricated concrete blocks in other forms on the sloping dike.

The company has developed a tooth-shaped block that can stand against waves, reduce flows, promote siltation and stabilize sand, which is particularly suitable for the construction of breakwaters and embankments and other harbor and waterway renovation buildings under harsh natural conditions.

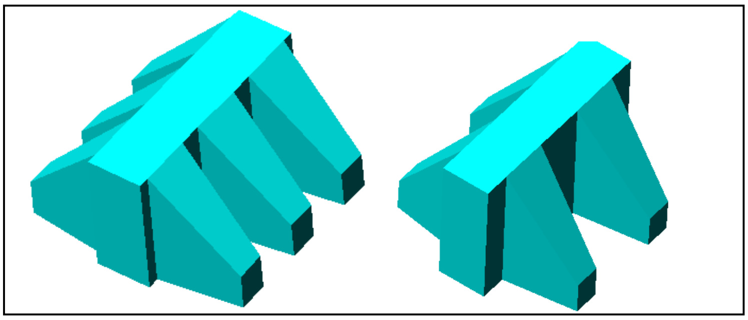

Figure 1. Tooth-shaped blocks and optimization.

There are three types of structural types for revetments, island walls and dams, namely sloping, vertical and mixed structures in harbor hydraulic works and marine engineering both at home and abroad. Reinforced concrete caissons are a type frequently used in the vertical structure. The caissons which can be rectangular and circular are generally provided with a concrete breast wall structure, to form a vertical beach wall with the caissons.

Rectangular caissons, thanks to its good retaining performance, good prevention of leakage of fillers, good connection with upper breast wall, and simple template production, are generally applicable to terminal wall structures. However, when used in revetment structures, their upright front wall to increase the reflection of the waves and wave run-up, so they need to rely on their own weight and structural scale to resist the wave force.

The curved wall of the circular caisson can appropriately reduce the wave force acting on the structure, save the amount of reinforced concrete, and present better landscape effects. When used in revetment structures, the connection with adjacent caissons cannot stop the linkage of fillers in the back, so other engineering measures should be introduced, and that is why they are generally used in breakwater structures. Rectangular curved surface caissons integrate the advantages of rectangular caissons with those of circular caissons. Under the same wave condition, the curved front wall can reduce the wave force acting on the caisson by forming an appropriate wave phase difference and angle difference. Also the plane side wall of the structure itself play a filtering and leak-proof role, providing a better comprehensive performance than rectangular and circular caissons integrated performance. In addition, it can form a unique landscape effect. The structure is particularly suitable for revetment and artificial island walls and other hydraulic buildings with larger waves, a higher demand for rear soil conservation performance and landscape effects.

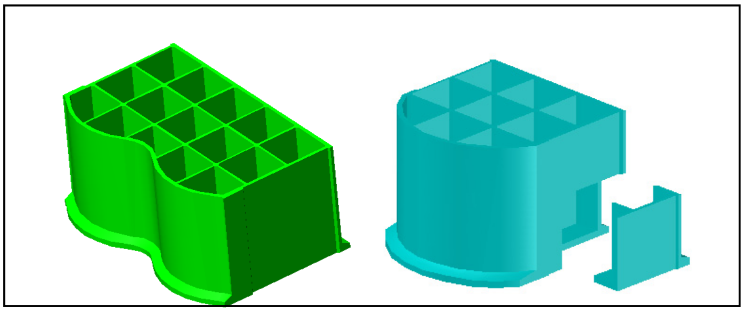

Figure 2. Rectangular curved-surface caissons.

3.4 Salt water-proof studies related to marine reservoirs

The company has conducted extensive studies on the anti-salt water issue of the shop lock in Xingang, Tianjin in 1970s and 1980s in an effort to prevent the sea water from flowing into the river to salinize fresh water. The followings are part of our technological achievements:

(1) Air curtain method
The air curtain is a facility that reduces saltwater exchange velocity. Perforated pipes are set underwater outside of the ship lock and the compressed air is released from the holes on the pipe. The bubble rises to form a vertical water flow, and water flow reduces the water momentum and exchange caused by water density differences, so as to achieve the purpose of lowering salt water exchange.

(2) Salt water pit method
A salt water pit is furnished below the threshold of the ship lock at the freshwater side, and salt water is retained in the pit because of a difference between the density of freshwater and saltwater. The pit is connected to salt water through a salt water discharge corridor so that it can be discharged or pumped into the sea from the corridor.

(3) Diaphragm method
Flexible materials are laid at the bottom of the reservoir for separate freshwater and salt water.

(4) Film dam method

(5) Double ship box method
The double ship box anti-salt water facility is used for water exchange when the lock chamber is completely closed.

4 SIMILAR ENGINEERING EXAMPLES (ENGINEERING EXAMPLES APPLICABLE TO MARINE RESERVOIRS)

4.1 Example of marine reservoir project

The construction of the gate dam in the inland river and the sea side makes it possible to control floods, impound water, regulate water level, store freshwater resources and form a marine reservoir. Flood and draught control as well as water conservancy regulation can be achieved; microenvironment will be changed and local ecological environment can be repaired and compensated; landscape tourism resources in the lake area are developed.

Figure 3. Ecological landscape project designed by the company in East China.

4.2 Example of island reservoir project

China-Myanmar Oil and Gas Pipeline Wharf Project is located on the eastern coastline, Maday Island, Kyaukpyu, west coast of Myanmar. The waters are surrounded by islands, which provide a good cover. The abundant precipitation provides sufficient water supply to reservoir construction. The main function of the reservoir is to supply water to the wharf, the origin station, so the hub layout only needs to consider the water impoundment and flood discharge problems in wet seasons. The reservoir is mainly composed of the dam and discharge buildings.

4.3 Example of artificial island project

The marine reservoir is not only built on the existing coast. An artificial island will be built first, if needed, before the impoundment of the reservoir. CCCC First Harbor Consultants Co., Ltd. develops the curved-surface caissons as the revetment section in the design of an artificial island in Hainan to handle the complicated hydrological meteorological conditions in the open sea to ensure the overall stability and safety of the artificial island and achieve an ecological landscape effect.

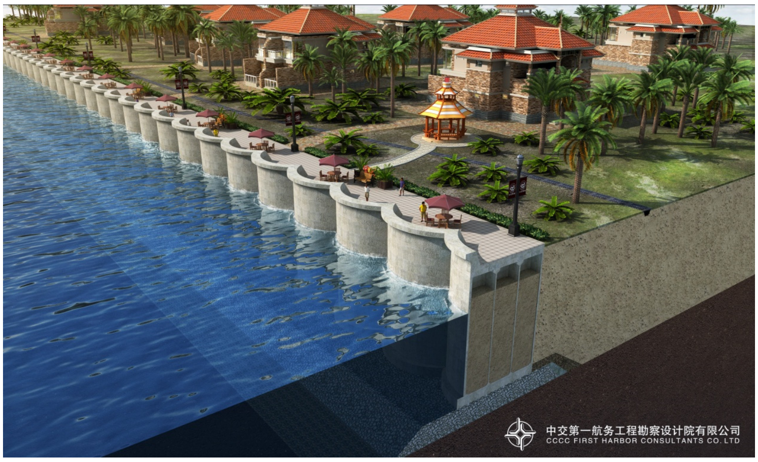

Figure 4. Artificial island project.

4.4 Examples of reservoir survey

Located in the middle of Jinlintai Gorge of Kashgar River on the upstream of Yili River (International river), Jilintai First-grade Hydropower Station is the largest hydropower project in Xinjiang. The company introduces advanced marine surveying equipment (high-precision RTK GPS equipment, high-resolution electronic multi-beam system, etc.), reasonable surveying methods to investigate the front blanket. Detailed data analysis is carried out and a wealth of survey results is produced based on collected mass data, which provides the basic data for the safety evaluation of the dam.

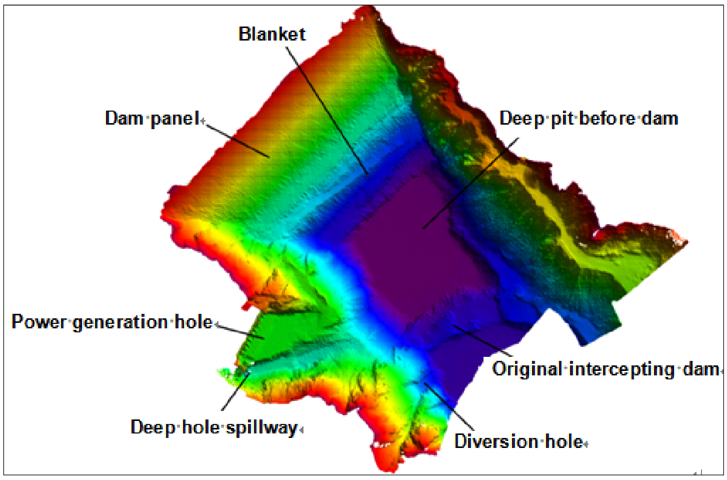

Figure 5. Reservoir survey.

4.5 Example of Harbor Sewage Cyclic Utilization project

In addition to continued population growth, water pollution is also one of the main reasons for water shortage. In harbor operation, sewage discharge will cause different degrees of pollution to the water body, and the landscape environment, dust suppression and rinsing in the industrial area of the harbor need a lot of water. Sewage discharged by the treatment plant in the industrial area will be collected and further treated with the artificial wetland technology. The wetland plants are salt-tolerant plants like reed, cattail and so on, and measures will be taken to control the salt content of sewage in the water; as soon as the earthwork in the artificial wetland is completed, anti-seepage treatment will be performed to solve the problem of high salt content on artificial wetlands. The sewage is finally used in the landscape lake in the industrial area as water supplement and fire water reserves, so that the sewage in the industrial area will be recycled and a green ecological harbor will be built.

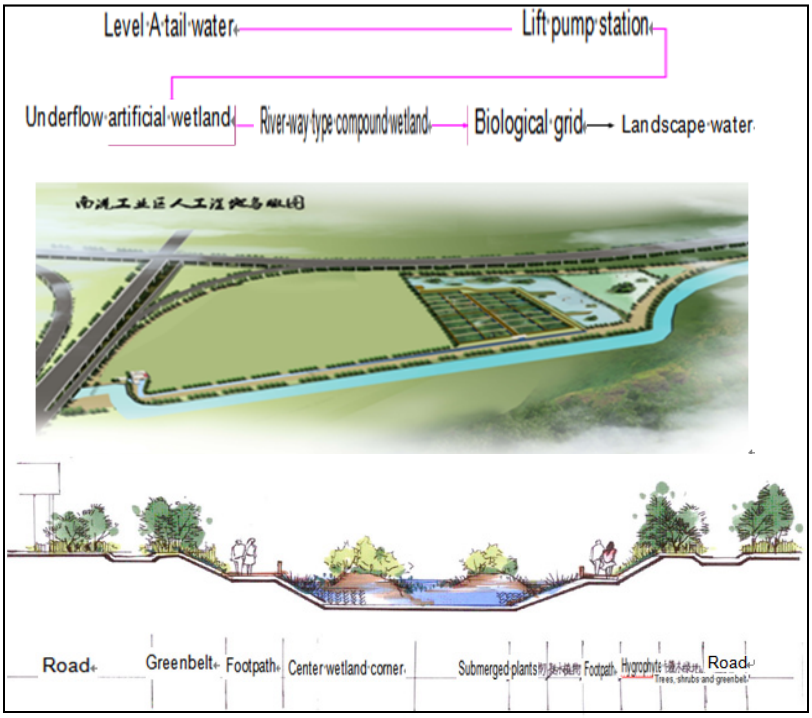

Figure 6. Sewage Cyclic Utilization Project of a Harbor.

5 EXAMPLE OF RELATED COASTAL LANDSCAPE AND COASTAL ECOLOGICAL ENGINEERING

5.1 Ecological engineering I: First stage renovation works of a waterway in Yangtze River

Renovation buildings have to cross over the original greenbelt, and the project plan is to lay soft body mattresses and press with lined stones. Based on the protection of the original ecological environment, ecological restoration technology and design concepts to expand ecological area are studied before the ecological mattress solution is proposed. Artificial intervention is introduced in the project to develop a bottom protection structure that allows beach, plants cultivation and restoration of the ecological environment. Studies on ecological soft body mattress structure and construction technologies are also carried out in the progress of the project.

Studies on geogrid grid scale research and optimization of occlusal cross-block structure are implemented in the ecological protection area. Cultivated high beach plants from the same location can be removed, grown in the same year and replanted in the next year. Ecological geotextile with high strength, high durability and high deformability is developed, and the stability test of the soft body mattress press and protection structure is carried out under the action of wave current. Indigenous plants suitable for the Yangtze River Basin are selected trial-tested at site and summary is made for selection of plant species, planting season, way of planting and anti-erosion; effective construction technology is studied.

The project was awarded the CCCC 2016 outstanding design prize, CCCC first batch energy-saving environmental protection and circular economy demonstration project and first prize of China Institute of Navigation Technology Award in 2016.

Figure 7. First stage renovation works of a waterway in Yangtze River.

5.2 Ecological engineering II: Second phase project of a deep-water channel

According to the field survey, the original lush plants are on the beach as an ecological continuum of trees, shrubs, and grass. The embankment structure of the renovation building laid out according to the engineering scheme and connected to the beach will affect the original plants. New structural style is developed on the basis of the protection of original economic environment and renovation effects to ensure the sustainable development of the ecological environment, specially shaped ecological cage structure solution is proposed in the design for basically full protection of plants in the ecological area.

Figure 8. Second phase project of a deep-water channel.

5.3 Landscape revetment and ecological engineering III: Water transport design project of a science & technology city in North China

The project is a landscape revetment project, and once completed, it will greatly improve the moisture-proofing standard in the enclosed area and enhance moisture resistance, reduce the loss caused by storm tides, improve the scenic environment, strengthen city functions, improve coast stability, advance anti-erosion ability of the coast, protect land resources, and improve the surrounding ecological environment. At the same time, tourism landscape will also be optimized.

Figure 9. Aerial View of Landscape Revetment of Science and Technology City.

The structure of this project is diversified in style, enriched in landscape modeling. There are retaining walls, flower beds, stepping, sculpture bases, glass platforms, landscape lampposts, landscape booths, overlooking platforms, barrier-free ramps, and other landscape structures of different shapes.

Figure 10. Artificial beach.

Figure 11. Ecological shoreline Suaeda and Reed community.

Through the selection and cultivation of ecological engineering species, aquatic plants or hygrophyte are combined with traditional hard revetment with the assistance from special planting methods, materials and medium; in this way, traditional hard revetment is converted into flexible revetment or semi-flexible revetment for the optimization of ecological service functions while satisfying the safety requirements of water conservancy projects.

COASTAL RESERVOIR AS AN INNOVATIVE AND SUSTAINABLE SOLUTION TO RAW WATER RESOURCES DEVELOPMENT IN MALAYSIA

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ABSTRACT

The Coastal Reservoir concept is globally recognized as an effective long-term solution to water resources shortage in regions with adequate rainfall but insufficient land area for storage. The concept has been adopted and successfully implemented in many countries, and one of the largest coastal reservoir schemes—the Qingcaosha Reservoir Scheme—currently supplies water to a population of 13 Million in Shanghai. This concept can be similarly implemented in Malaysia which has an abundance of rainwater but faces water supply shortage.

Keywords: Coastal reservoir; water resources; water quality; hydrology; marine structures.

1 INTRODUCTION

The latest Malaysian National Water Resources Study (2010) highlighted escalating water demands over the 21st century and the need for improving water supply efficiency and distribution. Based on the 2010 census, the population of Malaysia is 28.6 million and is estimated to increase to 41.5 million by year 2040—an increase of 13 million over the next 30 years. The present water resources situation is already experiencing stress both in terms of quantity and quality, and thus water resources planning is one of the main concerns of the Malaysia Government. A sustainable solution to water resources development is critical in order to support the increasing water demand due to the population growth.

Currently, the main source of water is river runoff. Surface water is the most extensively developed resource due to the abundance of rainfall in Malaysia, as shown in Figure 1, which varies from 3310mm at Terengganu (East Coast) and 3640mm at Sarawak (East Malaysia) to 1830mm in Negeri Sembilan (West Coast). Some of the schemes are supported with upstream storage dams to store and regulate the flow downstream. Groundwater usage is still minimal and limited to remote areas where water pipeline distribution is unavailable.

The uneven distribution of rainfall, particularly with relevance to the Western Coast urban centers where water demand is concentrated, has led to extensive interstate pipeline water transfers, which are known to suffer significant (as much as 50%) non-revenue water losses over time. The Malaysian Government embarked on the biggest interstate water transfer scheme in 2010—the Pahang-Selangor raw water transfer scheme, which involved transferring of raw water from Sg. Semantan at Pahang through three diversion tunnels measuring 44.6km in length, to the Langat 2 water treatment plant at Selangor, scheduled to be completed by the end of 2017. Other interstate transfer schemes currently under the planning stage include the Johor-Melaka, Melaka-Negeri Sembilan, and Perak-Selangor water transfer scheme.

The overall current situation suggests increasing infrastructure maintenance costs and non-revenue water losses in the future. In the interest of developing newer and more innovative water resources technologies, the Selangor government initiated the Hybrid Off-River Augmentation System (HORAS) in year 2014. The scheme utilized the existing tin mining ponds located within the water catchment as storage to contain sufficient water for river flow regulation during the dry season. While HORAS managed to increase the water resources yield, there were concerns on the water quality due to the residuals of heavy metals within the beds of the ex-tin mining ponds.

An alternative solution is needed to increase storage capacity without compromising water quality, and the downstream/coastal reservoir concept fits this purpose very well.

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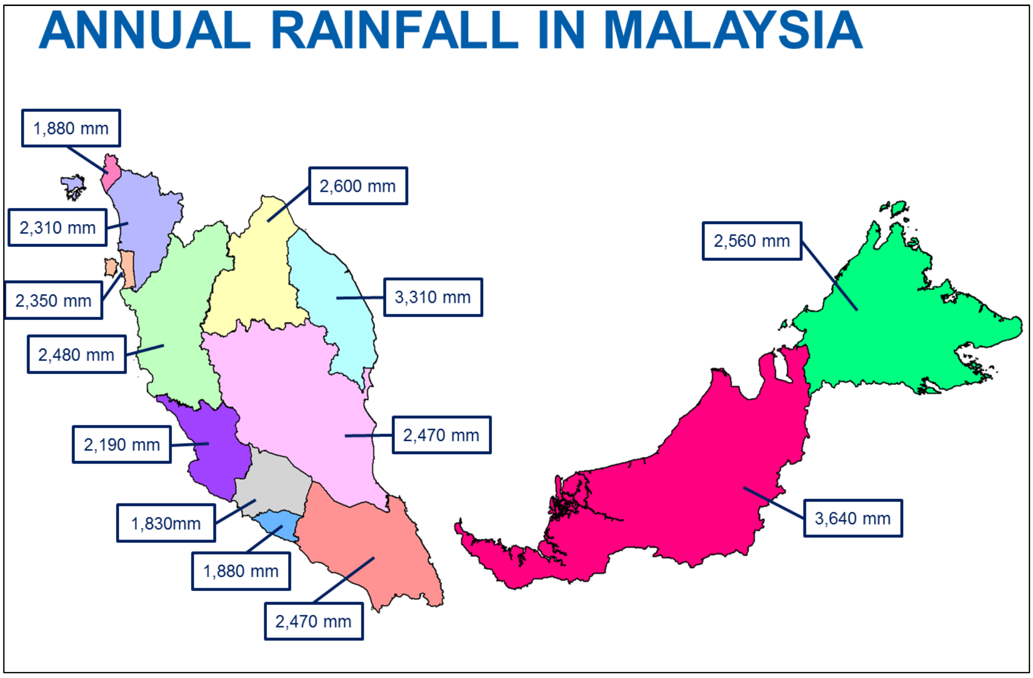

Figure 1. Annual rainfall distribution in Malaysia.

2 AN ALTERNATIVE AND INNOVATIVE SOLUTION

Based on the rainfall depths and recipient land surface area, there is an annual rainfall volume of roughly 990 billion m^3. After the assumption that 57% of rainfall translates to surface runoff, factoring evaporation losses and groundwater recharge, the surface runoff volume is approximately 560 billion m^3. The total water demand as of 2017 is only 3% of this volume.

The concept of a downstream/coastal reservoir has been promoted as a potential long term solution for water resources in Malaysia. The present river runoff and dam system utilizes about only 3% of the available water, with most of the remaining water discharged into the sea. Water shortage is primarily an issue of storage rather than supply. Instead of existing mining ponds, storage can be created downstream or nearshore by utilizing a river reservoir, oxbow lake, or by constructing the reservoir at nearshore (refer Figure 2). Utilization of a downstream/coastal reservoir will be able to increase potential available water resources to 15% or more, which is more than sufficient to meet the long-term water demand in Malaysia and resolve the water shortage problem during drought by storing the excess water during wet seasons.

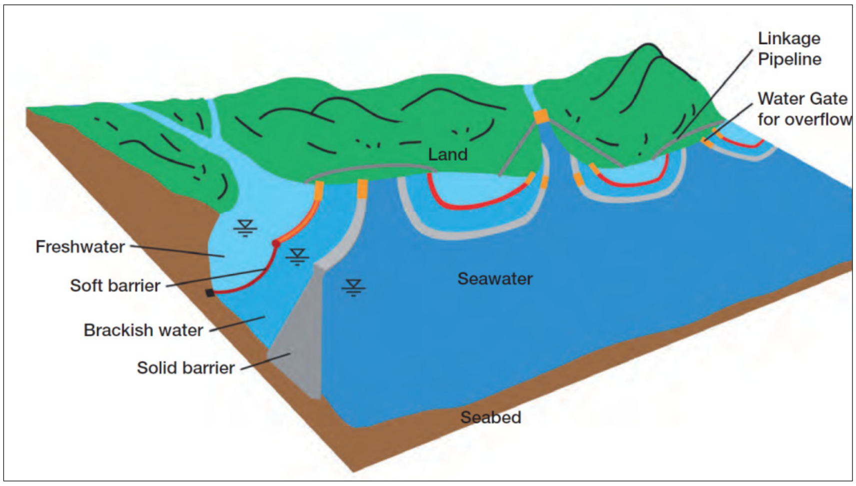

Figure 2. Downstream or coastal reservoir concept.

The location of the downstream/coastal reservoir also resolves a traditional issue of water resources management, which is that conventional dams and reservoirs are emplaced in the upper part of a water catchment, with the river intakes located along the upper to middle catchment, and the demand centers located typically at the lower catchment or coastal areas. By locating the reservoir close to the demand center downstream, it captures a greater portion of catchment runoff and alleviates the need for regulating environmental flow from a dam or to other river intakes. In contrast to conventional downstream river intakes, a downstream/coastal reservoir is also protected from salinity intrusion by virtue of its containing structure, and is able to be selective about receiving flow of suitable water quality.

3 DOWNSTREAM/COASTAL RESERVOIR

A downstream/coastal reservoir is a freshwater reservoir located at the river mouth, nearshore or alongshore. It is capable of providing extensive water storage capacity as it is not limited by land area. The water in the coastal reservoir can be used for drinking, irrigation or industrial usage. Compared with water from seawater desalination processes, the water quality is similar to storm water or dam water in inland reservoirs, which saves costs by using natural resources. Unlike inland dams, a downstream/coastal reservoir harvests the catchment runoff before it escapes into the sea, and has the potential to catch all runoff from a catchment (refer Table 1).

Table 1. Examples of downstream/coastal reservoirs.

Name	Catchment (km^2)	Dam Length (m)	Capacity (mil m^3)	Year Completed	Country
Qingcaosha	66.26[a]	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
West Sea Barrage		8000		1986	North Korea

Downstream/coastal reservoirs can extend below the sea level, and existing freshwater lakes or lagoons on the shore can be regarded as special or natural coastal reservoirs. The dam of a downstream/coastal reservoir can be constructed of concrete, earth or other materials depending on the soil condition, and consists of a primary and secondary barrier. The primary barrier should be high enough to avoid tidal influx and significant wave height, and be able to withstand the forces imparted on the wall by wave and tidal actions. The secondary barrier is typically a floating barrier with a suspended skirting that extends to the floor of the reservoir and can be weighted with ballast to fix it in place. It can also be moved with an anchor and chain system. This allows a buffer zone that can be varied in volume to maintain and separate contaminated water from uncontaminated fresh water (refer Figure 3). The reservoir is filled by either passing fresh water through a gate system during river flow or flooding or by way of a conventional catchment system where the downstream/coastal reservoir is fed directly by catchment runoff. Downstream/coastal reservoirs are designed in such a way that they can be adapted to different locations without blocking off entire waterways as shown in Figure 4, and thus do not disturb environmental flows or require rerouting of channels.

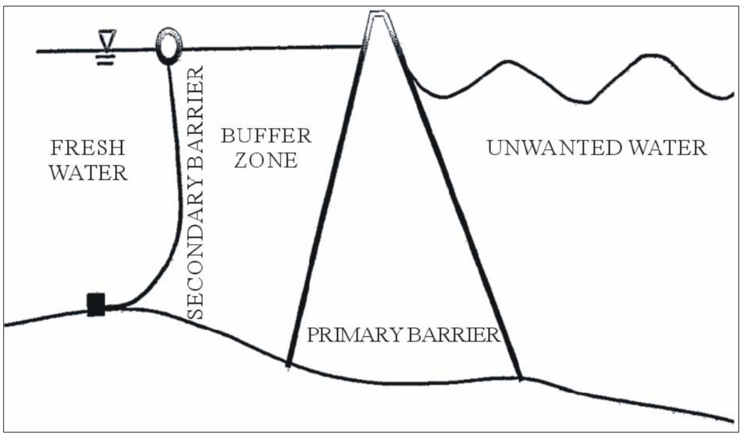

Figure 3. Illustration of buffer zone created by primary and secondary barriers.

[a] This figure refers to reservoir area instead of catchment area.

Figure 4. Qingcaosha reservoir maintains freshwater storage without obstructing waterways.

The downstream/coastal reservoir also takes advantage of the monsoon patterns in Malaysia, which dominates rainfall patterns and monthly distributions (refer Figure 5). The highest rainfall typically falls within the end of the year, while dry seasons are typically about 2 to 3 months in which water shortages emerge. Storage of excess flood water during wet seasons allows for distribution during the next dry spell. Sizing of the storage required at the downstream/coastal reservoir can be estimated by assuming zero inflow into the reservoir during drought. Actual storage requirements may require detailed design and detailed reservoir storage simulations to calculate recharge.

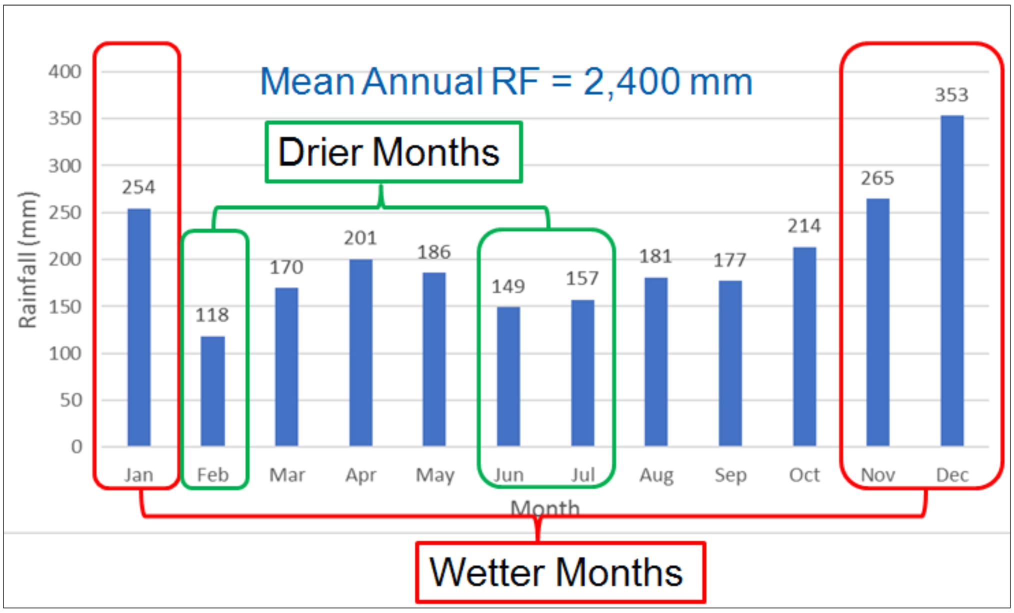

Figure 5. Typical monthly rainfall distribution of Malaysia.

4 ADVANTAGES OF DOWNSTREAM/COASTAL RESERVOIR

In addition to effectiveness, the downstream/coastal reservoir is also a long-term cost saving solution. Comparison of construction costs per kilolitre of water and costs per kilolitre of water was conducted for coastal reservoirs against the costs of other water resources solutions, based on conditions in Australia (Yang et. al., 2013). Coastal reservoirs costs are calculated based on the existing coastal reservoirs in the world.

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Inland reservoir data is based on statistical data of the United Nations. Desalination costs are from evaluation of case studies in Israel, Singapore, Australia, America and India. Water recycling data is based on Remco Engineering on Water Systems and Controls in USA and National Snapshot of Current and Planned Water Recycling and Reuse Rates in Australia. The data resource on mass water transport is with respect to water transportation projects in Australia, the USA, China and Africa. Table 2 illustrates that coastal reservoirs are more cost effective compared with other alternative approaches.

Table 2. Cost comparison for water resources.

	Construction cost per kilolitre of water (US$)	Cost per kilolitre of water (US$)
Coastal reservoirs	2.67-6.01	0.15-0.25
Inland reservoirs	5.83-7.5	0.34-0.4
Desalination	6.41-10.08	0.43-1.13
Water recycling	5.57-8.30	1.44-1.53

In comparison with traditional inland dams located upstream in Malaysia, downstream/coastal reservoirs provide the following advantages as shown in Table 3.

Table 3. Advantages of downstream/coastal reservoirs against conventional dams.

Comparison	Dam	Downstream/Coastal Reservoir
1. Land Acquisition	- A large land area is required to be inundated	- Minimum land acquisition, utilizing river reserves, buffers, waterways, shore area etc.
	- Loss of productive land	- Potentially creates new land area and enhances surrounding property value with a significant waterbody
2. Environmental impact	- Loss of fauna and flora - Loss of green area and thus carbon absorption	- Minimum or no impact
3. Social impact	- Creates social issues and faces strong objection from locals and public	- Less social issues as site selection can be very flexible
4. Heritage/ Historical site	- Sometime may inundate heritage or historical site	- Unlikely and can be avoided as site selection is flexible
5. Distance to demand point	- Very far, up to hundreds of km	- Very near to demand points
	- High energy cost as it involves booster pumping from source to demand points	- Low energy
	- More losses due to longer pipe length	- Less losses due to much shorter pipe length
6. Catchment area	- Often sited at upstream, thus having smaller catchment area	- Sited downstream, thus having much larger catchment area
	- During drought, reservoir gathers no rainfall	- Gathers flow potentially throughout the year
7. Expandability	- Limited and difficult	- Can be easily expanded
8. Risk	- Create dambreak risk to downstream population and properties	- Minimal or no risk
9. Maintenance cost	- Higher	- Lower
10. Construction	-Slower	-Faster

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5 CONCLUSIONS

Malaysia is a water-rich country. Improving water resources management by adopting the new and innovative approach of downstream/coastal reservoir can potentially increase the utilization of raw water resources from the present 3% to 15% or more depending on the region. This potentially resolves the water shortage problem during drought by storing the excess water during wet seasons. There are many significant advantages to adopting downstream/coastal reservoirs as compared to inland dam reservoirs or other alternate solutions. It is overall a cost-effective, environmentally friendly, green and sustainable solution for raw water resources development in Malaysia.

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INNOVATIVE SEA BASED FRESH WATER RESERVOIR TO IMPOUND RIVER FLOOD WATERS: AN INITIATIVE FOR INDIA'S WATER SHORTAGE

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ABSTRACT

Most of India's rainfall comes over a 4-month period and average annual rainfall is very high. India receives years of excess monsoons and floods, followed by below average or late monsoons with droughts. Some regions see shortages of drinking water as well. The geographical and time variance in availability of natural water versus the year-round demand for irrigation, drinking and industrial water creates a demand-supply gap that has worsened with India's rising population. For India's water problem, the solution is to conserve the abundant monsoon water and store it in reservoirs, and use this water in areas which have occasional inadequate rainfall. This paper highlights innovative solution of storing flood water in sea based reservoirs as against the land based reservoirs. Sea based reservoir can be constructed in shallow coastal waters at appropriate locations close to the mouth of the river with a sea dike along with a spillway at one or two ends. This basically replaces the salt water in the shallow coast with fresh flood waters from the rivers. This paper discusses the clear plans along with some case studies across the world highlighting the advantages of sea based / coastal reservoirs. The paper highlights on the cost of construction per BCM of water stored and also cost per kilo litre of fresh water through this sea based (coastal) reservoirs when compared to recycling of sewage water, stored water in inland dams, ground water and desalination processed water.

Keywords: Sea based (Coastal) reservoirs; flood water; India's water resources; storage per capita.

1 INTRODUCTION

With the ever-increasing population, demand for water keeps on increasing day by day. For example, an average rainfall in India is about 4,000 billion cubic meters. But most of India's rainfall comes over a 4 months period starting from June to September. India also experiences years of excess monsoons and floods, followed by below average or late monsoons with droughts. Despite an abundant rain's in July to September, some regions face shortage of drinking water, while some other parts of the country receive excessive rains resulting in floods. This spatial and time variance in availability of rain water versus the all-round the year demand for irrigation, drinking and industrial water creates a demand-supply gap that keeps worsening with rising population. Solution to India's water problem is to conserve the abundant monsoon water bounty and store it in sea based reservoirs. Further use this water in areas which have occasional inadequate rainfall or known to be drought-prone or in those times of the year is when water supplies become scarce.

Thus, various measures are taken to overcome the water shortage crisis around the world to overcome above mentioned problems. Some of the measures include use of groundwater, formation of inland reservoir across rivers, seawater desalination, water diversion, treated wastewater reuse, rain water harvesting and the like. However, all these techniques have their own disadvantages. The water supply source of inland reservoir relies on rainfall. Besides, a location of inland reservoir across a river is difficult to be sited, as the construction of inland reservoir requires a correct combination of topography, hydrology and geology. Building of these inland reservoirs also requires a migration of people residing in that area or changes the local ecological environment which is against the interest of the people and submergence of forest land and villages.

The currently available water solutions are unable to satisfy people's increasing need for water. As far as rain water is concerned, one area receives too much rain in the wet season thereby causing floods and excess rainwater discharge into the sea, while receiving a shortage of rain fall in dry season. Hence, the solution lies in utilizing or conserving the abundant monsoon water which runs off to the ocean.

Hence, there is a need for a method for developing a sustainable water source for managing rain water. There is also a need for developing sea based fresh water reservoirs for storing flood water. There is a further need for storing flood water in sea based reservoirs by building impermeable sea walls and interlinking these reservoirs for transfer of water from one place to another. The primary objective of the present paper is to present a method for developing a sustainable water source for managing rain water and in particular river flood waters.

2 CURRENT WATER SOLUTIONS

Different kinds of water supply options exist in the world, for example groundwater, inland reservoir across rivers, desalination of seawater, reuse of treated wastewater, and diversion of water from a remote source. Each of these have their own characteristics. The primary renewable source of freshwater is rainfall. Rainwater runoff, surface water, subsurface flow, ground water and sea water are other sources of water available for water supply options. Followings are the different options:

i. More inland reservoirs - very few large dams after the year 2000; more and more people have realized the problems of large dam construction on land, silting process which reduces storage – 75% silt will be left on land. Furthermore, India is the third largest dam building nation in the world with more than 500 dams (large dams).
ii. Interlinking of rivers – to optimize the surface water.
iii. Ground water.
iv. Desalination plants.
v. Wastewater reuse facilities.
vi. Coastal (Sea based) reservoirs.

3 COASTAL RESERVOIR TO STORE FLOOD WATER

The various embodiments of the present methodology are to create a fresh water reservoir located near the mouth of a river at the sea for the collection of fresh water from the river during flood. The fresh water reservoir includes an impermeable sea wall for containing the fresh water and preventing a mixing of the fresh water with the sea water. The sea wall is located on the sea bed having three sided structure to prevent ingress of sea water into the fresh water/river course. By keeping out seawater, the construction of sea wall along with one or two barrages (with sluice gates) close to the mouth of river forms the fresh water reservoir in the ocean. Sea-based reservoir is part of the river watershed which is formed by the convergence of the rivers and allows fresh water and salts to join the ocean. The reservoir will be in shallow waters and have an average depth of 10 to 20m with a maximum depth of about 30 to 40 m. When it rains heavily during low-tide, the sea reservoir outflow crest gates has to be lowered to release the excess rain water from the reservoir into the sea. If heavy rain falls during high-tide, the outflow crest gates remain closed and large reservoir can be designed so as to absorb the flood water shocks during high tide and releases water out to sea only during low tides. The method suggested in this paper further includes interlinking of these reservoirs at different locations across different rivers through underwater subsurface pipes for transferring water from one reservoir to another in shallow sea water (here in, we called this as Sarovar Mala; Sarovar means freshwater pond in Sanskrit language and mala means necklace around the land) – ref: Sitharam, (2016).

4 SCENARIO IN INDIA

On an average, India receives about 4000 BCM of precipitation (includes rainfall and snowfall) every year. Rough estimates of west flowing rivers Netravati, Narmada, etc. add up to 276 BCM (9800 TMC feet) of water every year. Even if we assume just 45% of average monsoon rainfall during floods flows into ocean, it will be about 124 BCM (4400 TMCft) of water from west flowing rivers draining into Arabian Sea. Similarly, east flowing rivers, namely Krishna, Godavari, Kaveri, Mahanadi, discharge 350 BCM (12500 TMC feet) of water and out of this 5625 TMC ft of water per year flows into Bay of Bengal beyond the storage capacities of existing dams and natural water bodies in about 4 months of monsoon season. This huge amount of water merges with the salt water of the oceans when there are severely water stressed cities and towns in Tamilnadu, Andhra Pradesh, Telangana, Karnataka, Maharashtra, Madhya Pradesh and Orissa states. India is an agricultural country and 80% of stored water in dams (which is about 174 BCM) is used for agricultural activities. Due to silting the actual water stored is much lesser than 174 BCM.

India has built more than 5000 dams so far. Dams are constructed at number of places to stop running water of the rivers and store them. Subsequently they are pumped to meet the drinking water requirements of the people. The land area submerged (mostly very precious agricultural land and villages /towns) is not clearly quantifiable and no data exists in public domain for all the dams. Available estimates of people displaced by large and medium dams in India show that (based on the 140 dams for which such figures are available) over 4.4 million people have been displaced. However, firstly, these are only government or World Bank estimates and hence are likely to be very conservative figures. Secondly, these figures of people displaced within the reservoir area only, that does not include people displaced by related works of dam projects like canals, colonies, downstream impacts, compensatory afforestation, catchment treatment and sanctuaries. With the strict environmental regulations and guidelines, there is no possibility of constructing new dams as there is acute shortage of land and there are serious problems of displacements and compensations and rehabilitations associated with this.

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Thus, we have about 6 months of storage of water for domestic purpose. This is too small when compared to developed countries. It is wise to invest in storage of this excess flood water (which is reasonably diluted and cleaner), i.e. fresh water in sea based reservoirs close to the place where river joins the sea.

5 CONFIGURATIONS OF SEA BASED RESERVOIR / COASTAL RESERVOIR

A freshwater reservoir is located in the sea close to the mouth of a river with sustainable annual river flow/flood water (see figure 1a). Flood water is a natural resource, and water quality is more close to drinking water. An effective impermeable barrier between the fresh water (flood water) and the salty sea water is needed. Figure 1a also shows different options of coastal reservoirs. It can also be in bay, gulf and estuary.

Separation of clean river water from salt water is an important step in this technique. Protection of collected fresh water against external pollution is critical. Prevention of salt water intrusion into the stored fresh water is a key step. A Sea Based Reservoir (SBR) or a coastal reservoir is a reservoir that is primarily created within the marine environment where the mouth of a river is situated. Sea based reservoirs collect runoff from the entire watershed and provide greatest potential. In Indian context and in general, all the flood waters. which are lost to the sea forever. can be stored before it joins the ocean and thus reclaim. As an example, a typical western flowing river from a level of 1000 m above mean sea level flows in to the ocean within an about 150-200 km distance in the western ghats of Southern India. A typical river is shown in Figure 1b. This concept deals with preventing the flood waters of the rivers from mixing with the sea waters by creating a reservoir with suitable walls / wall with barrier lining between sea and the shore line. The walls / wall with barrier lining is so designed that it will prevent mixing of surrounding sea waters with the impounded flood waters. The SBR can have any one of the three configurations: (i) SBR fully situated within the sea with no contact with the land except by channels or pipes, (ii) SBR which borders with the land on one side and the other side with the sea, and (iii) SBR which partly covers the river mouth and allows the rest of river to flow in to the sea (see Figure 1a). Broadly speaking, there are 3 ways to build sea based reservoirs: Building the SBR by completely encircling the river mouth (inset iii in Figure 1a); Building SBR by keeping it at a short distance from the river mouth (inset ii in Figure 1a). The river flood water impounded will be transported to different locations on the land to meet the fresh water needs.

(a)

(b)

Figure 1. a) Different Configurations of a sea based reservoir. b) A typical west flowing river in Southern India.

The following different configurations are detailed as below: *building the SBR by completely encircling the river mouth has the following advantages:* All the flood waters are impounded effectively. Minimum sea wall cost. River mouth is protected from tidal waves / tsunami. This is desirable if we do not want to impound all the flood waters. Nutrients are allowed to go into the sea which would affect aquatic life. The reservoir can be designed to take care of occasional very heavy floods by providing adequate gates for discharge of the flood waters into the sea.

Building SBR by partially encircling the river mouth: advantages: permits nutrients to reach the sea which will support the aquatic life. River mouth is not fully protected from the tidal waves / tsunami, and thus backwaters can be brackish: is one of the disadvantages.

Building SBR by keeping it at a short distance from the river mouth: *advantages:* all the salts/nutrients can reach the sea for supporting the aquatic life. In case of very heavy floods, the waters can be easily diverted in to the sea. Convenient for the fisherman to go in to the sea from coast line. *Disadvantages:* Expensive piping / tunnelling is required for transporting the flood waters in to the SBR which is situated in the sea.

6 COMPARISON OF SEA BASED RESERVOIR VS LAND BASED RESERVOIR

There are many advantages of sea based reservoirs as against land based reservoirs. Table 1 shows the comparison of sea based reservoir to the land based reservoirs. There are many advantages of the sea based reservoirs when compared to any conventional land based reservoirs.

Table 1. Comparison of sea based reservoir vs Land based reservoir (modified after Yang et al., 2013).

Item	Sea based Reservoir	On land reservoir
Dam Site	Sea (Inside / outside river mouth)	Valley (limited area)
Water level	At sea level	Above sea level
Pressure	Low pressure along with wave surges	High water pressures
Catchment area	Entire Catchment of the river course	Partial catchment
Seepage	By density difference (Slow)	By head difference (fast)
Pollutant	Land based and sea water	Land based
Land acquisition	Nil	High
Environmental damage	Nil (no forest damage, no displacement of people, etc.)	Very high (difficult to build dams now a days)
Water Supply	By pumping	Mainly by gravity
Construction cost	Low	High

Followings are the advantages of sea based coastal reservoirs:

i) No harm to any of the river basins and no alteration to the river course (no temporary diversions as well)
ii) No disturbance to any forest cover and No submergence of land
iii) No physical displacement of people and their villages / towns
iv) Agriculture activity can be augmented
v) Coastal erosion can be minimized
vi) Ground water recharge due to fresh water in estuarine areas
vii) Intrusion of saline water into wells will reduce
viii) Freshwater dredging will provide sand for construction
ix) Earthquake resistant sea walls
x) Solar panels on the sea wall – Solar energy
xi) Tidal energy at the wall
xii) Roadways over the sea wall, Fresh water Fishing, Navigation and Tourism
xiii) real estate opportunities
xiv) Length and width of sea wall - serve as a deep-water fishing harbour - benefit the fishing community.
xv) Increase in industrial, recreational and fisheries activity around this fresh water

The existing and planned sea based / coastal reservoirs in the world can be summarized as below (updated after Yang, 2016). Table 2 shows the existing coastal reservoirs in the world along with the purpose.

Table 3 gives the cost of water and cost of construction using coastal reservoirs in comparison to desalination, inland reservoirs, water recycling (from waste water). Cost of water per 1000 liters (1m3 or Kilo liters) and cost for construction for storing 1 Billion Cubic meter (BCM) of water has been estimated considering the costs of labor, materials and execution in India. Cost of water has been estimated at the location of coastal reservoir without considering the cost of pumping.

Under Planning Stage: 1. Pluit Reservoir Revitalization Project, Jakarta, Indonesia, 2. Kalpasar project, Gulf of Kambhat, Indian Water Project, Gujarat, 3. Sydney and other coastal cities , Australia, 4. New York , USA

Table2. Existing sea based reservoirs around the world (modified after Yang and Kelly, 2015).

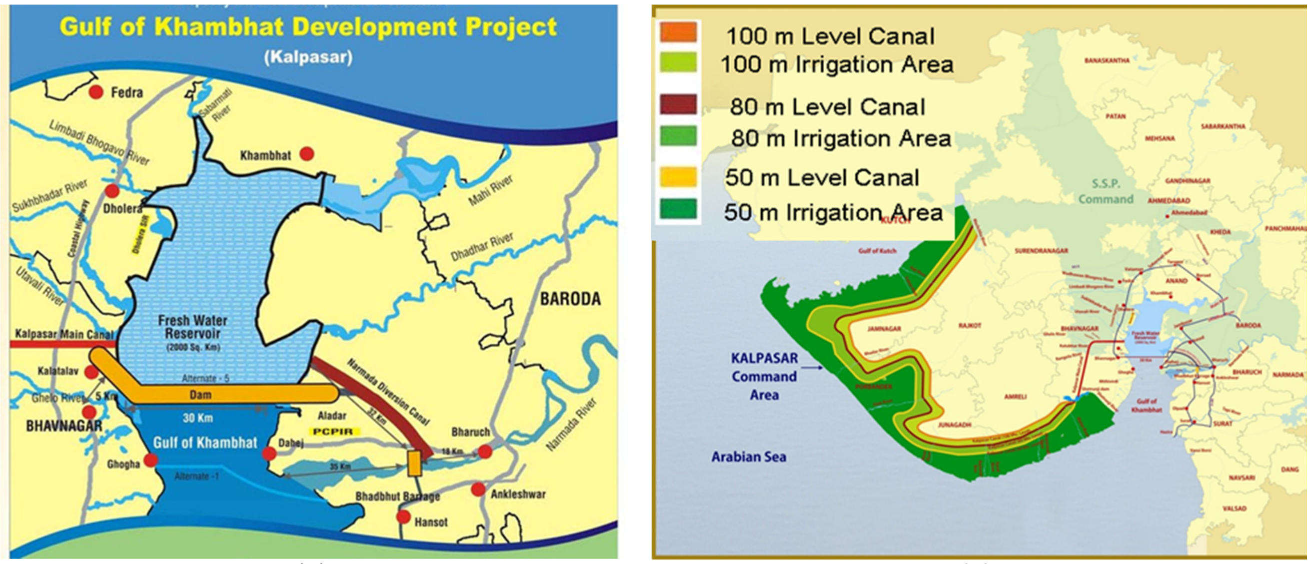
Country	Name	Purpose
Netherlands	Afsluitdijk in the Ijsselmeer (1932)	Flood control
South Korea	1. Sihwa (1994) 2. Saemanguem (2010)	Tidal energy Land reclamation and fresh water
Hong Kong	1. Shek pik (1968) 2. Plover cove 3. High land	Fresh water
China	1. Qingcaosha (2011) 2. Chenhang (1992) 3. Baogang (1985)	Fresh water
Singapore	Marina barrage (2008)	Fresh water

Table 3. Cost of water and cost of construction (1 US Dollar = Indian Rupees 70).

	Cost per Kilolitre of water in Indian Rupees (Rs)	Cost of construction / Billion Cubic Meters (in Indian Rupees)
Sea based reservoirs	Rs 2 -10 (Sea level)	Rs 20000 Million/BCM
Inland reservoirs	Rs 30-100 (above the sea level)	Rs 100000 Millions / BCM
Desalination	Rs 60-80 (Sea level)	Rs 80000 Millions/ BCM

7 INDIA'S KALPASAR PROJECT - INDIAN WATER PROJECT

The Gulf of Khambhat Development Project is mainly a water resources project involving creation of fresh water reservoir in the Gulf of Khambhat in the state of Gujarat, India for meeting demand of irrigation, domestic and industrial water supply. Associated components related to the fresh water reservoir are use at the top of the dam across the Gulf as a surface transport link, potential development of fisheries, reclamation of saline land around the fresh water reservoir. The Gulf of Khambhat extends from north to south about 200 km and the width varies from 25 km at the inner end to 150 km at the outer mouth, covering an area of about 17000 sq.km, of which only 2000 sq. km will be enclosed by constructing a dam across the Gulf between Bhavnagar and Dahej. Figure 2a and 2b show the Kalpasar project location and detailed plan of Gulf of Kambhat development plan, in which a coastal reservoir is envisaged in Gulf of Khambhat and it uses contour canals to supply water the entire Gujarat Coast. In the Kalpasar project, a dam across the Gulf of Khambat will be built for establishing a huge fresh water reservoir for irrigation, drinking and industrial purposes. A 10 lane transport road link will also be set up over the dam, greatly reducing the distance between Saurashtra and South Gujarat by 225 km. A state government release highlighted that the Rs 55,000 crore (US$ 11.7 billion) project to be completed by 2020, will have a vast fresh water reservoir with gross storage of 16,791 million m^3. 64 km long dam across the Gulf of Khambhat connecting Ghogha in Bhavnagar with Hansot in Bharuch District of Gujarat state. State government of Gujarat has signed an MOU with Korean consortium to build the first ambitious sea wall project in the gulf of Khambhat in the first quarter of 2016 (Kalpasar, 2016). Once constructed, it will be one of the largest freshwater reservoirs in the sea with highest priority for irrigation and drinking water in the region for Saurashtra and Central Gujarat regions of India.



(a) (b)

Figure 2. a) Coastal reservoir in Gulf of Kambhat in Gujrat state. b) Developmental plan to supply water for entire Gujarat using the Coastal reservoir (Kalpasar, 2016).

8 CONCLUDING REMARKS

India receives most of its fresh water during a four months monsoon period, during which time the lakes are filled, rivers experience floods and ground water is recharged. But due to onset of climate change, the rainfall pattern changed resulting extreme variability of the rainfall experienced. While some rivers receive huge quantities of rain resulting extreme flooding, other rivers and water bodies are bone dry. Indian population over the decades has increased so much that the density of population and dwindling forest coverage is not allowing creation of fresh land based reservoirs. The original Indian proposal of interlinking of rivers to overcome the ill effects of variable rainfall is practically dead and impossible to implement under the changed circumstances and huge cost of the project. Considering all the above, the solution lies in storing flood water in sea based reservoirs as this does not submerge lands which are of immense value. If there is heavy rain during high-tide, the outflow crest gates remain closed and large reservoir of about > 100 TMCft (2.8 BCM) can be designed so as to absorb the flood water shocks during high tide and releases water out to sea only during low tides. Even the sand, silts and salts can join the ocean through the sea based reservoir along with the rest of the river flow. Sea based reservoir can be constructed in shallow waters at appropriate locations close to the mouth of the river along with a barrage at one or two ends. A detailed study is needed even considering salt water intrusion through river estuarine, bays and gulfs. Sarovar mala by connecting coastal reservoirs around the Indian peninsula will be a sustainable solution for Indian water requirements specifically in the coastal areas connecting many smaller coastal reservoirs. More species of fish call these reservoirs their home. This reservoir will increase India's fresh water supply for generations to come and use the rivers flowing into Arabian sea and Bay of Bengal.

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SEA DIKE CONSTRUCTION CHALLENGES IN COASTAL WATERS FOR STORAGE OF RIVER FLOOD WATERS: SUSTAINABLE STRATEGY FOR WATER RESOURCE DEVELOPMENT USING COASTAL RESERVOIRS

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ABSTRACT

In this paper, marine civil engineering structures such as breakwater and sea dikes are discussed along with the challenges of constructing a sea dike in coastal waters close to the coast for storage of flood waters or coastal reservoirs. Here, the solution in utilizing or storing the abundant monsoon water, which runs off to the ocean close to the coast itself using coastal reservoirs bounded by sea dikes with suitable modifications, is proposed. Sea dike is an earthen dike, often meant to prevent flooding of the hinterland and the primary function is to protect low-lying coastal areas from inundation by the sea. For creating costal reservoirs for storing river flood waters within the shallow waters of the coast close to the point where river joins the ocean. Breakwaters and sea dikes are structures which provide protection against the wave action of the sea and provide coastal protection. The same can be suitably modified for construction of coastal reservoir dikes. Each type of structures, which are being considered in the marine environment, will be discussed along with their advantages and disadvantages. Construction types of the sea dike or breakwater with specific modifications and alternatives will be presented with necessary design principles and different types of structures which are feasible in this marine environment. A case study of Ennore coal project, India is briefly presented, where a construction of breakwater has been done to protect coal harbour and incoming ships. This case study will be presented in brief to highlight the need of new construction technology for building sea dikes using geotextiles. Emerging geosynthetic materials and innovative geosynthetic applications is presented for the construction of sea dikes for creation of coastal reservoirs.

Keywords: Sea dikes; coastal reservoirs; flood waters; water resource development; geosynthetics.

1 INTRODUCTION

A sea dike is an embankment widely used to protect low-lying areas against inundation and acts as a backwater to prevent erosion of the coast and encroachment of the sea. The purpose of a sea dike is to protect areas of human habitation like towns & villages, and, conservation and leisure activities from the action of tides and waves. Storage of the abundant monsoon water is done close to the coast using coastal reservoirs, which otherwise runs off to the ocean. Coastal reservoirs are bounded by these impermeable sea dikes and the coast on one side. These sea dikes with suitable modifications can be used for creating costal reservoirs with in the shallow waters of the coast. Sea dike is a static feature and it will conflict with the dynamic nature of the coast and impede the exchange of sediment and salt water between land and sea at the mouth of river. Sea dikes are classified as a hard engineering shore based structure used to provide protection and to lessen coastal erosion. Sea dikes may also be constructed from a variety of materials, most commonly: geosynthetic tubes, geocells, reinforced concrete, boulders, steel, or gabions. A sea dike is also used for land reclamation projects. Sea dikes are primarily used at exposed coasts, but they are also used at moderately exposed coasts and in this case, use of sea dikes is presented for the separation of ocean salt water from the flood water from rivers stored in coastal reservoirs (bounded by sea dikes). These sea dikes can protect populated areas, economic areas like aquaculture areas, tourism places and also reduce coastal erosion. The dikes across estuarine can reduce the impacts of tides and waves from the sea and also help in reducing salt intrusion into the river course through the estuaries.

Due to erosion and accretion, the shoreline changes are natural processes that take place over a range of time scales. They may occur due to small scale events, such as storms, wave action, tides and winds, or in response to large-scale long-term events such as glaciations or cycles that may significantly alter sea levels (rise/fall) and further, tectonic activities that cause coastal land subsidence. Hence, coastlines are dynamic, and cycles of erosion are often an important feature of their ecological character. Wind, waves and currents are natural forces that easily move the unconsolidated sand and soils in the coastal area, resulting in rapid changes in the position of the shoreline. The sea dike as part of coastal reservoir actually is a boone to reduce these ill effects permanently and bring economic prosperity to the coastal areas. Here, the objective of the sea dike is to store abundant monsoon flood waters close to the coast in the ocean by replacing salt water with fresh river flood waters.

2 SEA DIKE DESIGN ASPECTS

Sea dike route is selected based on the basis of techno-economical reasoning after considering following points:

i) Topographic and geological conditions
ii) Master plan of the entire area development including transportation system, national security and defense
iii) Evolution of coast lines, beaches and estuaries
iv) Location of existing structures
v) Protection of the cultural, historical remains and administrative land boundaries and projects of national importance if any in that area
vi) Design of sea dike shall conform to navigation development strategy and also adaptable to the impacts of climate change

Sea dike alignment shape is also critical and it shall be designed as straight lines or smooth curves without many zigzags which can cause local concentration of wave energy. Orientation should be favorable avoiding the perpendicular direction for the prevailing wind direction. Techno-commercial aspects are also critical in selecting the shape of the sea dike route shape. Appropriate solutions to wave attenuation or dike resistance shall be adopted by conforming with the planning of river channel system, enclosure dike system and drainage sluices in the reservoir so created.

Hydrodynamic conditions at the connection zone, waves, nearshore sediment flow, imbalance of sand transport in nearby areas, forecast of development trend of the foreshore in the future needs to be considered in designing the reservoir bounded by sea dikes. Recent topographic survey data for at least 100 m from the dike toe on either side (up to 200m in case of variability of sea bottom) along with coastline evolution in the last 20 years is needed for sea dike design. In addition, geological data which is based on actual conditions along with meteorological, hydrological and oceanographical data shall be collected for studying the impacts of typhoons and natural disasters within the project area. Further, data on existing population and development trend along with current economic condition and development orientation is needed for dike project. Environmental conditions and evaluation of the impact level of the dike on the surrounding environment in the future is needed. For these sea dikes, which are generally closer to the developed industrial urban areas, a return period of 100 years has to be used for safety standards.

3 TYPICAL SEA DIKE CROSS SECTION DESIGN

Items of sea dike cross section design include: crest level, cross sections dimensions, crest structure, dike body and dike toe which fulfil the technical and economical requirements. Design cross sections of the dike are selected on the basis of geological conditions, materials used for construction of dyke, filling materials, external forces, layout of the dike and also the operational requirements. Sloping dikes, wall-type dikes and composite dikes are three different types of sea dikes based on geometrical shape. One need to carefully design the dike crest level, dike body, filter layers, slope protection layers (both on sea side and land side/coastal reservoir side), toe protection. There is different usage of sea dikes and mainly it reduces the amount of energy dissipated by the waves reaching the coastlines. It also protects the coastline from the tidal action and provide coastal defense. Further, it prevents the erosion of the coastline and create a calm water in the coastal reservoir area for many activities. Most important function of the dike, in this case, is to separate the salt water and the freshwater in the coastal reservoir and also allow freshwater fishing and other activities in calm water conditions and it can also provide dock or quay facilities along with support of floating solar panels for energy production.

The main features of the sea dike can be seen in Figure 1. Figure 2 shows the different sea dike cross sections such as sloping dikes, wall-type dikes and composite dikes with geometrical shapes.

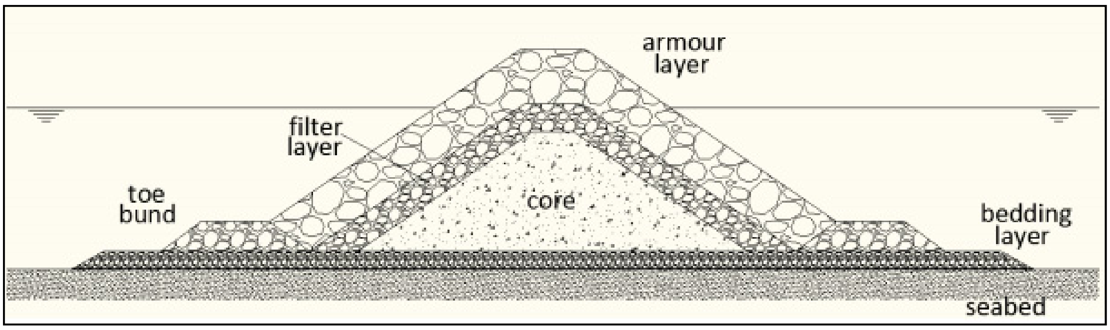

Figure 1. Typical Features of Sea Dike.

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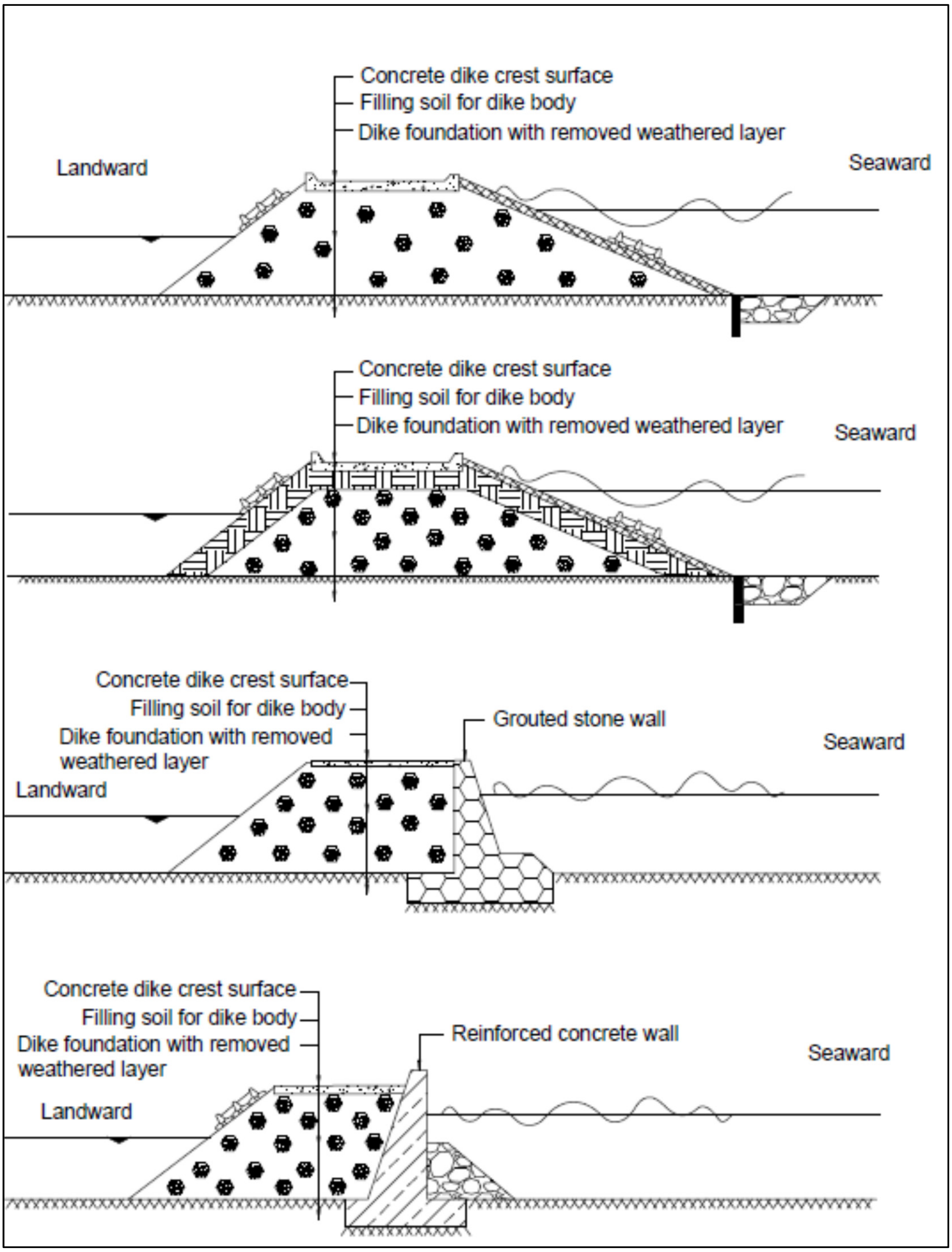

Figure 2. Different types of Sea dike cross sections.

The energy of the waves approaching is partially destroyed by breaking, partially reflected, and partially expended in run-up on the sea side. The wave height, water depth, and wave period determine the initial wave steepness. It is obvious that a more complicated situation exists when irregular waves are involved. If the crest elevation is lower than that corresponding to maximum run-up, then up-rushing water will spill on and over the crest of the structure. The usual unit of measurement of overtopping is volume per unit time and crest length. This quantity of overtopping is sometimes used as damage criteria for sea dikes and this is the critical design aspect in the sea dikes for coastal reservoirs. This is not permitted in this case for coastal reservoirs. The variety of armor unit shapes are available and no single type of armor unit is universally acceptable for all applications. Quarry stone armor is usually cheapest per ton but a larger volume is needed than when concrete units are used. It is advantageous to limit the area covered by primary armor units as much as possible consistent with the stability needs. Filter layers are the important layers of a rubble mound breakwater which serve to prevent excessive settlement of the structure. This is accomplished by hindering the erosion of bottom material by water moving through the pores of the breakwater. Thus, filter construction is the most necessary, when the natural bottom consists of easily eroded material such as fine sand.

4 IMPERMEABLE SEA DIKE FOR COASTAL RESERVOIR

A freshwater reservoir located in the sea close to the mouth of a river is bounded by sea dike to store required quantity of river flow/flood water. Flood water is a natural resource, and water quality is more closed to drinking water. Sea dike which bounds the coastal reservoir shall be impermeable so that salt water on the sea side does not mix with the fresh water stored in the coastal reservoir. The walls / wall with barrier lining is so designed that it will prevent mixing of surrounding sea waters with the impounded flood waters. An effective impermeable barrier between the fresh water (flood water) and the salty sea water is needed to do the following.

- Separation of clean river water from salt water.
- Protection of collected fresh water against external pollution.
- Prevention of salt water intrusion into the stored fresh water

A typical cross section of the sea dike for the coastal reservoir is suggested in Figure 3, as shown below.

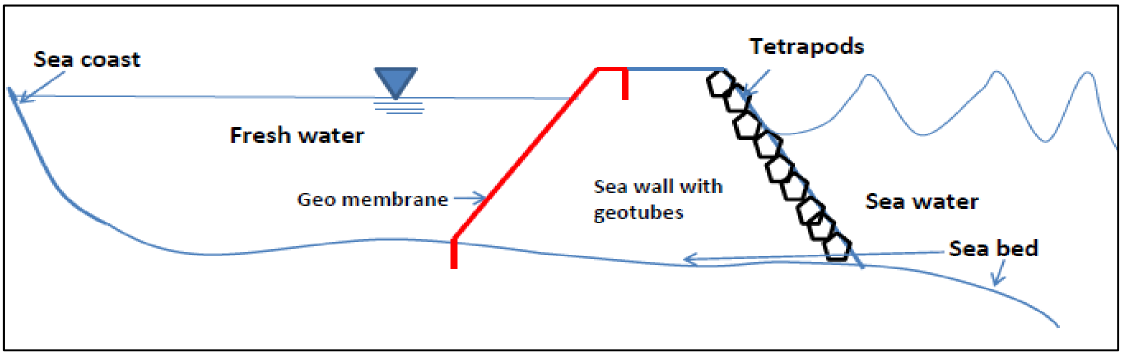

Figure 3. A typical impermeable sea dike for the coastal reservoir (Sitharam, 2016).

Further development (after Yang, 2016) has been the one using soft dam to separate freshwater from salt water or brackish water in the buffer zone. This is a patented technology of soft dam costal reservoir by Yang and Lin (2011) [Ref: Yang et al., 2013]. Soft dam will be built using a membrane at the river mouths to uphold the river runoff lost to the sea in front of the primary barrier. This provides an additional safety against mixing of salt water into freshwater stored. To be effective as a soft dam, the motions of a floating structure holding the membrane must be of small amplitude so that the structure does not generate waves into the protected harbor side. Thus soft dam has to be protected a primary barrier such as breakwater or a sea dike. Although at resonance the oncoming waves can be out of phase with the transmitted waves (resulting in lower coefficients of transmission), the structure must respond to a spectrum of incident wave conditions. Hence, the design of a floating structure for resonance characteristics is possible behind a primary barrier given the wide spectrum of ocean waves.

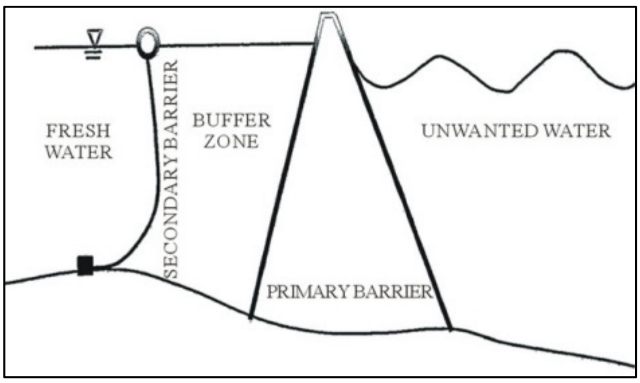

Figure 4. Soft dam concept by Yang, et al. (2005).

Table 1 shows the list of some of the coastal reservoirs constructed across the world. Sea dikes are constructed to a total of 43 km in QingCaosha reservoir in China. However, the longest sea dike constructed in Saemanguem bay is 33.9 km (slightly longer than the one Afsluitdijk causeway in Netherlands). One can clearly see that construction of sea dikes for coastal reservoir is not new and good experience exists across

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the world including the oldest sea dike in Netherlands as early as 1932 (Afsluitdijk causeway constructed between 1927 -1932 between Wadden sea and freshwater lake of Ijssemeer).

Table 1. Coastal reservoirs Dike length and capacities.

Coastal reservoir name	Catchment (km2)	Dike length, km	Capacity (million m3)	Year completed	Country / river
Qingcaosha	66.26	43	435	2011	China/Yangtze
Saemanguem	332	33.9	530	2010	South Korea /
Silhwa	56.5	12.4	323	1994	South Korea
Marina Barrage	113	0.35	42.5	2008	Singapore
Yu Huan	166	10.80	64.1	1998	China/Zhejiang
Plover Cove	45.9	2	230	1968	Hongkong

4 CURRENT AND FUTURE DEVELOPMENT OF GEOTEXTILES IN COASTAL CONSTRUCTIONS

Geosynthetics and geotextiles have contributed to many new innovations in Geotechnical engineering, which comprises of new textile products used in geotechnical applications pertaining to soil, rock or earth. This class of products is loosely called as Geotextiles and they refer to flat, permeable, polymer-synthetic or natural textile materials which can be non-woven, woven, knitted or knotted textile materials. They are used in contact with soil or rock in civil engineering earthworks and building constructions. In fact, geotextiles is one of the members of the geosynthetic family which comprises of geogrids, geonets, geotextiles, geomembranes, geosynthetic clay liners, geopipes, and geo-composites. The conventional coastal structures (i.e., breakwater, groins, revetment, and seawalls) have been constructed using wood, rock, and concrete materials in earlier days and still being constructed that way. The recent consideration of environmental approaches and the limited resources of natural rocks in certain regions led to an increase in the application of geosynthetics in coastal protection and coastal structures. The design of new, cost effective shore protection structures as well as for the repair of restoration of existing threatened coastal barriers and structures involves geotextile materials effectively. This has been done even for dune reinforcement and scour protection measures. Geotextiles are more versatile materials and innovative solutions in recent days which are economical and also supplement the conventional methods.

Problematic soils in shallow subsea in particular soft and liquefiable soils to support the dike and ground improvement of these materials is inevitable. Bearing capacity improvement, settlement reduction, long term liquefaction resistance is some of the critical aspects one has to deal under severe coastal conditions for dike construction. Mechanical modification (compaction, blasting, dynamic compaction), hydraulic modification (grouting), physical (stone columns, micropiles, jet grouting, Geosynthetics) & chemical modification (admixtures, soil cement, freezing, dewatering) along with inclusion and confinement (reinforcements, geotubes, geotextile tubes, geofabrics, geogrids, etc) or combination of the above is available for the use of development of foundation of sea dikes. Development of new machinery, barges for the construction of sea dikes are already available. In particular, for foundation improvement new construction materials like geosynthetics in particular geotextiles, geotubes, geocells are available and emergence of better guidelines for determining the suitability of specific techniques for certain types of coastal conditions and soils / site conditions is necessary. In today's context, we have better understanding of the geotechnical and marine processes involved and appreciation of the significance of construction sequence and challenges in the difficult conditions. Refinement of methods of analysis and computer modeling technique provides a better option for engineered solutions for dike construction for coastal reservoirs. Advances in the techniques of performance evaluation of the modified ground conditions, advance geotechnical and geophysical techniques put us in better spot in designing, constructing and maintaining these sea dikes under different environments. Due to sea or river current, fine soils of the bank start migrating causing erosion. Conventional design of cementing the banks is not a solution due to hydraulic pressure of the soil. Only feasible solution is the application of geotextiles or geosynthetics. Geotextiles allow water to pass through but resist the fine soil migration. Geotextile tubes are made of high-strength geosynthetic fabrics that enable the water to flow through pores retaining sand materials that have been used for the filling.

5 BREAKWATER CONSTRUCTED IN INDIA FOR THE NEW ENNORE COAL PORT PROJECT

The primary purpose of the new coal port ay Ennore in north of Chennai city in Tamilnadu, India is for the importation of coal for the north Madras thermal power station and other power stations in south Indian region. Eastern coast is subjected to lot of storms and cyclones during monsoon and also the littoral drift creates a sand transport along the coast more when compared to the west coast of India in Arabian sea. Two new break waters have been constructed to create the port on this coast at Ennore coal port project. The breakwater consists of south and north breakwater, which are of lengths 1040m and 3070m respectively, out of which the north breakwater is considered to be the longest in India. The rocks were supplied from a quarry (karikkal) 125 km away. The Karikkal quarry is a virgin narrow and high hill rocks interspersed by layers of murrum and other soft material making quarrying of rock difficult. Specialized and controlled drilling and blasting was used to get various rock sizes (1 kg to 18 tons). Specially fabricated steel skips of 20 tons capacity were loaded on trucks/trailers for transporting rocks to a railway siding 25 km away, and loaded in railway wagons by gantry. Each railway wagon carried 3 skips and travelled 100 km away carrying 1800 tons of rock and unloaded at a specially designed stacking area near the breakwater to hold up to 1.5 million tons of rocks. The total quantity of rock required for the two breakwaters is about 3 million tons having seven grades of rock from 1 kg to 18 tons to form the quarry run, filter layer, toe layer, and the armor layers, etc. One could have used the geotextiles very effectively in this project.

Figure 5. Breakwater constructed in New Ennore coal project (http://www.ennoreport.gov.in/).

6. CONCLUSIONS

Sea walls constructed for storage of flood waters will be a remedial measure for an increasing hazard to the coastline and provides protection against the wave action of the sea and in addition to store river flood waters in coastal reservoirs. Coastal reservoirs use the sustainable storm flood waters which are reasonably cleaner. This will emerge as a sustainable strategy for water resource development in the coming years. Emerging geosynthetic materials and innovative geosynthetic applications are essential for the construction of sea wall dikes. Construction of coastal reservoirs using sea dikes will increase the use of innovative materials and new construction techniques are required to build these sea dikes to safely harvest the river flood waters.

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REVIEW OF THE HISTORICAL DEVELOPMENT OF COASTAL RESERVOIRS IN THE WORLD

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ABSTRACT

Water is the most important substance for human's survival. People are always chasing water for better life, this is why old civilizations were located near large rivers like Yellow River, Indus River, Grange River, Nile River etc., and all megacities always appear at deltas of large rivers. In the 21st Century, the biggest challenge is how to provide sufficient quantity of fresh water to urban communities. We believe that coastal reservoirs would dominate the future water supply rather than other alternate water source strategies like existing inland reservoirs, desalination plants, wastewater reuse and rainwater tanks etc. A coastal reservoir is a freshwater reservoir inside seawater. The statistics shows that the world discharges 40,000 km^3/year of water into the sea, most of it is floodwater. Human society only uses 5.6% of the surface runoff. Thus, it is not that the world is running out of fresh water, it is that fresh water is running out of the world. To solve the water crisis, few coastal reservoirs have been constructed, their advantages and disadvantages are reviewed, problems are summarized, and possible solutions for future coastal reservoirs are suggested.

Keywords: Coastal reservoir; non-point source pollution; soft dam; water crisis; inland dams.

1 INTRODUCTION

The groundwater development plays an important role for human survival in history. Hand-dug wells are present in every corner in the world. But this way gradually became ineffective after the industrial revolution that cuts off the connection between arable land and people's living places, and people start to live in cities, or the urbanization era has begun. River valleys and deltas are very important for civilization due to its fertile lands for food production, water supply and navigation. Ancient civilizations all come from large rivers like Egyptian civilization (Nile River), civilization of Tigris and the Euphrates, the Indus Valley civilization and the Chinese civilization (Yellow River).

The earliest known Dam to store water for human settlements seems to have been constructed between 4000-3500 B.C. in the desert of Jordan based on more recent Jawa excavations (Helmes, 1977). During 2950-2750 B.C, the ancient Egyptians started to build the second recorded dam called the Sadd el-Kafara, meaning "Dam of the Pagans". The third known dam is called Nimrod's earth Dam in Mesopotamia around 2000 BC. In Syria, Lake Homs Dam is one of the oldest dams in the world still operational today was made by rockfill and earth, the embankment dam was constructed around 1300 BC. In Sichuan China, a system of dams and canals called Dujiangyan was constructed in 2280 BC. Recently archaeologists discovered that networks of canals and the Marib dam in Yemen were constructed as early as 750 BC. Sri Lankans have been pioneering water reservoir constructions for irrigation and water supply purposes as early as 500 BC. *Basavakkulama* is the oldest reservoir in the recorded history of Sri Lanka that has been built by King Paduwasdeva (504-474 BC) still in use today. About 100 AD, the Romans used concrete and mortar in their gravity dams at Ponte di San Mauro which has a great block of concrete among its remains. One of the oldest dam in India is the 'Kallanai' Dam (means a bund with rocks) in the South of India across the Kaveri River built by the Chola king Karikalan in 2nd Century AD but still used today. The most famous Roman dam was the Cornalbo earth dam in southern Spain which had a height of 24 metres and a length of 185 metres. Historically, after the Roman era, very little progress took place in dam construction until the Spanish began to build large dams for irrigation at the end of the 16th century.

In the 19th century, engineers in Europe started to design and construct dams using modern knowledge, most dams were small and constructed using earth and rock due to the nature of the water needs they served. At the end of the 19th century, due to the invention of cement and concrete, larger concrete dams started to emerge. In the 20th century, large dams are regarded as symbols of human capability to "control nature". For example, the Hoover Dam across the Colorado River is an astonishing achievement. The US President Roosevelt proudly announced "I came, I saw and I was conquered" in his inauguration speech. Figure 1 shows the dam construction in the 20th century. Most of these dams were constructed in 1960-2000, and the peak time appeared was in 1980. From 1960-1980, the dams constructed each year increased steadily. After 1980, the number of Dams constructed was reduced year by year, because many negative ecological impacts of dams on the environment have been discovered and ideal sites are rare due to heavy industrial and agricultural development for those with suitable hydrological and geomorphological combinations.

The average world population is currently increasing steadily by approximately 80 million per year. Due to environmental pollution of existing water bodies and new fresh water sources are not being found to cater for this rapid population growth, the availability of freshwater per capita is decreasing drastically. Currently about 80 countries and regions, representing 40% of the world's population, are experiencing water stress, and about 30 of these countries are suffering water scarcity during a large part of the year. During the last four decades, the number of countries experiencing water scarcity, most of which are developing countries, has increased. It is believed that by 2025, approximately 1.8 billion people will live in countries with absolute water scarcity (UN Water, 2013). To meet the crop demand projected for 2025, an additional 800 km^3 of water per year could be required; a volume nearly equivalent to nearly 10 times the annual flow of the Nile (Gleick, 2001). Therefore a natural question to ask is: what happens if the water deficit becomes larger and larger and how should it be solved? In addition to the natural scarcity of freshwater in various regions and countries, the quality of the available freshwater is also deteriorating due to environmental pollution, further intensifying this water shortage. Every day, 2 million tonnes 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 Water, 2014). Presently, global water resources are grossly polluted by wastes to the point that vast stretches of rivers are dead or dying, and many lakes are cesspools of waste. Many options have been proposed worldwide to address the water supply issue, such as more inland reservoirs, desalination plants, wastewater reuse, rainwater tanks etc.

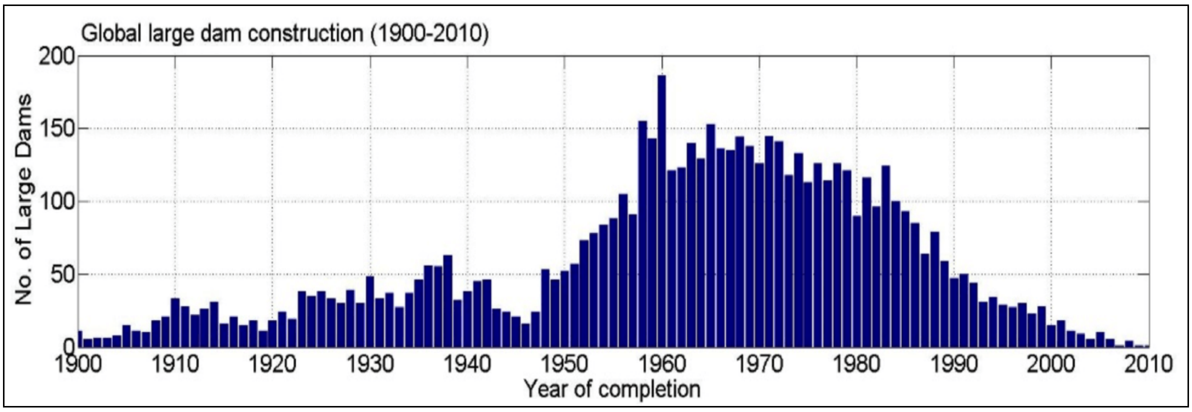

Figure 1. Global dam construction over the past 100 years, Source: Global Reservoir and Dam (GRanD) Database.

- More Inland dams?

  The primary renewable source of freshwater on earth is continental precipitation, which generates a global supply of 40,000–45,000 km^3 per year. Figure 1 clearly shows that more inland dams cannot supply water increasingly with the time as its dam number keeps reducing. Besides, a concrete dam's design life span is about 100-200 years, and its life span of such reservoirs also depends on their sedimentation rate which is reducing the storage capacity of the world's reservoirs by more than 1~1.5% per year (White, 2001). Consider the average life span of a dam is about 150 years, the total number of dams and reservoir storage capacity can be predicted and the results are shown in Figure 2, which clearly indicates that by 2150, all reservoirs will disappear and the water infrastructures will lose their function.
- Wastewater recycling and reuse?

  As water shortage is a worldwide problem, advanced wastewater treatment to potable standards could be a cheaper solution relative to desalination, because wastewater is less brackish than seawater. It is natural that potable wastewater recycling and reuse have been proposal for some populous cities like Singapore. Currently, people are still reluctant to drink the recycled wastewater and a big psychological barrier ('yuck factor') exists in the mindsets of people for its toxicological and microbiological issues. One example is the West Corridor Project in Australia. In total, $2.5 billion was spent in the southeast Queensland to treat wastewater, which was mixed with the reservoir water via a 200km pipeline by pumping stations. The Recycled Water Project construction began in 2006 and was completed in late 2008. However in November 2008, the government declared that recycled water will not enter the dam unless water levels drop to below 40%. In September 2013, former Premier Peter Beattie admitted that the scheme was a "tragic error of judgment". The costly experience may be a frustrating lesson for other places in the world—potable wastewater reuse may not be a feasible solution to the water crisis.

- Seawater desalination?

  To quench the world's growing thirst, desalination has been assumed to be a good solution as 97% of water in the world is saline. Some believe desalination is the most promising solutions to the problem. Brine from widespread desalination plants could form a disastrous threat to ocean biodiversity. Desalination is "an expensive, speculative supply option that will drain resources away from more practical solutions" as claimed by Adam Scow, California Director of Food and Water Watch (http://www.thesourcemagazine.org/desalination-right-choice/). If the required energy and gas emission are calculated, this method only serves to worsen the problems that they are attempting to solve. Table 1 shows the required energy and option sustainability if a medium sized city is supplied with 0.5×10^9 m^3 of water per year. It can be seen that a 500 GL/year desalination plant will produce 3.33 million tons of carbon dioxide.

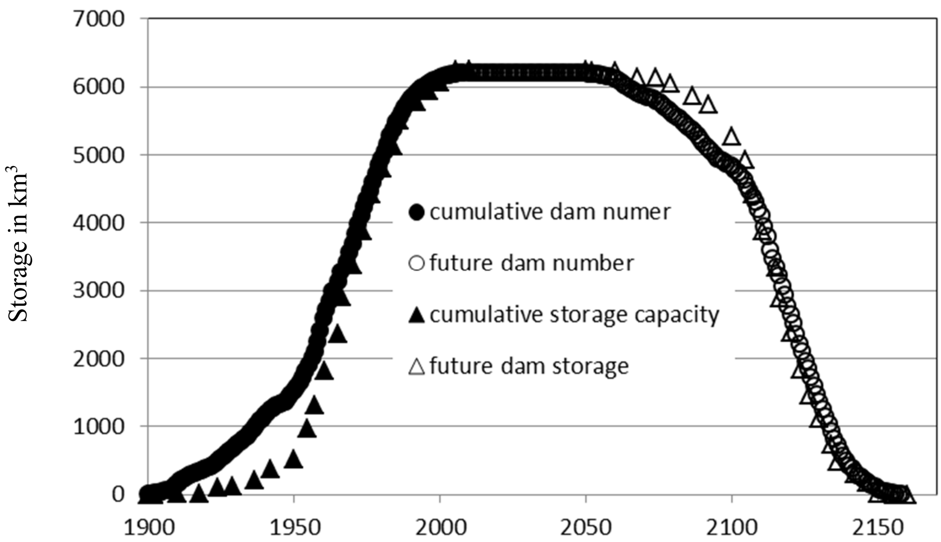

Figure 2. The cumulative dam number and storage capacity in the world for the period of 1900-2160 based on the assumption of 150 years dam life span.

Table 1. Comparison of different proposals to secure 0.5 billion m^3/year water supply in terms of sustainability, cost and carbon emissions.

	Inland dams	Desalination	Recycled wastewater	Coastal reservoir
Energy used for tertiary treatment ($\times10^9$ kWh)	0	2.0	1.0	0
Green-house emission (CO_2) in million ton	0	3.33	1.67	0
Construction cost (A$ in billion)	11.42	9.28	10	2.8
Maintenance/operation cost	Low	High	High	Low
Impacts on ecosystem	Loss of biodiversity	Brine disposal on marine biodiversity.	Low	minimal impacts on the ecosystem
Life span	100	20 years	20 years	100
Sustainability	Social/ Environ. problems	The damage on ecosystem is not remediable.	No damage on the ecosystem, except solids disposal	Sustainable

2 COASTAL RESERVOIR BEFORE 1950S

Besides the seawater and wastewater, it is common that every year a large amount of floodwater runs to the sea worldwide, and it is natural that people start to think how to develop the floodwater. Many proposals have been suggested and most of them aim at its development in the land above sea level. Obviously the high risk for flood disasters limits its applicability. However, few pioneer projects were carried about.

Before 1950s, there were very little problems for water shortage. When the first author was growing up in 1960s, there were only about 3 billion people on the planet. At that time, water was an abundant resource, almost none of us worried about the sustainability of water supply. The world's population is increasing quickly after 1950s. The main scarcity for human survival before 1950s was its food shortage.

To increase the arable lands, many land reclamation projects were conducted, one of the most famous project is Zuiderzee project in Netherland, whose development plan was drafted in the second half of the 19th century to protect areas from the wave forces of the open sea and creating new agricultural land. It consisted of a large dam and created a large lake and arable land. The initial water body had a surface of 3,500 km^2. In 1918 the government approved the Zuiderzee Act with the following objectives:

- Protect the central Netherlands from the effects of the North Sea;
- Increase the Dutch food supply by development and cultivation of new agricultural land; and
- Improve water management by creating a freshwater lake from the former uncontrolled salt water inlet.

The reclaimed land for farming and housing is the new province of Flevoland by the 32km long IJsselmeer dam in 1932 as shown in Figure 3a. The 1100km^2 artificial lake became freshwater 5 years later after the dam is enclosed. When keyed in "environmental impacts of Zuiderzee" in WSI database, only one paper appeared in Feb. 17, 2017 by Lammens et al. (2008). Their research reveals that "damming and fixing the water table prevented the development of emergent vegetation and caused steep water-land gradients. The Maximum Ecological Potential includes the effect of these hydromorphorlogical changes after all mitigation measures have been considered. Other pressures on the lakes are high nutrient loads, which cause phytoplankton blooms, the disappearance of aquatic macrophytes and intensive fishery, which over-exploits the pikeperch and eel populations and causes indirect negative effects on water quality. Good Ecological Potential for these lakes is derived by estimating the effects of all effective hydromorphological measures that have no significant negative impact on existing functions or the wider environment, and the effects of all other measures".

However, when keyed in "environmental impacts of Three Gorges Dam (TGD)" in the same data base on the same day, 769 journal papers appeared covering from middle reach to the estuary. Obviously, the environmental impacts of coastal reservoir are much less than the inland dams, e.g. the TGD in the Yangtze River, China, which its operation started from 2007.

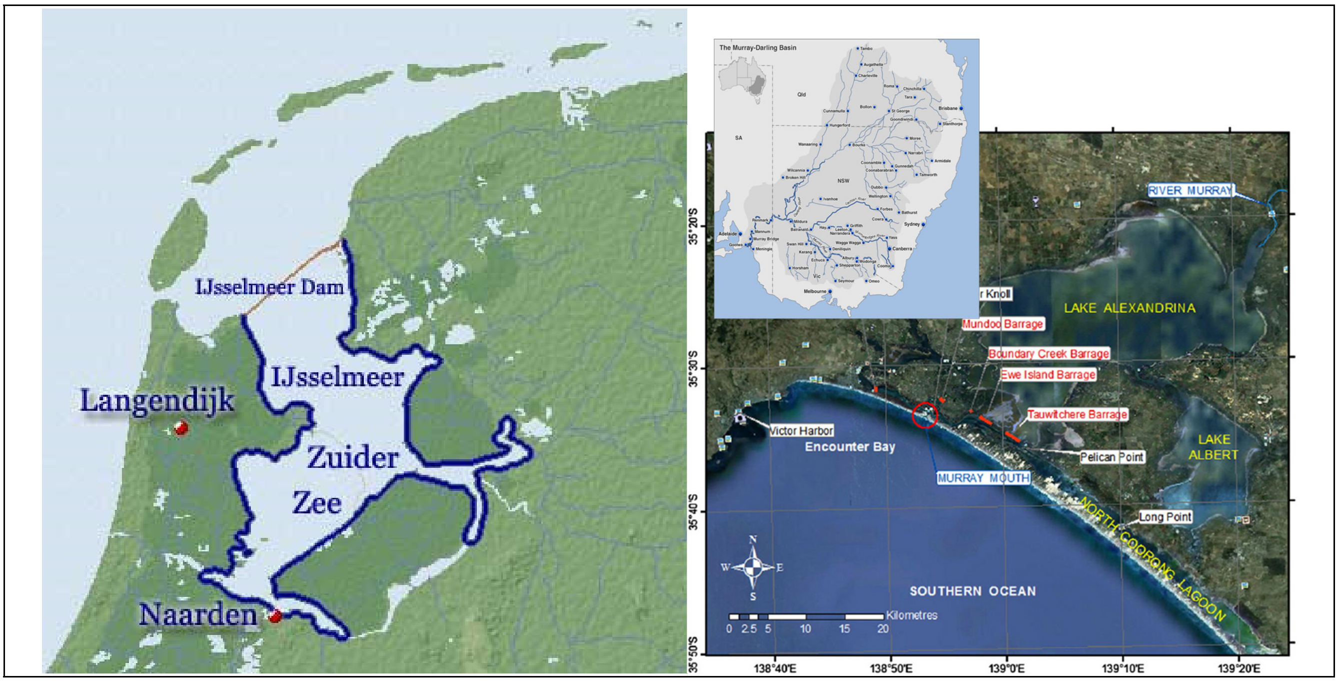

Figure 3. Coastal Reservoirs in Netherland (a), and Australia (b).

Almost at the same time, Australia, the driest inhabitated continent made its first attempt to change the Alexandrina Lake at the Murray-Darling River into a freshwater lake in 1930s, as shown in Figure 3b. In total 5 barrages were constructed at the lake's outlets, "The primary reason for their construction was to keep the water fresh in the lower reaches of the River Murray, as well as Lake Albert and Lake Alexandrina". Before the barrages were built, seawater intrusion occurred during periods of low flow, up to 250 km upstream from its mouth. Its impacts on irrigation and farmers were further intensified by the seawater. In 1931, it was decided to construct 5 barrages which was commenced in 1935 and was completed in 1940. During the Australia Millennium Drought in 2000-2009, the measured salinity in the lake was found being higher than seawater. This failed coastal reservoir implies that its original design is not perfect. More innovative design is needed.

3 COASTAL RESERVOIR DEVELOPMENT 1951-2000

Many researchers have realized that one day human needs to develop its floodwater in a feasible way, and most of them also worry about its environmental impacts. For example, Kassas (1980) foresaw that "in the near future, practically all the world's major rivers will be brought under control". He also worried "Some rivers will even be sealed off by estuary barrages (e.g. barrages across Morecombe Bay and the Solway Firth in the UK). But rivers represent an important agency in the hydrologic cycle: collecting surface drainage and discharging it into seas and oceans. Estimates of world total run-off of water from land to sea (mostly river flow) are in the order of 91,000 X 10^9 Litres per day (1.05 billion m^3/s). This is equivalent to about 7 percent of the total evaporation from land and sea. Rivers discharge into the Northeastern and Pacific Oceans between California and the Aleutian Islands about 21,000 m^3 /s. Freshwater discharges into the Bering Sea by Alaskan and Siberian rivers average 10,000 m^3/s. The Columbia Rivers discharges about 3,200 m^3/s, and its surface water of the ocean is perceptible several hundreds of kilometres out to sea. The water masses emerging from the Bering Straits northward to the Chikchi Sea bring fresh waters and sediments together with warm water. What would be the effects of sealing off these rivers on climate, biota and the hydrological cycle?" Obviously, it is not acceptable to seal off estuaries by barrages.

Larson and Malm (1992) proposed a floating coastal reservoir made by bottomless tank based on the principle that freshwater is lighter than seawater, thus it can be contained by the tank without severe mixing on the interface. Further study carried by Nanyang Techn. Univ. of Singapore shows that this is not a feasible solution for freshwater water storage (Chua and Shuy, 2006). It is important that these researchers have realized that floodwater lost to the sea is a resource and attempts have been made to develop it. The failed experience may inspire its followers for further improvement.

- Coastal reservoir's definition

  We believe that coastal reservoirs may dominate future water supply rather than other solutions like existing inland reservoirs, desalination plants, wastewater reuse and rainwater tanks etc. Before we explain why coastal reservoirs can achieve this, it is appropriate to define a coastal reservoir--- a water body is enclosed by a barrier or barriers inside water for some specific purpose, and the water quality inside and outside the reservoir can be different in terms of density, salinity, turbidity or other water quality parameters. For the purpose of freshwater supply, the coastal reservoir could be simply defined as a freshwater reservoir inside seawater, and the water inside the coastal reservoir could be used for drinking purpose or, if its quality is not so good, it could be used for other purposes like industrial, or agricultural or environmental purposes. The said coastal reservoirs could be classified into various categories, in terms of location: inner river mouth, beyond river mouth and beside river mouth; in terms of barrage: impermeable solid dam, soft dam and permeable solid dam + soft dam; in terms of water quality: freshwater, ballast water and polluted water, etc. Differing from in-land reservoirs that can only collect water from a small portion of a catchment, a coastal reservoir has the potential to collect every single drop of water from a given catchment. Existing freshwater lakes or lagoons on the shore can be regarded as special or natural coastal reservoirs.

- First generation coastal reservoir

  Currently, the water supply to deltas mainly relies on infrastructures like mountainous reservoirs to regulate stream flows, which has produced, and will continue to provide a large proportion of water to users. By noticing that the existing solutions cannot quench the thirst in deltas, people have started to make attempts to develop the runoff using traditional way, i.e., first generation coastal reservoirs, and the summary of existing coastal reservoirs is shown in Table 2. Currently, many coastal reservoirs exist. Probably the Plover Cove in Hong Kong (see Figure 4) is the first coastal reservoir in the world specially designed to hold water for drinking purposes. The construction work commenced in 1960 and was completed in 1968. Its storage capacity is about 170 GL. In 1970, its 2km long dam was arisen to 28m high and, and its capacity was increased to 230 GL.

To provide sufficient freshwater to Pyongyang, the capital of North Korea, from 1981-1986 a coastal reservoir was constructed at the mouth of Taedong River. The works include an 8km long dam, 3 lock chambers, 36 sluices, 3 fish ladders and barrage monument. There are railway, motorway and pavement on the dam and lock chamber capable of passing 50000-ton ships through. The reservoir provides water for irrigation, industrial uses and drinking and tourism.

Most reservoirs in Singapore are coastal reservoirs like Pandan Reservoir, Kranji Reservoir, and Marina Bay reservoir (see Figure 4). In China, Shanghai constructed the Baogang Coastal Reservoir in 1985, and Chenhang Coastal Reservoir in 1992; now their water supply mainly comes from Qingchaosha Coastal Reservoir with a capacity up to 644 million m^3, and the Qingchaosha is by far the largest coastal reservoir in the world for drinking purpose (Figure 5). Zhejiang province of China built the Yuhuan coastal reservoir in 1994. Table 2 shows the details of these coastal reservoirs, among them the Zuider Zee and Saemanguem coastal reservoirs were developed for land reclamation. Baogang and Chen Hang coastal reservoirs in Shanghai are used for industrial water use. West Sea Barrage was constructed for multiple purposes including water supply for drinking, irrigation and industrial purposes. From these reservoirs, one can find the common features of first generation coastal reservoirs:

1) A solid and very expensive dam or barrage is used to separate the seawater and freshwater. In other words, the construction method of inland dams is extended to the coastal reservoirs, this leads to a costly barrage and, to reduce the construction cost, the barrage is often constructed on the places where the dam or barrage has the shortest length. In reality, a coastal reservoir is totally different from the inland reservoirs and the water depth of estuaries is generally less than 10m, and

the water level inside a reservoir is almost the same as the sea water depth, thus the pressure difference is significantly smaller than that of inland reservoirs. Thus the existing coastal reservoirs may have over-designed barrages, and it is predicted that in future the new technology will reduce the construction cost of barrages.

2) Around the world, there are many rivers having a barrage at their mouths similar to those in Table 2. These reservoirs have the potential to collect all rainwater runoff from the catchment, but also carry the pollutants from the catchment, such as domestic waste overflows, industrial and agricultural chemicals, pesticides and fertilizers. As a result, there is an accelerated growth of algae and other life-forms that thrive on the nutrients in the coastal reservoir, and eventually some coastal reservoirs have become a wastewater reservoir that needs membrane technology to treat its water (like Singapore Marina Barrage). The Sihwa Lake in Korea (see Figure 5) could serve as an unsuccessful example, this coastal reservoir was initially designed as a freshwater supply source, and in 1994, a 12.4km wall was built to separate Sihwa Lake from the sea, severe water contamination occurred with high concentrations of Perfluorooctanesulfonic acid (PFOS), resulting from an excessive inflow of polluted waste waters, mainly from a nearby industrial complex. The polluted water was not even fit for agricultural use. In order to improve the water quality of the basin, the decision was made to abandon the original freshwater reservoir scheme and allow seawater exchange. In 2005 seawater entered into the lake and the reservoir was converted and became the world's largest tidal power generation plant. It can be predicted that as the wastewater amount keeps the same growth pace as population, in future the raw water quality from all coastal reservoirs cannot meet the requirement if no new technology solves this problem caused by the point and non-point source pollution.

Table 2. Existing coastal reservoirs in the world.

Name	Catchment (km^2)	Dam length (m)	Capacity (million m^3)	Year completed	Country/river
Zuider Zee	170,000	33000	5600	1932	Netherlands
Plover Cove	45.9	2000	230	1968	Hong Kong
Baogang/Shanghai	1.8milliom	3700	12	1985	China/Yangtze
West Sea Barrage	20344	7800	2700	1986	North Korea/Taedong
Chen Hang/Shanghai	1.8milliom	4700	8.3	1992	China/Yangtze
Sihwa	476.5	12400	323	1994	South Korea
Yu Huan	166	1080	64.1	1998	China/ Zhejiang
Marina Barrage	113	350	Not available	2008	Singapore
Qing Chaosha/Shanghai	1.8milliom	43,000	553	2011	China/Yangtze
Saemanguem	332	33000	530	2011	South Korea

3. Except coastal reservoirs in Shanghai, China, the alignment of all existing reservoir barrages is perpendicular to the flow direction. This is partly why the construction of coastal reservoirs is so expensive. This alignment of barrage changes the river flow significantly and causes many environmental and ecological problems, for example the passage of fish upstream has been cut off, navigation is disrupted and severe flood disasters could be worsened. Just as people are abandoning the large inland dams, it is predictable that in future no such coastal reservoirs that cut off the river flow would be approved by any governments.

Because of the problems highlighted above, the runoff development at river mouths has not been widely carried out using coastal reservoirs. Subsequently the desalination plants have emerged due to the shortcomings of coastal reservoirs in water quality, environmental impacts and construction costs. On the other hand, if we compare an inland reservoir with a coastal reservoir in depth, we may conclude that coastal reservoirs have their own advantages. In term of water quantity, the inland reservoir can only collect the water from part of a catchment, and its basin generally is small, but a coastal reservoir has the potential to collect practically all runoff reaching the downstream tip of the catchment as its size is unlimited. The construction cost of an inland reservoir is generally 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, and the storm and tidal wave surge is the main concern for its design.

The most challenging problem for the design of a coastal reservoir is pollution prevention as the land based pollutants and seawater could lead to a project's failure. The seepage from an inland dam is caused by the high water pressure, but for a coastal reservoir, the seepage is most likely caused by the density difference between seawater and freshwater, which is negligible relative to the seepage in large dams. The water quality of stream flow at estuaries is often not of sufficient quality due to the upstream point and non-point source pollution. This is evident at Shanghai's Qingcaosha Coastal Reservoir that was constructed in 2010 (see Figure 5), and also at South Korea's Sihwa Coastal Reservoir, which was forced to be re-developed as a tidal power station due to poor water quality. Therefore it is important to find an environmentally sustainable method of treating polluted water as a solution to the scarcity of water, in which wetland ecosystems play a major role. In order to get the most out of these wetland ecosystems, engineers and scientists have created wetlands in an industrial and commercial setting, which are called "constructed wetlands". These facilities have been proven to be the most environmentally sustainable and inexpensive water treatment method, and if properly designed can become the most effective and efficient water treatment method (Boudreau and Jorgensen, 2005; Biggs et al., 2005; Kadlec 2000; Statzner, 2008).

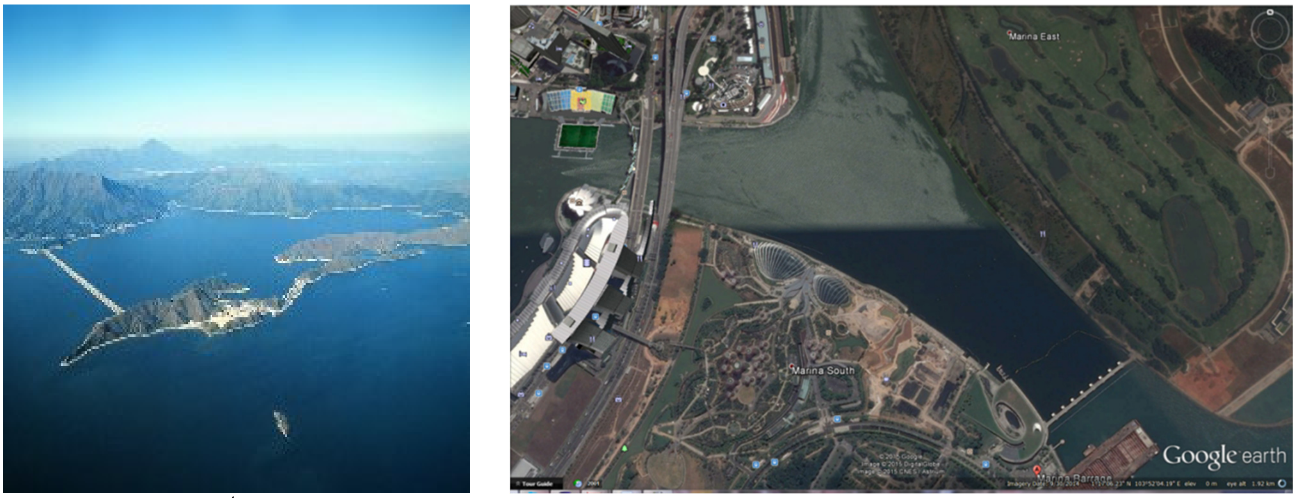

Figure 4. Typical 1st generation coastal reservoir in Hong Kong and Singapore (Plover Cove—left, and Marina Barrage on the right in Singapore).

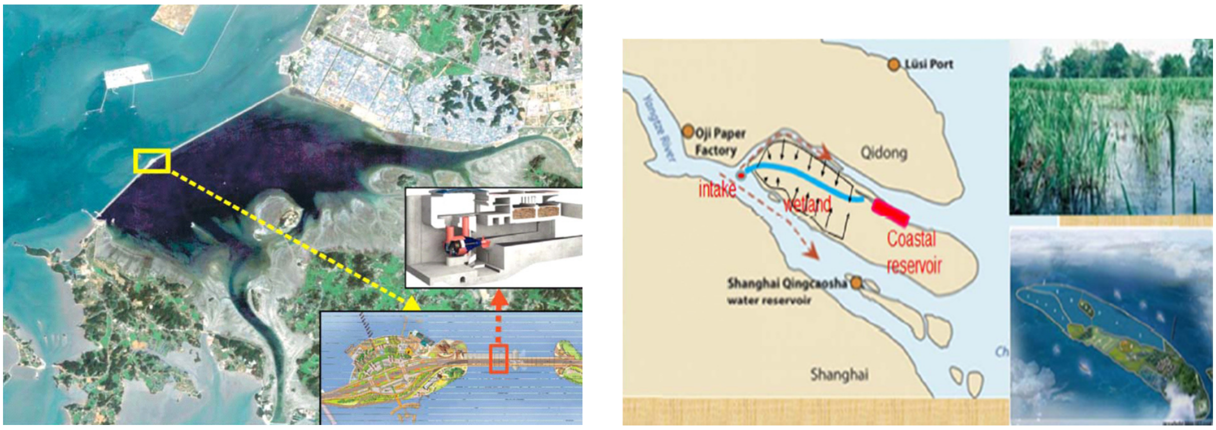

Figure 5. Coastal reservoirs in Korea on the left (Shiwa), and in Shanghai on the right. (in 2005 the first author proposed to construct the intake in red dot, the river water is pre-treated by wetland, the underground perforated pipeline in blue collects the infiltrated water to the coastal reservoir for storage marked by red block. In 2010, Qingcaosha Coastal Reservoir was constructed in the place marked by yellow dot, and its shape is shown in the bottom of right side.

4 SECOND GENERATION OF COASTAL RESERVOIR

As the shortcomings of first generation coastal reservoirs, the second generation of coastal reservoirs is proposed, which can be simply defined as: a freshwater reservoir inside seawater without pollution by unwanted water, it is able to mitigate flood disasters (Yang et al., 1991), which also stores river run-off by damming a river mouth or enclosing the coastal water inside or outside the mouth using barriers. The main differences between the first and second generation coastal reservoirs and on-land reservoirs are summarized in Table 3, which shows that the biggest difference is the water pressure. For existing inland reservoirs, the wall should be very strong to sustain the very high water pressure, and this is one of the reasons why the construction cost is very high. The water pressure for a coastal reservoir is relatively small (less than 10m) between the inside and outside water levels. As the sea is the biggest reservoir in the world, the coastal reservoir can be constructed in any place in the sea, even offshore if it is required.

The primary barrier is located at least in part in a body of unwanted water (see Figure 6). The reservoir's primary barrier can be a solid barrier of a height sufficient to withstand normal tidal surges and wave action of the unwanted water. A concrete dam, caisson, earth/rock dike or huge sandbag could be used for its construction, similar to a port's breakwater. All are traditional except the technology of huge sandbags. Small sandbag use is an old technique used to prevent or reduce floodwater damage, recently large scale sandbags have successfully been used for embankment construction as shown in Figure 6. An embankment of 60 km long is fully constructed using sandbags in Yangtze River mouth, China, which is used to secure navigation transport and a seawall will be constructed to defend against wave and tidal attacks in the latter stages. It is interesting to note that after the operation of coastal reservoirs for 50-80 years, so far no significant environmental impacts by these coastal reservoirs have been reported. Of course, these primary and simple designs for coastal reservoirs should be improved in order to improve the water quality and reduce potential impacts.

Table 3. Difference between inland reservoirs and coastal reservoirs.

Parameter	Inland Reservoir	1st generation Coastal Reservoir	2nd generation Coastal Reservoir
Water quality	Good (virgin catchment)	Poor (collect and store all contaminants)	Good (only collect clean water, bi-pass polluted water)
Water level	Variable water level, above sea level	Variable water level near sea level	Almost constant water level near sea level
Dam alignment	90° with flow direction	90° with flow direction	Small angle with flow direction
Dam-site	Limited (Require narrow width or Gorge)	Limited (only inside a river mouth)	Unlimited (inside/outside river mouth)
Dam design	High pressure, concrete, earth/rock	Low pressure but with wave/tidal surge, concrete, earth/rock.	Low pressure but with wave/tidal surge, concrete, earth/rock with/without soft dam.
Dam length	Short	Short	Long
Environmental impacts	High	Median (obstruction to floodwater, fish, navigation)	Low
Seepage	By pressure difference	By density difference	By density difference
Pollutant	Land lased	Land-based + seawater	Land-based + seawater
Emigrant cost	High	No	No
Water supply	By gravity	By pump	By pump
Water from % of catchment.	10~50%	100%	100%

The soft barrier can be used to separate fresh water and unwanted water, such as freshwater with seawater, clear water with turbid water, or polluted water. The buffer zone between the solid and soft barriers traps unwanted water to minimize the potential contamination, so that freshwater contaminated with unwanted water will be in the buffer zone, but clean and high quality water is collected and stored within the inflatable barrier. The best quality water is collected and stored inside the soft dam, but polluted or unwanted water on the other side. A multitude of similar reservoirs can be inter-connected to each other by artificial channels or pipes as shown in Figure 6. Also, in one reservoir, there can be a plurality of secondary barriers. Hence, the water diversion route should be along the coastal line.

The primary barrier in Figure 6 provides a relatively calm environment against tidal flows, storm and wave surges, and it also separates freshwater and seawater, the complete separation is possible because the introduction of soft barrier. This could significantly lower the construction cost of the primary barrier, and this is also achievable as the water levels on both sides of the coastal reservoir are almost the same and the net pressure force is very small. A soft dam can solve water quality problems in a coastal reservoir because:

As shown in Figure 6, the barrage is not perpendicular to the river flow, thus the drag force induced by the river flow is reduced, and this is helpful to reduce the construction cost. Most importantly, the river flow is not disrupted and fish can swim back to the river's upper course for breeding. This can minimize the environmental impacts, and a win-win solution can be achieved for water supply and ecosystem protection.

The introduction of a soft barrier and the parallel alignment with the primary barrier can ensure that the reservoir water has quality as good as the water quality of inland reservoirs, this is because the wastewater carried by first flush storm water will by-pass the coastal reservoir via the buffer zone between primary and secondary barriers, together with the appropriate operation of the reservoir's intake.

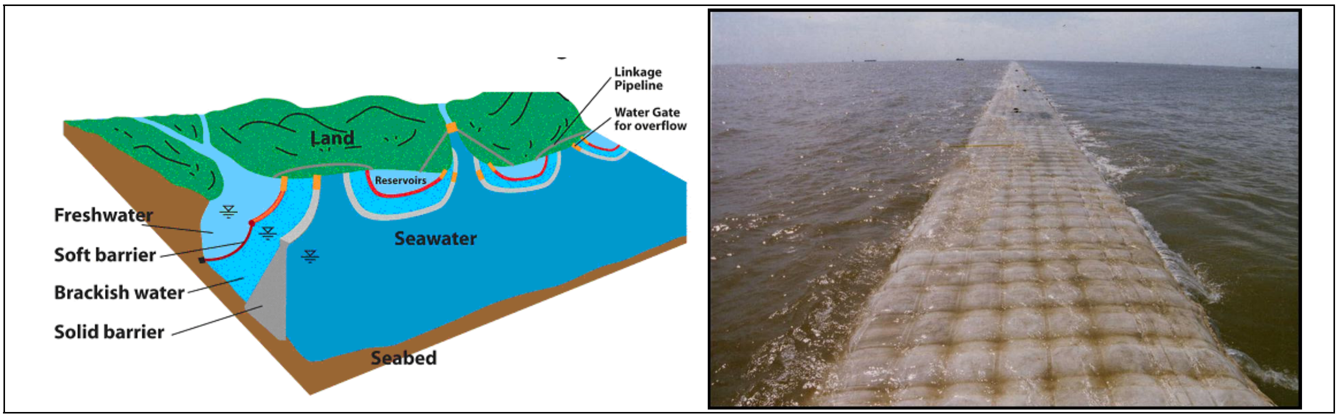

Figure 6. The second generation coastal reservoirs (with a bypass channel for polluted water) on the left and the dam by giant bags on the right.

Is water quality of coastal reservoir better than inland reservoir? Unfortunately the answer is “no” for the first generation coastal reservoirs. Almost all existing coastal reservoirs including Qingcaosha Reservoir have water quality problems. The reason is simple because they collect almost all contaminants generated from their catchments. As the population is increasing, more sediment is eroded, and more nutrients are produced, thus the first generation coastal reservoir becomes a wastewater reservoir sooner or later. Because of this, Singapore coastal reservoir needs the membrane technology to treat its reservoir water, and the Korea Sihwa Coastal Reservoir has been abandoned for water supply. If this problem cannot be solved, then the water inside the reservoir will not be drinkable.

For every watershed, rivers always play a major role in assimilating or carrying off municipal and industrial wastewater as well as surface runoff from the catchment. The river mouth receives almost all of the pollutants from the river basin. If 100% of pollutants enter the coastal reservoir like the Marina Barrage in Singapore, therefore excessive wastewater inputs can cause serious deterioration of water quality in the reservoir. However, rivers also constitute the main clean water sources to the estuaries. River water quality is heterogeneous spatially and temporally. In order to control water quality in a coastal reservoir, the temporal and spatial variation in water quality during flood events must be understood.

The “first flush” phenomenon has the highest concentration of pollutants, it means the first runoff has high concentration relative to runoff later in the storm event and it occurs when both concentration and the initial runoff are high relative to the later runoff. This is called a “seasonal first flush.” The second generation coastal reservoirs can solve this simply by the Separation, Protection and Prevention (SPP) strategy, thus the most important feature of second generation coastal reservoirs is their capacity to discharge polluted runoff out of the reservoir, and to store water whose quality is similar to or better than the water in inland reservoirs . Yang (2001) outlined SPP (3 guidelines) for the successful construction of a coastal reservoir. The first guideline of SPP is to separate freshwater and seawater by a barrier, and to separate clean water from polluted river water by intake regulation. Next is protection, i.e., to protect the collected fresh water against polluted river water and external pollution. Last is prevention, meaning the successfully prevention of salt water intrusion into the stored fresh water. The SPP strategy is effective to collect good quality water, because the intake gates in Figure 6 will be closed when poor quality water or first flush appears in the river mouth, the polluted water will then flow to the sea bypassing the coastal reservoir. The water in the reservoir could be improved in its quality if wetland pretreatment is allowed.

It is necessary to use multiple pre-treatment wetland areas to reduce nutrients such as TN, TP and other organic and inorganic pollutants in the water, vegetation uses these nutrients as their food and other pollutants get absorbed, it can further improves water quality. It is also helpful to conduct catchment education and catchment management, thus waste amount from domestic, industrial and agricultural sources can be reduced.

The most fundamental difference between the first and second generation coastal reservoirs is the separation and selection of runoff based on its quality. The first generation coastal reservoirs have no such method to select the best quality water, and the water with lower quality is allowed to enter the reservoir and to pollute the high quality water inside the reservoir. This is not a desirable outcome, both in terms of aesthetics as well as the higher water treatment cost when this water is abstracted for potable use. But the second generation coastal reservoir only accepts good quality freshwater, and all unwanted water will be discharged to the sea.

4 CONCLUSIONS

The 21st century is the century of water, water shortage is a major socioeconomic and environmental problem facing society today and will soon become one of the major constraints for future economic development. The traditional ways of water resources development may not be able to fully accommodate the increasing demand, especially in the coastal regions. To meet the water demand in the regions, technologies like desalination of seawater, wastewater recycling and more inland reservoirs etc. cannot completely solve water shortage.

To date, a number of first generation coastal reservoirs have been built mostly in Asia to supply water for drinking, industrial and agricultural purposes with mixed success. By noticing that these problems in the existing or first generation coastal reservoirs, the world's water crisis can be effectively solved using the technology of a 2nd second generation coastal reservoir that is a freshwater reservoir in seawater by bypassing poor quality water to the sea without mixing reservoir clean water.

The coastal reservoir can develop freshwater from the sea without desalination, it can also can mitigate the flood disasters. To achieve this, it is required that the reservoir's water level is lowered prior to the arrival of peak flood waves. The coastal reservoir can also can prevent the seawater intrusion. Technology of coastal reservoirs is a sustainable, cost-effective and clean way for water supply, it will dominate tomorrow's water supply.

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COASTAL RESERVOIR IN LAKE ALEXANDRINA CAN QUENCH ADELAIDE'S THIRST

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ABSTRACT

Adelaide is the capital city of South Australia, the driest state in the driest inhabited continent on this planet. From its beginning, the city has been threatened by lack of available fresh water, the most precious substance that may constrain its further development if cheap and clean water supply is not sufficient. This paper reviews Adelaide's hydrological and geomorphological conditions, and found that the historical minimum flow in Murray-Darling River (5000GL/year in the Millennium Drought) can still meet Adelaide's water demand in full if a second-generation coastal reservoir is constructed. An initial coastal reservoir consisting of 5 barrages was constructed at Lake Alexandrina's outlets in the 1930s with a capacity of 2000 GL. The measured flow data in the driest period in 2007 shows that an effective coastal reservoir's capacity should be 580 GL. The research shows that once a smaller coastal reservoir is constructed inside Lake Alexandrina, Adelaide's water demand can be fully met, and also the lake's ecosystem is improved as its water level is stabilized, water detention time becomes shorter and salinity becomes lower under conditions equivalent to the Millennium Drought.

Keywords: Adelaide water supply; coastal reservoirs; Murray-Darling River; Lake Alexandrina.

1 INTRODUCTION

South Australia (SA) is a state, which has boundaries with Victoria, New South Wale and Queensland on the east, West Australia on the west and North Territory on the north. It covers 983,482 km^2 of arid land and had a total of 1.7 million people in 2015 with 75% of these people living in Adelaide where the mean annual rainfall is about 544 mm. This state is the most highly centralised and driest state in Australia and the state's water crisis is actually Adelaide's water crisis even though Adelaide is located in the Gulf St Vincent and the city is only 60 km away from the Murray Darling River, the largest river in Australia.

There are 16 inland reservoirs and dams servicing Adelaide's water supply. Many of these feed into each other to maximise inflows and minimise the need to pump water over long distances for immediate supply. The total capacity of all storage combined is over 250 GL however this is managed throughout the year so that water is not wasted in months of expected maximum inflows. The larger reservoirs for storing Adelaide's water supply system are the Mount Bold, South Para, Blue Lake, Myponga, Little Para and Kangaroo Creek reservoirs. These 6 main facilities hold over 75% of Adelaide's stored water and are located out of the city.

The Adelaide catchment comprises approximately 5,340 km^2 and extents from the Barossa Valley in the north to the Fleurieu Peninsula in the south (Table 1 and Fig. 1). It includes the Northern Adelaide Plains, the Western Mount Lofty Ranges and the Adelaide Metropolitan area. The terrain varies from flat plains near the coast to mountain ranges in the east.

The first major drought in the early 20th century forced people to search for water from outside Adelaide. Consequently, people realized that Murray-Darling river may provide a reliable and long-term solution for Adelaide. In 1920, many locks and weirs were constructed along the river. South Australia and Adelaide's development heavily depends on water diversion from Murray River via 5 pipelines (see Fig. 2): 1) from Morgan to Whyalla; 2) from Swan Reach to Stockwell; 3) from Mannum to Adelaide; 4) from Murray Bridge to Onkaparinga; and 5) from Tailem Bend to Keit. The Murray River provides on average of 40% of Adelaide's water supply but, in dry years, this percentage can reach 90% (Water for Good, 2012).

In 1999, a desalination plant was constructed on Kangaroo Island. During the Millennium Drought, the driest state in the driest inhabited continent decided to construct a desalination plant for Adelaide's water supply, which cost AU$1.83 billion for construction in 2013, its operating cost is AU$130 million/year at full capacity of 100 GL/year. Obviously, the assumption used for this decision was that Kangaroo Island and Murray River did not have enough reliable fresh water.

The Murray-Darling River basin (MDB) covers just over 1 million km^2 or about 1/7 of Australian land area. The MDB is one of the largest rivers in the world in terms of catchment area. Its water comes from the Murray and Darling Rivers, both merge in NSW and drain to the sea in South Australia via Lake Alexandrina. Its runoff comes from NSW, Queensland, Victoria and the Australian Capital Territory, where the annual rainfall is about 530 mm/year over the basin that hosts most significant agricultural areas in Australia. Most of the river water has been allocated and many weirs, locks and dams have been constructed, like the 3005 GL Hume dam. In

1917, the first River Murray Waters Agreement was signed for irrigation in the basin. Urban communities use only about 2% of total usage, mainly for Adelaide and Canberra.

Table 1. Basic information of catchments and runoff in South Australian Gulf Division.

Basin No.	River	Catchment	Annual Rainfall	Runoff			Variability (annual runoff)	
		10^3 km^2	(m)	GL/y	mm/y	Runoff coeff.	Max. /mean	Min. /mean
1	Fleurieu Pennisula	1.05	0.66	101	97	0.15		
2	Myponga	0.15	0.51	24	154	0.30	2.60	0.22
3	Onkaparinga	0.96	0.51	157	162	0.32	3.20	0.07
4	Torrens	1.18	0.43	109	92	0.21	4.0	0.01
5	Gawler	4.46	0.46	105	24	0.05	3.60	0.04
6	Wakefield	2.06	0.45	27	13	0.03	3.30	0.08
7	Broughton	16.63	0.46	84	5.1	0.01	-	-
8	Mambray Coast	3.97	0.35	50	12.5	0.03	-	-
9	Willochra Ck	6.48	0.35	16	2.6	0.00	-	-
10	Lake Torrens	26.4	0.20	57	2.8	0.00	-	-
11	Spencer Gulf	11.5	0.31	20	1.9	0.00	-	-
12	Eyre Peninsular	3.11	0.46	14	4.2	0.00	-	-
13	Kangaroo Island	4.35	0.76	216	50	0.07	-	-
	Total	82.3		980				

Figure 1. Main catchments in South Australian Gulf Division

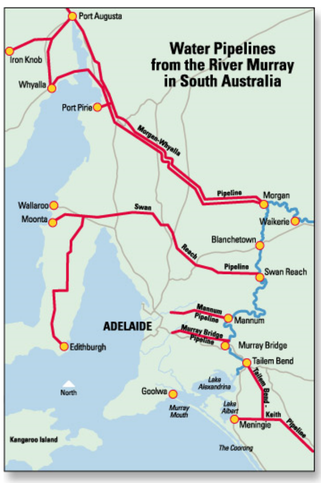

Figure 2. Water diversion pipelines in South Australia from Murray-Darling River

The Murray-Darling Basin receives 500,000 GL rainfall annually, but 94% of it is evaporated. Additionally 1,200 GL/year is transferred from the Snowy and Glenelg Rivers. The runoff to the sea via Lake Alexandrina is shown in Fig. 3. Adelaide and nearby farmers could not use the river water for irrigation and domestic purposes

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due to seawater intrusion in dry years until 1940, when barrages were constructed at the outlet of Lake Alexandrina. In some sense, this was the first attempt in Australia to construct a coastal reservoir because the design purpose of the barrages was to stop seawater intrusion and associated salinity increase and to maintain high water level in the lake. But because of the inappropriate design of the coastal reservoir, these purposes are only partially achieved, and this failure resulted in countermeasures like Adelaide's desalination plant and reduced availability of water for agricultural use.

The Australian Millennium Drought in the 2000s caused significant reduction in annual average runoff compared to historical averages as seen in Fig.3. In response to the Millennium Drought, the Australian Federal government tried to reduce existing water allocations and to increase environmental flows. In 2008, the SA government purchased an allocation of 30 GL at a cost of $14 million (SA Water, 2014), an average cost of $467 per ML. By the end of the 2009 financial year, the government had purchased 217 GL (NWC 2010). In 2015, the government set a 1,500 GL/year cap on the amount of water it can buy back from the Murray-Darling basin, and thus irrigation and other water users can take 10,873 GL/year of surface water, which is 2,750 GL less than in 2009. Thus, it can be predicted that in future more freshwater runoff will be lost to the sea. South Australia is a leader in recycling stormwater and leads the nation in rainwater tank ownership. Existing stormwater harvesting schemes in Adelaide generate 6 GL/year, with currently committed schemes expected to harvest an additional 12 GL/year. The SA government has estimated that by 2050, about 370 GL/year will be needed to satisfy water demand for Greater Adelaide in dry-year conditions (see Fig. 4), and government's plan is to use methods like desalinated water, recycling water and saving water to seal the gap.

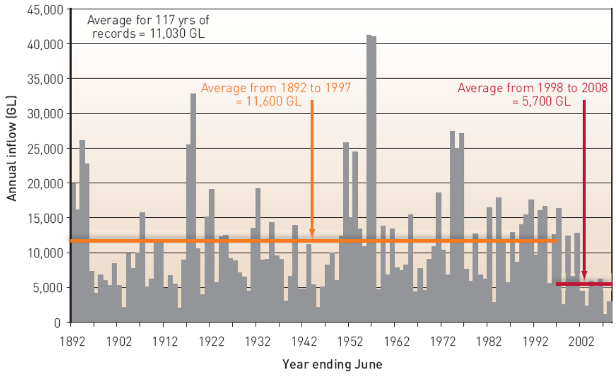

Figure 3. Murray-Darling River runoff from 1892 to 2008 (Murray-Darling Basin Commission 2008)

Marchi et al. (2014) investigated the financial cost, energy consumption and greenhouse gas emissions for various water supply options for Adelaide, and their results are shown in Table 2. The operation cost of Adelaide Desalination Plant is $30m per year regardless of output and $1.00/m^3 is used for energy, chemical and membrane consumption. In Table 2, the capital cost of the existing infrastructures are not included, like the inland dams, desalination plants, etc., the operational cost for existing infrastructures includes the net operational cost. Table 2 demonstrates that the desalination method has the highest capital cost (AU$1.82 billion which includes the cost of interconnecting pipelines) and operational cost, whilst the local reservoir has the minimum cost, which is the cost of wastewater reuse incurs just less than the cost of desalination.

In Table 2, the energy cost for 50 km water transfer from Murray River to Adelaide is equal to 1.6 kWh/m3 based on Spies and Dandy (2012) and Sustainable Focus and Clark's (2008) estimation for the average pumping energy cost of 0.3 kWh/m3 used for water treatment, and thus a total energy of 1.9 kWh/m3 is required. The energy price adopted for this source is equal to $0.15/kWh as in Spies and Dandy (2012) resulting in a cost of pumping equal to $0.29/m3. Besides, South Australia needs to pay for additional water allocation, which was $0.3/m3 from 2007-2011. Thus, the cost of supplying Adelaide using water from the Murray River is $0.59/m3. The maximum capacity of the Mannum-Adelaide pipeline is 123.4 GL/year, 180 GL/year for the Murray Bridge-Onkaparinga pipeline and 24 GL/year for the Swan Reach-Stockwell pipeline. All together, these pipelines can supply 320 GL/year. Adelaide's water supply heavily depends on water transfer from Murray River; the measured salinity at Morgan from 1970-2010 is shown in Fig. 5 which demonstrates that the water quality of Murray River is not always good; the high salinity could be 1600 EC (EC = 1000 μS/cm = 640 mg/litre TDS = 1 d Siemens/m), which is far higher than the acceptable level of the drinking water standard that is 800 EC. Thus, Adelaide's water supply has other threats - water quality or high salinity.

A close look reveals that the salinity depends on the river flow. Higher flow rate always corresponds to lower salinity, or the good quality water always appears during the flood period. Fig. 6 shows the measured salinity at Morgan versus the river flow rate in the year 1998-1999 during which the river flow to the sea is very close to 5 km3. Fig. 6 reveals that in the flood period (September-December) the salinity could be as low as 400 EC. This implies that if the floodwater can be harvested, the poor water quality relating to salinity in Adelaide's water supply could be solved. This highlights that a large reservoir is needed to store high quality water in flood seasons and the water can be used for dry seasons, when Adelaide should not pump water directly from the river.

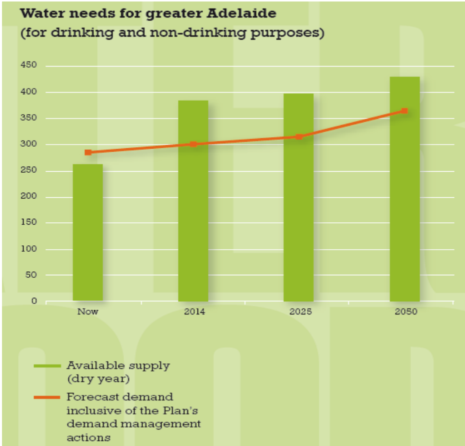

Figure 4. Projected water needs for Greater Adelaide (Source from Water for Good, Government of South Australia, 2010).

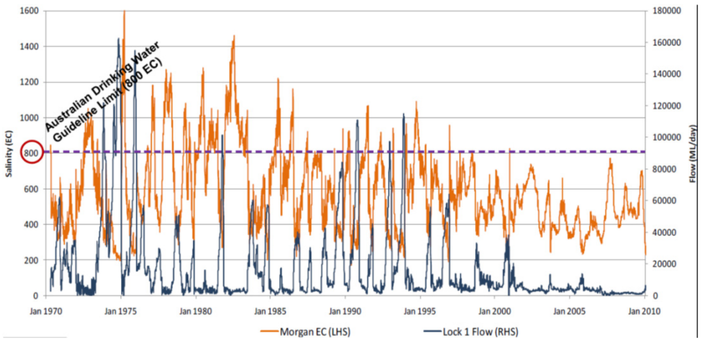

Figure 5. Measured salinity in Murray River and flow rate (Source: MDBC, 2013)

Table 2. Cost comparison for different water supply methods in Adelaide (Marchi et al, 2014)

Methods	Capacity (GL/year)	Capital cost $k/ML/year	Operation cost $/kL	Energy MWh/ML/yr	Capital GHG ton/ML/yr	Operational energy MWh/ML	Operational GHG ton/ML/year
Local dam	121 (30 in dry year)	0	0.24	0	0	0.3	0.24
Diversion from Murray	130 (current)	13.96M$ for pump renewal in 20 years	0.44	0	0	1.9	1.5
Diversion from Murray	190 (additional)		0.74	0	0	1.9	1.5
Desalination	100	1.7M$ for pump renewal in 20 years	$1.00+$30M $ per year	0	0	5	4.29
Wastewater reuse	98.6	20.3	2.00			0.69	0.84
Rainwater tank	1.3	254	0.36	61.6	48.7	1.45	
Water saving	7.7					29.7	14.8

2 COASTAL RESERVOIR IN GULF ST VINCENT

Currently 137 GL per year of Adelaide's water comes from local reservoirs in Adelaide Hills and 88 GL of water are diverted from the Murray Darling system annually. A possible location for a coastal reservoir in Adelaide would be the mouth of Torrens River. Table 2 shows the annual flows discharged into the ocean from various point sources, with the total amount from the 82300 km^2 catchment being about 980 GL/year. Some places in South Australia have relatively high rainfall, for example Kangaroo Island receives an annual rainfall ranging from 450 mm in Kingscote to around 900 mm near Roo Lagoon on the top of the central plateau. Table 2 shows that runoff from Kangaroo Island is about 216 GL/year from its 4400 km^2 catchment, higher than the runoff of Torrens River that supported Adelaide as a single source of water before 1940.

Being a coastal city, Adelaide allows a very large amount of flood water to be discharged into the ocean without utilising it to its full capacity. In this region, the rainfall is not always very low, for example Scott Creek, a tributary of the Onkaparinga River, receives 992.6 mm/year rainfall based on the record from 1884-1964. Table 2 shows that the runoff from Onkaparinga River is 157 GL/year, Torrens River is 109 GL/year and Gawler

River is 105 GL/year. In total, these three catchments have 371 GL/year water lost to the sea along the 60 km shoreline. In this driest state of Australia, coastal reservoirs should be able to store all runoff without discharging any of it to the sea even if its quality does not meet the standards. This means that a coastal reservoir in very dry areas should be divided into at least two parts according to its water quality. One stores the water that meets the raw water standards for drinking purposes, and the other for remaining runoff. The latter one should become the source for industrial water, gardening or desalination plant's feed-water. To capture and store all of Adelaide's runoff is far superior to the current strategies. The costs associated with coastal reservoirs are far lower than that of a desalination plant or a recycling plant. The land requirements are virtually zero as they are based out in the ocean and with an increasing population this is a key factor in their advantage.

The River Torrens catchment area is approximately 1180 km2. Its upper reaches are used to supply water to metropolitan Adelaide from three reservoirs. The average annual rainfall in the upper catchment ranges between 575 mm at its eastern end to 1,025 mm near Uraidla (Surface Water Group, June 2003). Floods are frequent disasters that have washed away many bridges constructed by early European settlers. For example, in June 1889 the measured flood rate was 129 m3/s, but normally this river is only a seasonal river with a chain of water pools along its water course. Situated through the heart of the city, the River Torrens could act as the fresh water inflow into a coastal reservoir. The reservoir would be constructed as shown in Fig. 7, and its radius, if semi-circular, could be 4 km giving an estimated reservoir area is about 25 km2, and its storage capacity would be 250 GL, if its average depth is 10 m. The length of dike would be 16 km (red line in Fig. 7) and three hydraulic/tidal gates should be constructed. The hydraulic gate into the grey sub-reservoir would be opened when the quality of incoming water is poor. All high-quality water would be diverted to the "clean water reservoir". All gates would be open if needed in flood conditions.

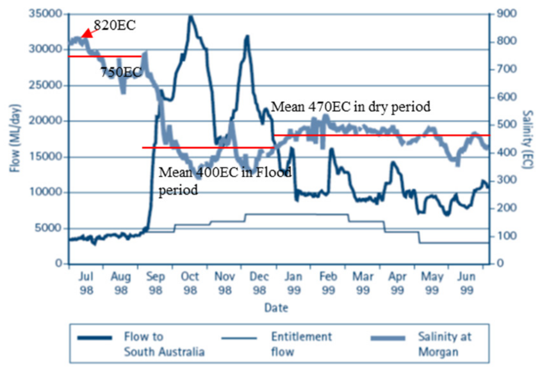

Figure 6. Relationship between flow rate and salinity in the lower Murray River for 1998-1999. (Source: MDBC, 2003)

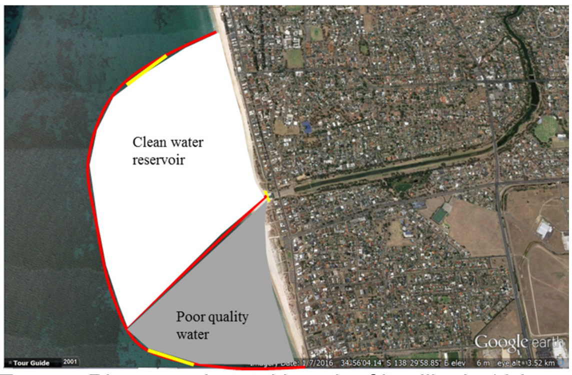

Figure 7. Coastal reservoir at Torrens River mouth, total length of its dike is 16 km, about 1/3 of its area is used for storage of poor quality water that can be used to feed the desalination plant or irrigation.

3 COASTAL RESERVOIR IN LAKE ALEXANDRINA, MURRAY-DARLING RIVER MOUTH

The Murray-Darling River mouth drains into Lake Alexandrina (620 km^2) where the mean water depth is 2.86 m. The lake's maximum depth is about 4 m. The river water passes through Lake Alexandrina to the sea. The lake receives the majority of its fresh water from the Murray, although some comes from local rainfall. In the pre-European period the lake would have occasionally become saline for short periods during extreme droughts. To reduce salinity levels in the lower reaches of the River Murray and associated lakes caused by tidal effects and salt water intrusion during periods of low flow, Lake Alexandrina was separated in the 1930s from the Coorong by a system of five constructed barrages (Fig. 8). These are low dams across the channels leading from Lake Alexandrina to the Coorong. These dams can stabilize the river level for irrigation, concentrate releases to the ocean to a small area in order to scour a channel for navigation, and maintain a pool of water that can be pumped to Adelaide and the south-eastern corner of South Australia. The 5 barrages in Fig. 8 reduce the tidal prism through the Murray Mouth by approximately 90% (Webster, 2005).

The 5 barrages are Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere Barrages. Goolwa Barrage, located 8 km upstream from the Murray Mouth, is the deepest of the barrages and contains a lock chamber of 30.5 m by 6.1 m. The barrages also contain fish-ways which, when operational, allow passage of estuarine species that require access to the fresh water environment of the lakes. The Mundoo and Boundary Creek Barrages are the shortest of the barrages and are founded on a limestone reef. Ewe Island and Tauwitchere Barrages are wide, shallow barrages built on a calcareous reef, with earth embankments at both ends. The Tauwitchere Barrage has a lock of 13.7 m by 3.8 m but no provision was made in the other barrages to allow the passage of shipping.

In normal operation, as designed, the barrages raise the level of fresh water in the Lower Lakes to approximately 0.75 m AHD (the datum), subsequently the barrages cause an increase in water level of approximately 50 cm as far upstream as Lock 1 at Blanchetown (274 km upstream, MDBC). At full supply the lakes hold approximately 1740 GL. Estimates of evaporation vary, but the lakes probably require 700-950 GL per year to maintain their normal level. When flow exceeds this volume it is released to the Murray Estuary and flows into the Coorong North Lagoon or out the Murray Mouth. Therefore, it can be seen that the Lake Alexandrina is actually a coastal reservoir. But this coastal reservoir belongs to the first generation of coastal reservoir, and is another example to indicate that not all first generation coastal reservoirs are successful for freshwater development.

The reasons why water in the Lower Lakes has been maintained above +0.60 mAHD include: (1) to minimise the ingress of seawater into the lakes via the barrages; (2) to reduce the potential for saline groundwater discharge into the lakes; (3) to facilitate irrigation diversions (but this is no longer critical since the construction of pipelines around both sides of the Lower Lakes in response to the recent drought); (4) saline groundwater intrusion and acid sulphate soils can present management issues at thresholds below +0.6 m AHD; and (5) wind effects can result in localised water levels ± 0.30 m different from the average for the Lower Lakes as a whole (Webster et al. 1997).

The failure of changing Lake Alexandrina into a coastal reservoir can be seen from two facts, i.e. the salinity of water in the lake and its water level. The historical recorded data are shown in Figs 9 and 10. It can be seen that from 1962-2014, the water level in the "coastal reservoir" has generally been operated at a level between 0.25 and 0.85 m AHD. After 2006, the water level dropped down quickly, and the recorded lowest water level was –1.0 m AHD in Lake Alexandrina and –0.55 m AHD in Lake Albert in April 2009, the lowest in 117 years of records. These represented 64% and 73% reductions in lake volume, respectively (Environment Protection Authority, 2013). Consequently, many environmental issues emerged, for example, the acidified dry lake bed increased to 2,173 ha. The Ramsar listed wetlands completely or partially dried out and exposed the acid sulfate soils. As no discharge occurred over the barrages from 2007-2009, salinity in the stagnant water increased substantially due to evaporation that caused the large reductions in lake volume. The lack of lake flushing also resulted in the observation of very high concentrations of nutrients and algae, and an increasing dominance of cyanobacteria. The lake was classed as hyper-eutrophic by the Environment Protection Authority (2013).

One of the worst deteriorations of water quality is its salinity; the average salinity level in Lake Alexandrina increased to 3,000 EC units in October 2008. Heneker (2010) modelled historical salinity data for Lake Alexandrina from 1975 to 2007 and his modelled results are also included in Fig. 11 (with no data measured in the period of 1999-2002). His research shows that the annual net evaporation loss in Lake Alexandrina and Lake Albert has ranged from 600 to 950 GL with an average of 800 GL. Losses from the main river channel between Lock 1 and Wellington ranged from 45 to 105 GL with an average around 80 GL. Total annual diversions from Lake Alexandrina and Lake Albert for irrigation, stock and domestic purposes have remained consistent over the period 1975 to 2006, averaging 20 GL (18 to 22 GL range) and 33 GL (30 to 36 GL range), respectively. It is recognised that in recent years, diversions from both lakes have reduced or essentially ceased. The annual flow to the lake and the sea is shown in Table 4.

Heneker's (2010) model shows that to maintain salinity in Lake Alexandrina below 1500 EC, an inflow of 1850 GL/year from the Murray River (or 1000 GL discharge to ocean) is required, the corresponding salinity in Lake Albert is 2550 EC. To keep the salinity less than 1000 EC in Lake Alexandrina an inflow of 2850 GL per year is required or equivalently 2000 GL/year discharge at a barrage, the corresponding salinity in Lake Albert would be 1800 EC. If salinity in Lake Alexandrina must be 700 EC or below (or 1400 EC in Lake Albert), the required annual inflow to the lake is 4850 GL (or 4000 GL outflow at the barrages). In most situations, water salinity of more than 700 EC is unsuitable for irrigating most horticultural crops, while 800 EC is the accepted maximum level for domestic supplies in larger towns and cities.

Adelaide's water crisis supports the claims that the shortage is not water, rather it is water storage, because the current water use is only 160 GL/year and in 2050 it will be 370 GL/year, but the runoff in the Murray River is about 5000 GL/year. The shortfall of storage has also been realized by the SA government. They compared stored water and storage capacity with other capital cities, and Adelaide has the lowest storage capacity that is equivalent to one-year's annual demand (200 GL/year). Probably, the designers of barrages at Lake Alexandrina tried to build the largest reservoir for Adelaide; the total surface area of two lakes covers 800 km^2

and its storage capacity is 2000 GL. It is necessary to investigate why their design failed for water supply, and how to improve its design by applying the concept of a second-generation coastal reservoir.

The design of a second-generation coastal reservoir is different from the first generation that had the minimum barrage length; the new coastal reservoir design would have a longer barrage (not expensive) but optimum storage capacity without storing poor quality water. To determine the optimum storage capacity, one needs to use the reliable flow data in dry years. For this purpose, the monthly flow data measured at Lock 1 is used from 2006-2009. The cumulative inflow data are plotted in Fig.11 for a target total water supply at 870 GL/year. The results show that the optimum capacity is 580 GL, and thus one may conclude that the failure of the first-generation coastal reservoir is its size, which is too big to function as a freshwater source in a dry climate.

Based on the calculated results shown in Fig. 11, one can design a coastal reservoir within the existing Lake Alexandrina as shown in Fig. 12, where the reservoir area is 150 km^2, over which surface the estimated evaporation loss is 150 GL/year because Heneker's (2010) analysis shows the evaporation loss is about 1 GL/km^2. The target water supply of 870 GL/year is partially lost by evaporation from Lock 1 to the lake, i.e. 80 GL/year based on Heneker's (2010), and thus the usable water will be 640 GL/year. By 2050, Adelaide's total water demand is 370 GL/year. If 100 GL/year of water is provided by local sources like mountain reservoirs, coastal reservoirs, rainwater tanks, etc., then the required water from the Murray River will be 270 GL/year, and thus 370 GL/year can be used for environmental flows or irrigation.

Figure 8. Lake Alexandrina and its barrages (South Australia, 2000).

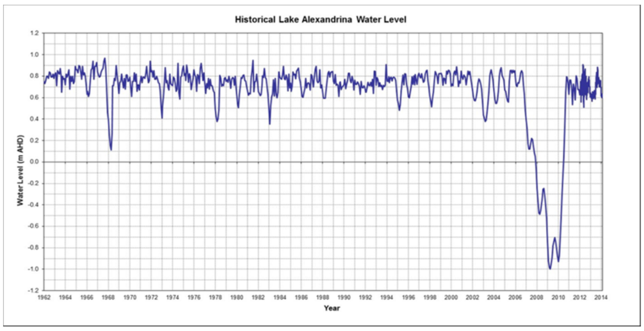

Figure 9. Daily water level (m AHD) of Lake Alexandrina at the Goolwa Barrage from November 1973 to November 2009. (Source: Murray–Darling Basin Authority, 2014)

4 ANALYSIS OF QUALITY/QUANTITY OF WATER SUPPLY TO ADELAIDE AND THE LAKE'S ECOSYSTEM

To analyze the feasibility of the coastal reservoir shown in Fig. 12, one has to compare salinity in the lake and inside the reservoir, the water level and residence time as well as the cost to supply sufficient water to Adelaide (i.e., 370 GL/year), the results are shown in Table 4. During the Millennium Drought, the lowest water level was recorded in 117 years, and the recorded annual discharge at Lock 1 was 1283 GL, 579 GL, 535 GL and 500 GL for 2006, 2007, 2008 and 2009, respectively.

The storage capacity of Alexandrina 1740 GL (620 km^2 lake area with 2.8 m water depth), but the water body outside of coastal reservoir is 1160 GL, if the 580 GL coastal reservoir is constructed. The annual discharge used in Table 4 for each system is determined by:

$$Q_{out} = Q_{in} - Q_{evaporation\ loss} - Q_{diversion} \quad (1)$$

The evaporation loss is 800 GL and 80 GL from the lakes and the river course from Lock 1, respectively. The water diversion to Adelaide in 2050 would be 270 GL/year. Q_{in} = incoming flow for a water body. For the case without the coastal reservoir, the water is pumped from the river (270 GL/year), and thus the discharge at the lake's entrance = discharge at Lock1 minus evaporation loss (80 GL/year) and diversion (270 GL/year). For the case with the coastal reservoir, the water is pumped from the coastal reservoir, so the discharge at the lake's entrance = discharge at Lock 1 after evaporation loss (80 GL/year) only. Discharge at Lock 1 is listed in the first column of Table 4.

For the case with the coastal reservoir, the reservoir's Q_{in} is assumed 1/2 of inflow at the entrance (the best quality water), and the other half of the inflow bypasses the reservoir as shown in Fig. 12 by black lines with arrows. Q_{out} is half of Q_{in} minus the reservoir's evaporation loss (150 GL/year) and Adelaide's water supply (270 GL/year). In the scenario with the costal reservoir during an equivalent Millennium Drought, it is assumed that 3/4 of runoff enters the reservoir (1/4 of water with poor quality bypasses the reservoir), Q_{in} = 3/4 *(870-80) = 592 GL/year (see Fig. 12), where $Q_{evaporation}$ = 150 GL/year for the reservoir, and thus Q_{out} = 172 GL/year after Adelaide's water demand is met (270 GL/year). For the water body outside the coastal reservoir, its Q_{out} is the discharge to the sea.

Table 3. Feasibility of coastal reservoir in Lake Alexandrina and its sustainability.

	Items	Without coastal reservoir shown in Fig. 12	With coastal reservoir shown in Fig. 12 Inside reservoir	Outside reservoir
Millennium Drought, inflow 870 GL/a at Lock 1 (2006-2009)	Lowest water level in mAHD	-1.0	0.05	0.75
	Highest salinity in water to Adelaide	750 EC	450 EC	
	Water body's highest salinity	3000~6000 EC	450 EC	seawater
	Residence time	Infinity	2.76 year	NA
	Environmental issues (algae, acid sulfate land)	20,000 ha of acid sulfate soil, algal blooms (MDBA, 2014)	Q_{in} = 592 GL/a at entrance, Q_{out} = 172GL/a at its outlets.	0 ha of acid sulfate soil, no algal blooms, but seawater
	Cost to provide Adelaide 370 GL/a water in AU$ m/a	341.3	146	
Inflow 2200GL/a at Lock 1	Lowest water level in mAHD	0.75	0.75	0.75
	Highest salinity in water to Adelaide	820 EC	400 EC	
	Water body's highest salinity,	1500 EC	400 EC	1500 EC
	Residence time of the lake Alexandrina	1.74 year	0.91 year	1.16 year
	Environmental issues (algae, acid sulfate land)	Q_{in} = 1850 GL/a at entrance, Q_{out} = 1000 GL/a to the sea for environmental flow	Q_{in} = 1060 GL/a at entrance, Q_{out} = 640 GL/a at its outlets	1060 GL at entrance, Q_{out} = 1000 GL to the sea
	Cost to provide Adelaide 350 GL/a water, AU$	341.3	146	
Inflow 3200GL/a at Lock 1	Lowest water level, mAHD	0.75	0.75	0.75
	Highest salinity in water to Adelaide	820 EC	400 EC	
	Water body's highest salinity,	1000 EC	400 EC	1000 EC
	Residence time of the lake	0.87 year	0.51 year	0.58 year
	Environmental issues (algae, acid sulfate land)	Q_{in} = 2850 GL/a at entrance, Q_{out} = 2000 GL/a to the sea	Q_{in} = 1560 GL/a at entrance, Q_{out} = 1140 GL/a at its outlets	1560 GL/a at entrance, Q_{out} = 2000 GL/a to the sea
	Cost to provide Adelaide 350 GL/a water, AU$	341.3	146	
Inflow 5200 GL/a at Lock 1	Lowest water level, mAHD	0.75	0.75	0.75
	Highest salinity in water to Adelaide	820 EC	400EC	
	Water body's highest salinity	700 EC	400EC	700EC
	Residence time of the lake	0.44 year	0.27 years	0.29 year
	Environmental issues (algae, acid sulfate land)	Q_{in} = 4850 GL/a at entrance, Q_{out} = 4000 GL/a to the sea for environmental flow	Q_{in} = 2560 GL/a at entrance, Q_{out} = 2140 GL/a at its outlets	2560 GL/a at entrance, Q_{out} = 4000 GL/a to the sea
	Cost to provide Adelaide 350 GL/a water, AU$	341.3	146	

The lowest water level was -1.0 m AHD in April 2009, but the coastal reservoir could enhance the lake's water level in the scenario of the Millennium Drought if the barrages were opened, and seawater was allowed to inundate the lake. This would temporarily connect the Murray Mouth and Lake Alexandrina by seawater. The barrages would be operated as usual when plentiful rainwater comes back. The South Australia government has investigated this option, and the conclusion is that the introduction of seawater can effectively address the widespread acidification, but there would be loss of salt-sensitive taxa in the first year. To achieve this, it is necessary to construct a weir at the lake's entrance to stop seawater intrusion to secure the water quality of Adelaide's supply (Muller 2011), this is actually another small coastal reservoir. After the proposed coastal reservoir is constructed, there is no problem to open the 5 barrages, the seawater level outside the coastal reservoir could be 0.75 m.

For the driest period, there were 3 consecutive months (July-Sept., 2007), when the Murray River salinity was higher than 500 EC and its inflow was below 25 GL/month. During this period, the hydraulic gate at reservoir's entrance would be closed and the water loss due to evaporation and water supply in 3 months is [(150+270)/12*3 =] 105 GL, or the water drop would be 0.7 m (=105/150), and thus the reservoir's water level would be 0.05 m AHD (=0.75-0.7). For other scenarios in Table 4, the water level can be maintain at 0.75 m AHD inside and outside the coastal reservoir.

The mass conservation equation for salinity in the coastal reservoir can be written as:

$$(S-S_o)V = (S_{in}Q_{in}-SQ_{out} -SQ_{diversion})\Delta t \qquad (2)$$

where S and V are salinity and water volume in the water body (V = 580 GL, and V = 580-105 = 475 GL for the reservoir in the Millennium Drought), S_o is the initial salinity. Δt = time. Q_{in} and Q_{out} are listed in the row of environmental issues in Table 4, $Q_{diversion}$ = 270 GL/year. In order to simply the analysis, it is assumed that the salinity at the Lock 1 is the same as that in the lake's entrance, or the salinity in water diverted to Adelaide is equal to the salinity at Lock 1. The coastal reservoir is flushed every year using floodwater, its salinity is assumed to be S_o = 300 EC. For the scenario of the Millennium Drought, it is assumed that S_{in} = 450 EC. For other scenarios, the salinity distribution is assumed to be valid, i.e., in the flood period (Sept. –Jan.) S_{in} = 400 EC, in dry period (Jan.-June) the average salinity is 470 EC, and the average from July to Sept. is 750 EC with the highest 820 EC that is possible in the water pumped to Adelaide, if the coastal reservoir does not exist. The calculated salinity based on Eq. 2 for coastal reservoir is shown in Table 4. The salinity in the water body outside the coastal reservoir is assumed to be the same as that obtained by Heneker's (2010). Table 5 clearly shows that the coastal reservoir can improve Adelaide's water quality, and the salinity is always constant and equal to 400 EC. The salinity of water body outside the coastal reservoir may be slightly higher than Heneker's (2010) prediction, but this is not important as high salinity outside the coastal reservoir would not affect water supply for drinking and irrigation.

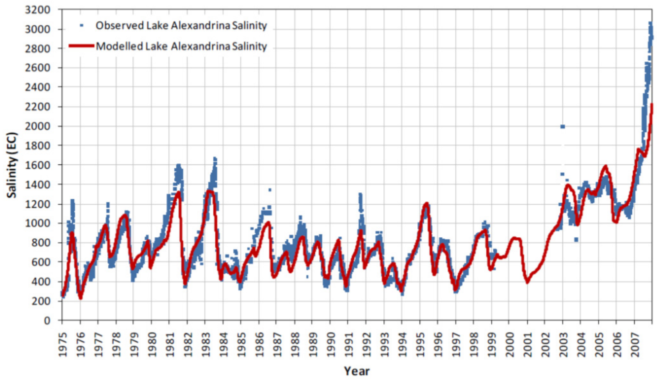

Figure 10. Observed and modelled historical Lake Alexandrina salinity (source: Heneker, 2010)

The residence time is the ratio of storage capacity to the discharge, or V/Q_{out}. It expresses the travel time for a water particle from entering a water body till leaving it, or the index of water mobility. A shorter residence time gives better quality water. In the Millennium Drought scenario, the average flow over this period is 870 GL/year at Lock 1, it is less than the annual evaporation loss, i.e. 880 GL/year and Q_{out} = 0, and thus the residence time is infinity for the case without the coastal reservoir. For other scenarios, V = 1740 GL, 580 GL and 1160 GL for the whole lake, coastal reservoir and water body outside the coastal reservoir, respectively. Q_{out} is listed in Table 4. The calculated results in Table 4 show that in every scenario where the residence time becomes shorter or water particle's movement velocity becomes higher, the coastal reservoir can improve the lake's water quality by reducing its stagnant water volume and constraining the growth of algae.

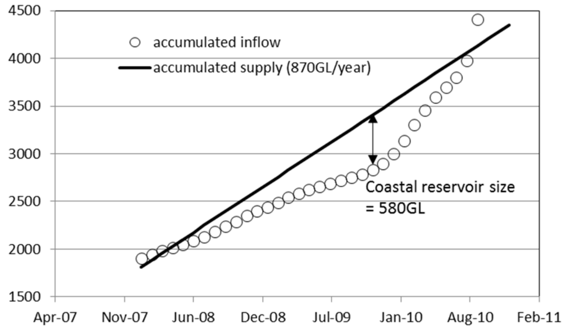

Figure 11. Determination of reservoir storage capacity using flow data at Lock 1 from 2007-2010 for the target water supply of 870 GL/year.

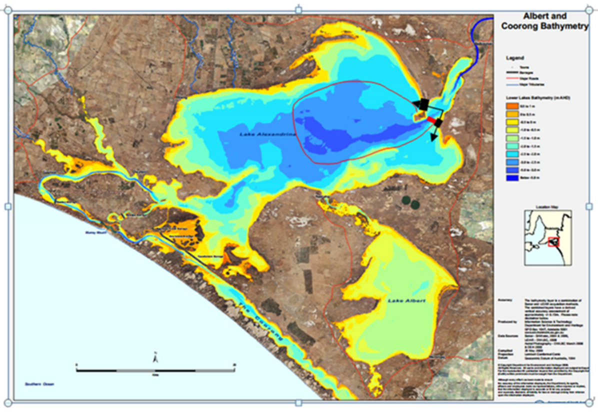

Figure 12. A proposed coastal reservoir enclosing the deep water by a dike (red line). The average depth of coastal reservoir is 3.5 m, area is 150 km^2 and storage is 580 GL.

This can be seen clearly from Fig. 12. The mobility of water bodies in the north/south channel of the coastal reservoir would be increased as river flow bypasses it; this improvement can be also expressed by the residence time using the channel's water volume and flowrate. MDBA (2014) claimed that by March 2009 without management intervention, over 20,000 hectares of acid sulfate soil would have been exposed in Lakes Alexandrina and Albert posing substantial risks to the region's ecology and the Ramsar listed wetlands. But the construction of a coastal reservoir eliminates this threat. In other words, the land acidification would not occur. Without coastal reservoirs, to provide 370 GL/year, Adelaide would need its desalination plant to provide 100 GL/year at the operation cost of AU$130 million; the remaining water would be delivered from the Murray River with its pumping cost for 130 GL/year of water that would be a total of AU$57.2 million and any additional water would have a higher cost (see Table 5), i.e. AU$88.8 million. The purchase of water entitlement for an additional 140 GL/year will cost AU$65.3 million (as mentioned before that Adelaide purchased 40 GL water entitlement for AU$14 million). So, the total cost to secure water supply for Adelaide in 2050 would be AU$341.3 million if a drought similar to Millennium Drought occurs again. If the coastal reservoir constructed, Adelaide only needs to pay the pumping cost without cost for water entitlement, i.e. AU$146 million, which is 42.8% of the cost for existing solutions (i.e., desalination and water buyback scheme). The additional pumping cost is negligible from the coastal reservoir to Murray Bridge, a distance of about 30 km.

5 CONCLUSIONS

This paper investigates how to provide Adelaide with sufficient clean water at an affordable cost. It is found that the main problem in Adelaide's water supply is the shortage of water storage, rather than a water shortage. If coastal reservoirs are developed in the Adelaide region, the water shortage can be greatly alleviated. If the desalination plants in Adelaide are fed with the water from the coastal reservoirs, the operational cost of water supply can also be lowered significantly.

The analysis in this paper clearly shows that the driest city in Australia, Adelaide, is not short of water but has inadequate reservoirs, because the largest river in Australia discharged 5000 GL/year of water into the sea even during the worst recorded drought period, the Millennium Drought (2002-2007). To develop its water resources, South Australia constructed a first generation of coastal reservoir in Australia, using barrages to impound Lake Alexandrina. The failure of this very large coastal reservoir in the Millennium Drought forced the South Australia government to investigate constructing a very small coastal reservoir – a barrage in Murray River near Wellington (Department for Environment and Heritage. 2009). But the historical data shows that these two coastal reservoirs are both inappropriate due to their sizes and designs. It is proposed that a second-

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generation coastal reservoir, which takes into account of both required water quality and the right size, is required. It is found that a 580 GL capacity coastal reservoir would be suitable provided the coastal reservoir is operated as a second-generation type. Once a coastal reservoir is constructed, Adelaide's water supply is secured even without desalination.

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STUDY ON RESERVOIR WATER AND SEDIMENT DISPATCHING OPERATION SYSTEM FOR THE PRE-CONTROL OF THE EUTROPHICATION

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ABSTRACT

As the largest water source in Shanghai, the water supply safety of the Qingcaosha Reservoir is of great importance and it is located at the estuary of the Yangtze River. The water quality of the reservoir is restrained not only by the water quantity and quality of the upstream, but also by the water environment of the estuarine area and the salinity changes. Due to the numerous influential factors and the high potential environmental risk, it has the characteristics of long-term, sudden and uncertainty. Meanwhile, Qingcaosha Reservoir also has the characteristics of the shallow lake because of the high nutrient source (e.x. phosphorus) in the Yangtze River. After the completion of the reservoir, the velocity of the water flow declines, the reservoir water residence time increases, and backwater area exists in some parts. This paper aims at the eutrophication and water bloom pre-control problems of the large shallow estuary reservoir, combined with the actual situation of Qingcaosha Reservoir, and according to the latest research results of Qingcaosha Reservoir sediment release pattern and optimal residence time. In order to conduct the research respectively on aspects such as, Hydrologic and Sediment Monitoring & Research of the law of water and sediment at the reservoir entrance, Optimization of reservoir dispatching scheme, Drainage and self-purification strengthening technology, Emergency dispatching operation scheme and Sediment control & siltation promotion measures are proposed to form a water and sediment dispatching operation system based on eutrophication pre-control, which is of "one frame, three kinds of operation mode, the four measures ". In order to guide the dispatching operation of the Qingcaosha Reservoir, and pre-control the reservoir eutrophication, this system improves the water quality and ensures the water supply safety of the reservoir.

Keywords: Qingcaosha reservoir; water supply safety; eutrophication pre-control operation; water and sediment dispatching; operation system.

1 RESEARCH BACKGROUND

Qingcaosha raw water project is mainly composed of Qingcaosha Reservoir and the corresponding water pump works, the Yangtze River pipe engineering and the relevant terrestrial water pipelines and booster pump station project. By 2020, the estimated water supply scale is 7.19×10^6 m^3/d, covering all of the Yangpu District, Hongkou District, Zhabei District, Huangpu District, Luwan District, Jingan District, Changning District, Xuhui District, Pudong New Area and Baoshan District, and part of the Nanhui District, Putuo District, Chongming County, Qingpu district and Minhang District, which will be of great benefit to more than 10 million people.

However, the Qingcaosha River estuary area is located at the end of the Yangtze River Basin; hence the water quality is restrained not only by the water quantity and quality of the upstream, but also by the water environment of the estuarine area and the salinity changes. Due to the numerous influential factors and the high potential environmental risk, it has the characteristics of long-term, sudden and uncertainty. On the other hand, Qingcaosha Reservoir also has the characteristics of the shallow lake, due to the high nutrient source (e.x. phosphorus) in the Yangtze River. After the completion of the reservoir, the velocity of the water flow declined, the reservoir water residence time increased, and backwater area existed in some parts. These factors raise the risk of eutrophication, and even "water bloom", which have a certain impact on the quality of raw water.

2 RESEARCH OBJECTIVES

Here in this work, we studied the eutrophican control as the goal of the Qingcaosha reservoir water and the sediment dispatching operation technology, proposed the scheduling scheme of cyanobacteria occurred events, and provided technology and gathered experience for the domestic large estuary avoid salty storage of light reservoir water quality protection technology and experience.

3 RESEARCH CONTENT AND METHODS

The research content included Hydrologic and Sediment Monitoring & Research of the law of water and sediment at the reservoir entrance; Optimization of reservoir dispatching scheme; Drainage and self-

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purification strengthening technology; Emergency dispatching operation scheme and Sediment control & siltation promotion measures. All these were carried out by making scientific reservoir water and sediment dispatching scheme, combining with other control measures to prevent the large area of reservoir water bloom, and protecting the water quantity and quality of Qingcaosha reservoir.

The main research methods included field monitoring of hydrological data, analysis of measured data, calculation of water balance, three-dimensional flow, two-dimensional sediment mathematical model simulation and analysis.

4 RESERVOIR SEDIMENT RELEASE PATTERN AND OPTIMAL RESIDENCE TIME

The results showed that the phosphate release flux in the reservoir area reached the highest value in summer (July to September). By increasing the amount of water in reservoir, the amount of phosphate release from the sediment could be increased dramatically compared to the original value. The residence time and the water level in the reservoir area have obvious effects on the growth of algae, and the inhibition effect on the algal bloom risk gets more obvious with the increasing water level in the reservoir area and the decreasing residence time of the reservoir area, and vice versa. In conventional reservoir operation, by remaining the reservoir water level at 2.7m and controlling the reservoir water retention time within 15 to 20 days, there can be effective inhibition of the algae growth and reduction of algal bloom risk, consequently being able to prevent the reservoir eutrophication.

Based on the previous conclusion, in the research of water and sediment scheduling scheme, in order to achieve the goal of water and sediment dispatching with reservoir eutrophication control, the amount of sediment getting into the reservoir and the total amount of nutrients in sediment storage should be reduced to the lower limit, and the reservoir water retention time should be no more than 15 to 20 days. As a result, the phosphate release can be reduced, and so as the algal bloom risk.

5 THE RULE OF WATER AND SEDIMENT AT THE RESERVOIR ENTRANCE

The change of the sediment concentration near Qingcaosha reservoir intake was small during spring tide from 2008 to 2010, and the sediment concentration increased activity during the neap tide of flood season and the spring tide of the dry season. The sediment concentration showed decreasing trend during the neap tide of dry season, and the changes were within 0.05kg/m^3. At the beginning of reservoir construction, there was some scour near the intake because of the action of the dike flow. The composition of the sediment in the bed showed that when the proportion of sand increased, the proportion of silt and clay decreased, and the median particle size increased. But with the reservoir embankment construction completed and put into operation, together with the surrounding beach protection engineering, water flow velocity near the intake got stable and decreased slowly, and decreased sediment silting in this part, hence the composition of bed for continuous refinement. Overall, after the beach was relatively stable, the sediment concentration near the intake changed accordingly to the change of Yangtze River.

6 OPTIMIZATION OF RESERVOIR OPERATION SCHEME

6.1 Fundamental rule of reservoir operation

The reservoir is mainly applied for drainage during the period of non-salt tide. According to the characteristics of reservoir operation, combining with the general objectives of the dispatching operation, the replacement time of the reservoir water and the water supply, the basic principles of reservoir operation were developed:

(1) Principle of ensuring water supply safety: satisfy the requirement of normal water supply (7.19×10^6 m^3/d) and the emergency water supply. In case of water pollution or any other emergencies, it must be ensured to have water supply for 12 days. In summer, the water retention time should be no more than 15~20 days to reduce the amount of sediment and nutrient.

(2) Principle of ensuring building safety: The flow rate of drainage should meet the requirement of energy dissipation and erosion prevention. The control of water level in the reservoir should meet the safety requirements of hydraulic infrastructures.

(3) Principle of energy saving operation: During non-salt tide, the upstream dam should be applied mainly on diversion and the downstream dam mainly on drainage, start the pump operation when necessary and reduce the energy consumption of water intakes.

6.2 Dispatching scheme drafting and assessing

6.2.1 Dispatching scheme during the shakedown period

The Qingcaosha reservoir had its trial operation in October 2010. During the test run, the reservoir water level should not exceed 3m since the reservoir seepage had not been completed. In the meantime, considering the evening lighting conditions, in order to prevent the night operation accident and ensure the safe operation of the reservoir, water diversion using tide can be applied for only one time for upstream sluice and no more than two for the downstream sluice every day, and no diversion and drainage in isolated cases. Scheduling period is mainly concentrated in the daytime and the number of scheduling at night is reduced if possible.

Based on the analysis of reservoir operation in September 2011, the upstream sluice diversion lasted for 24 days, and except for the diversion of two tide water on September 9th, there was only one diversion every day at all other times. Downstream sluice operated on daily basis, but mostly once a day. There were 13 days with operation twice a day, accounted for 43% of the total number of operation days. By means of analysis and calculation, the amount of water diversion from the upstream sluice was about 2.42×10^8 m^3 in September, and drainage from the downstream sluice was about 0.55×10^8 m^3, and transfer from the Wuhaogou pump was about 1.21×10^8 m^3, the water exchange cycle was 41 days.

Consideration of previous incidents, the rate of water exchange was low during the shakedown period, but the water exchange cycle was long. It is far more than the requirement that the water retention time should be less than 15~20 days which can prevent the reservoir eutrophication.

6.2.2 Conventional operation scheme

The conventional scheduling scheme is the scheduling scheme for the design of Qingcaosha reservoir. In this study, according to the reservoir underwater topographic survey results in September 2011, we checked the storage-capacity curve, and performed analyzes of the reservoir operation according to the upstream and downstream sluice discharge curves, which was provided by physical model test, the reservoir dispatching principle, the water supply of 7.19×10^6 m^3/d, the reservoir water level changes in a range of 2.0m~4.0m and the sea level with typical tide. Research showed, during the non-salt tide from May to September, the reservoir's water level fluctuated between 2.03 to 3.54 m, and the average water level was 2.91m, as illustrated in Figure1. There was about 3.04 ×10^{9}m^3 water fell into the reservoir, and the displacement for downstream sluice and pump station was 3.02 ×10^{9}m^3. The water exchange cycle was 13 days. The reservoir scheduling scheme can meet the requirement of water retention time being less than 15~20 days.

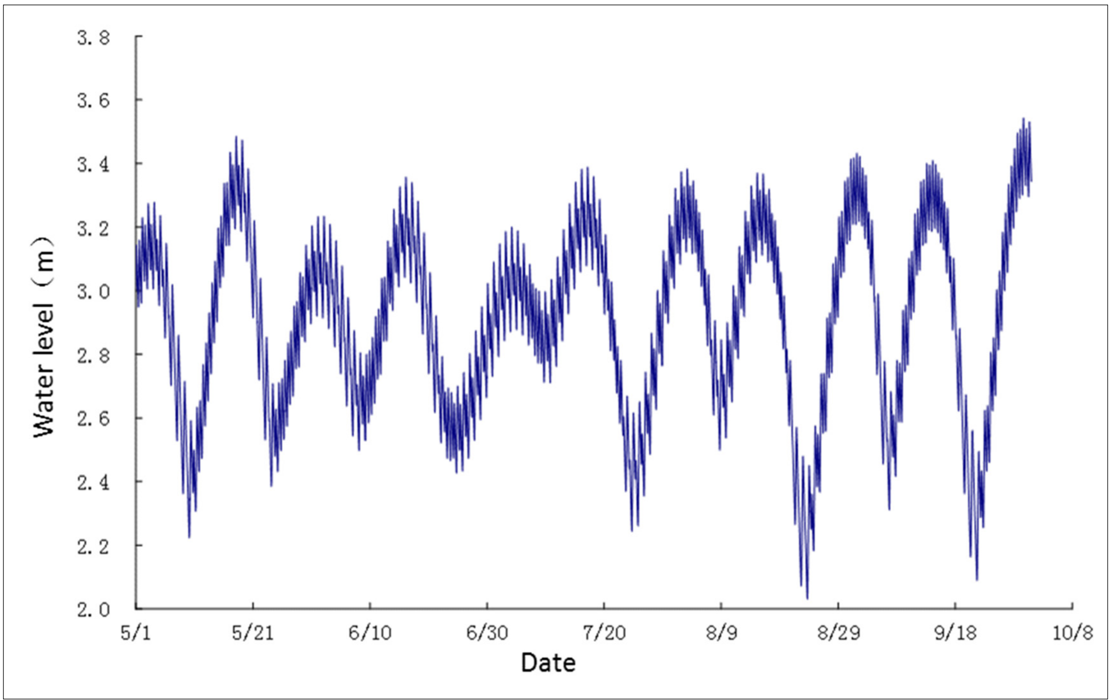

Figure 1. The water level in the reservoir of conventional operation scheme.

6.2.3 Scheduling scheme for water cleaning and sand controlling

According to the monitoring data acquired near the Qingcaosha reservoir intake from 2008 to 2010, during flood season, the average sediment concentration was about 0.18kg/m^3 in spring tide, and was about 0.18kg/m^{3}in neap tide. The results of the tracking monitoring of the sediment concentration near the intake in November 2011 showed the average sediment concentration in spring tide was about 0.5kg/m^3, the average sediment concentration in middle tidal was about 0.21kg/m^3, and the average sediment concentration in neap tidal was about 0.097kg/m^3, affected by the measured position changes and water conditions. Although the sediment concentration was different, the variation trend of sediment concentration was constant for different tides, which was large for the spring tide, medium for the middle tide and small for the neap tide. Therefore, in order to reduce the inflow sediment, the reservoir scheduling scheme of no inflow in spring tide was proposed under the premise of not affecting the normal water supply.

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Based on preliminary calculation, the reservoir's water level changed from 2.00 to 3.35m in non salt tide from May to September. The average water level was 2.73m, and the water level process is depicted in Figure 2. There was about 2.86 $\times 10^9 m^3$ water fell into the reservoir, and the displacement of downstream sluice and pump station was 2.86 $\times 10^9 m^3$. The water exchange cycle was 13.3 days. Compared to the conventional scheduling scheme, the sediment load can be reduced by 2.4×10^4t, and the particulate phosphorus fell into the reservoir by the sediment was decreased about 9t, and the water exchange cycle increased by 0.3 day.

The results showed that the scheduling scheme can meet the demand of water supply, and can reduce the amount of incoming sediment and the amount of particulate phosphorus in the sediment, and the reservoir water transfer period increase was not obvious. It can meet the requirement that the water retention time was no more than 15~20 days.

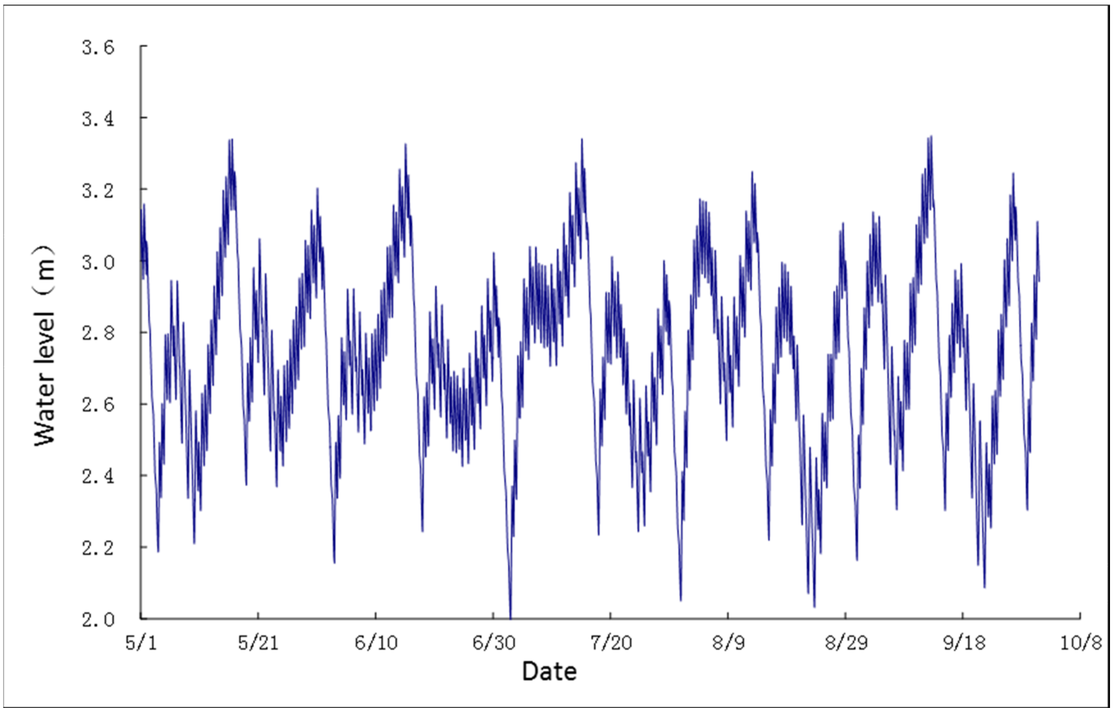

Figure 2. The water level in the reservoir of water cleaning and sand controlling scheme.

To sum up, the scheduling scheme for water cleaning and sand controlling is recommended.

7 DRAINAGE AND SELF-PURIFICATION STRENGTHENING TECHNOLOGY

7.1 The influence of reservoir operation control water level on discharge capacity

The maximum operating water level of the reservoir was 4.00m, and the minimum operating water level was 2.00m. In order to analyze the influence of different operating water levels on the discharge capacity of reservoir in flood season (May to September), and to calculate and study the reservoir regulation, 5 calculation schemes were developed at 2.0m、2.5m、3.0m、3.5m and 4.0m, respectively.

With scheme 1 (2.0m) ~ scheme 5 (4.0m), the average water level of the reservoir was 1.97m, 2.42m, 2.78m, 2.91m and 2.91m. The water level process in the reservoir of the 5 schemes is shown in Figure 3. As can be seen from the figure, the reservoir water level variation between program 4 (3.5m) and program 5 (4.0m) was very small. It can be seen from the different schemes of reservoir drainage (Table 1)that with the increase of the reservoir water level, the amount of water diversion and drainage from the upstream sluice and downstream sluice increased gradually, and the water exchange cycle was decreased from the 15.4 days (scheme1, 2.0m), and remained stable at the end of the 13 days (scheme3, 3.0m). The variation trend of the exchange water cycle in different schemes is shown in Figure 4. It is therefore appropriate to control the reservoir operating water level. Being not less than 3.0m, this can be considered by increasing the amount of water discharged from the reservoir and reducing the exchange water cycle and operation costs.

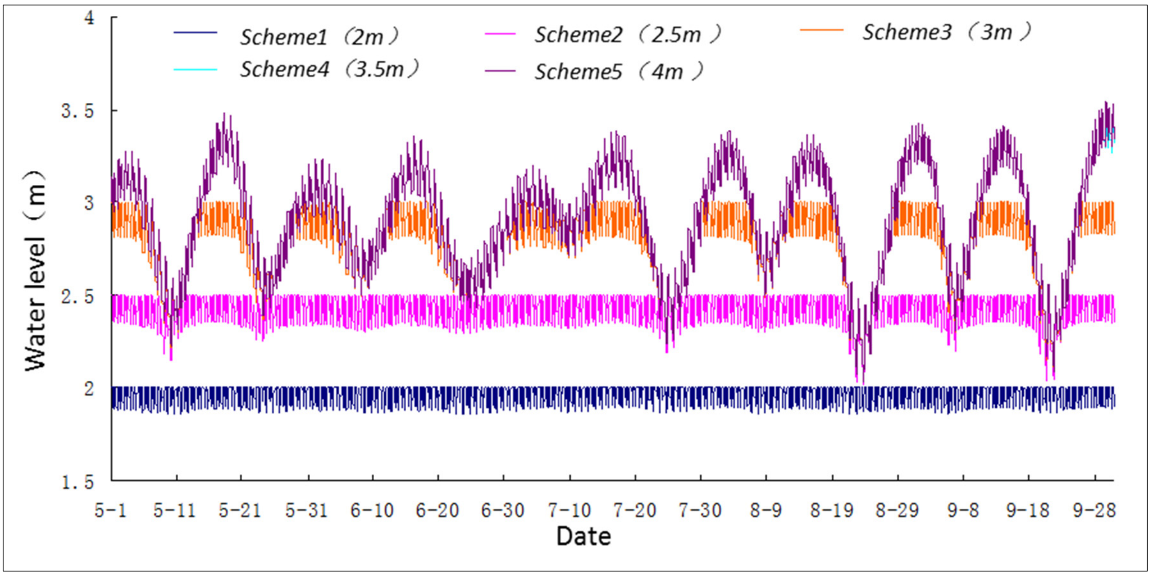

Figure 3. The water level process in the reservoir in different schemes.

Table 1. The Statistical value of discharge capacity under different operation control water level.

Study scheme	Computation time			Reservoir's water level ↖ m↗	Reservoir storage capacity ↖ 10^4m^3↗		Diversion of upstream sluice ↖ 10^4m^3↗	Drainage of downstream sluice ↖ 10^4m^3↗	Water supply amount ↖ 10^4m^3↗	Water exchange cycle (day↗
	Start	End	Last days		Start	End				
scheme1	5-1 0:00	10-1 0:00	153	2	21000	20640	207151	89799	117710	15.4
scheme2	5-1 0:00	10-1 0:00	153	2.5	22900	22348	253857	136698	117710	13.6
scheme3	5-1 0:00	10-1 0:00	153	3	24900	24232	288869	171827	117710	13.0
scheme4	5-1 0:00	10-1 0:00	153	3.5	24900	26210	303719	184699	117710	13.0
scheme5	5-1 0:00	10-1 0:00	153	4	24900	26342	303873	184721	117710	13.0

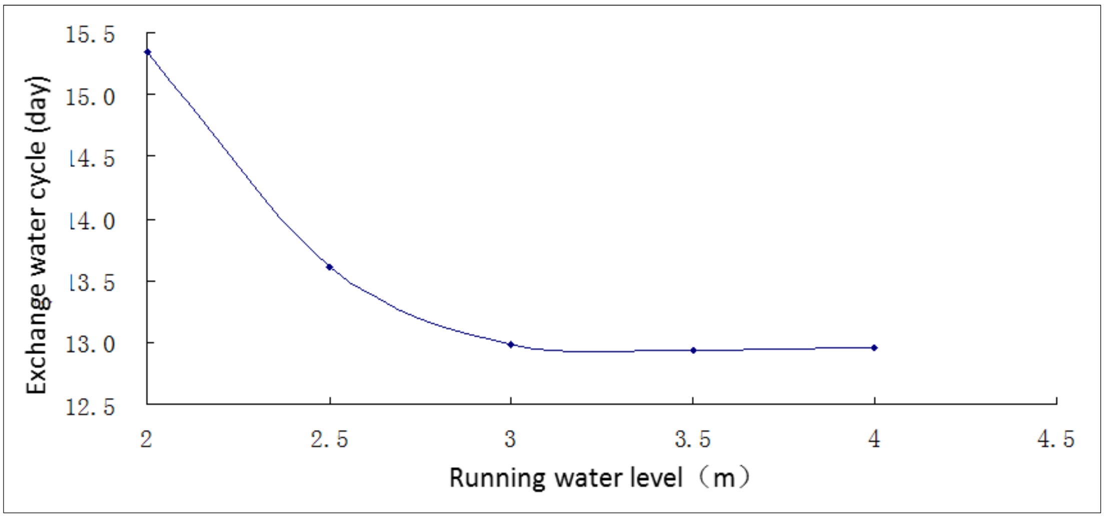

Figure 4. The variation trend of the water exchange cycle in different schemes.

7.2 The effect of additional drainage gate on the reservoir discharge capacity

Considering the impressive length of the Qingcaosha reservoir, it takes a long time for water to go through from the upstream to the downstream. Therefore, we planned to add a drainage gate in the middle of a 50m net width between the up and downstream sluice, and analyze its influence on the water supply capacity.

According to the regulation computation of reservoir, the reservoir water level fluctuated in the range of 1.74m to 3.14m, and the average water level of the reservoir was 2.09m during the calculation period. The water level process in the reservoir is shown in Figure 5.

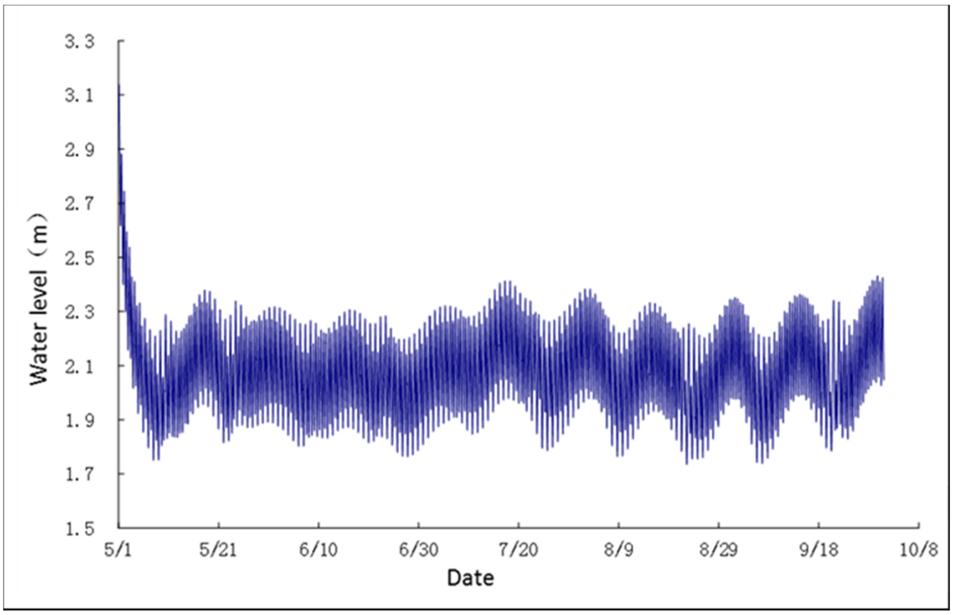

Figure 5. The water level process in the reservoir after adding a 50-meter sluice.

The amount of water diversion from the upstream sluice was about 4.87×10^9 m^3. The total amount of water diversion from the upstream sluice and the downstream sluice and the additional 50-meter sluice was about 4.90×10^9 m^3. Among them, the additional 50m sluice discharge was about 2.65×10^9 m^3. The results showed that the water exchange cycle was 7.2 days. Compared to the scheme of no additional drainage sluice, the effect of water exchange was improved significantly.

7.3 The effect of promoting the downstream discharge capacity on the discharge capacity of reservoir

The drainage capacity of downstream sluice of Qingcaosha Reservoir was affected by the reservoir water level, the water level, and also by the energy dissipation limit. Therefore, it can improve the drainage capacity by improving the downstream energy dissipation and erosion control ability. The following calculation was based on the proposal of two schemes, improving the discharge capacity to 1.5 and 2 times of the original, respectively. The average water level of the conventional operation scheme was 2.91m. The average water level of the 1.5 times operation scheme was 2.78m. And the average water level of the 2.0 times operation scheme was 2.75m. The water level process in the reservoir of different schemes is illustrated in Figure 6. As can be seen from the figure, the increase of the downstream sluice energy dissipation and sluice discharge capacity had a certain effect on the reservoir water replacement. The amount of diversion and drainage of the upstream and downstream sluice is listed in Table 2.

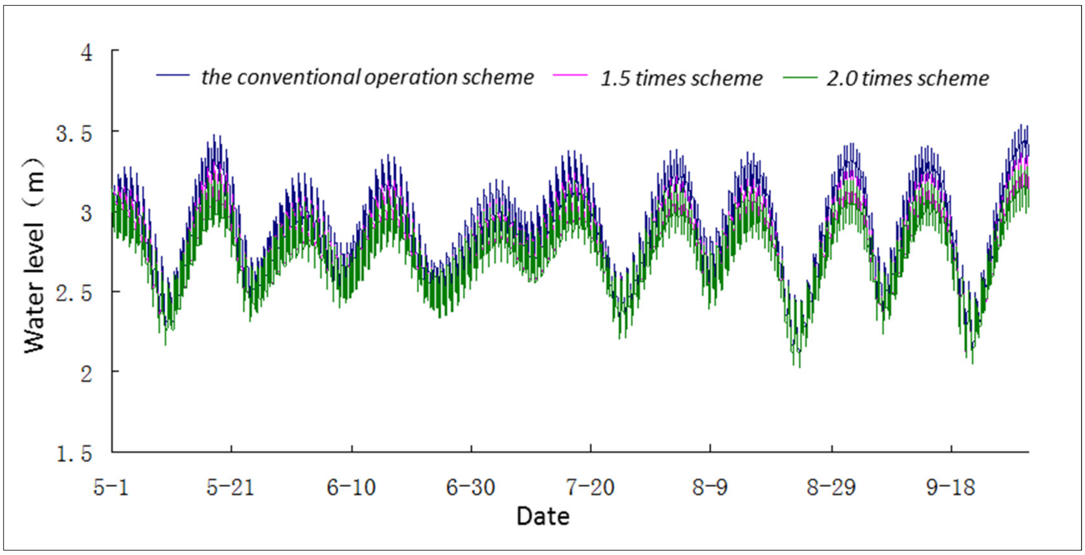

Figure 6. The water level process in the reservoir of the different single grace flow in the downstream sluice.

Table 2. The Statistical value of discharge capacity under different operation control water level.

Discharge capacity improvement scheme	Computation time			Reservoir storage capacity ↖ 10^4m^3↗		Diversion of upstream sluice ↖ 10^4m^3↗	Drainage of downstream sluice ↖ 10^4m^3↗	Water supply amount ↖ 10^4m^3↗	Exchange water cycle ↖ day↗
	Start	End	Last days	Start	End				
1 time	5-1 0:00	10-1 0:00	153	24900	26342	303873	184721	117710	13.0
1.5 times	5-1 0:00	10-1 0:00	153	24900	25381	344980	226788	117710	11.2
2 times	5-1 0:00	10-1 0:00	153	24900	24989	352400	234601	117710	10.8

According to the study mentioned above:

(1) With the increase of the reservoir water level, the amount of water diversion and drainage from the upstream sluice and downstream sluice increased gradually, the exchange of water cycle gradually decreased, and remained stable at 13 days after 3.0m.

(2) The water retention time of the reservoir water quality in the reservoir area was shortened and the water flow in the reservoir was enhanced with the addition of the sluice gate scheme and the improvement of the downstream discharge capacity. The water exchange cycle of the reservoir by adding a 50m drainage scheme can be shortened to 7.2 days, and the effect on improving water exchange was obvious. Improving the downstream sluice control capacity can also play a role in increasing the flow of water in the reservoir area. The average residence time of water quality in the reservoir can be reduced by about 1 to 3 days.

8 EMERGENCY DISPATCHING OPERATION SCHEME

8.1 Analysis of water supply capacity to cope with unexpected water pollution

According to the analysis of the lifting capacity of the reservoir, the water level characteristics of the reservoir were different within different schemes. When there was a serious water pollution incidents near the intake of the Qingcaosha reservoir, and the reservoir cannot draw water for a long time， the water supply of reservoir was based on the salt tide（$7.19×0.8×1.07×10^6m^3/d$）. The water supply of the reservoir can be calculated based on the average water level of the different schemes, and the water supply of the reservoir can remain for 16.0 to 23.6 days (Table 3). It fulfilled the requirement of 12 days in emergency water supply.

Table 3. The statistical value of water supply when the reservoir encounters the sudden water pollution incidents and cannot divert water.

Scheme	Water level		Effective storage ↖ 10^4m^3↗	Daily water supply ↖ according to the salt tide↗ ↖ $10^4m^3/d$↗	Sustainable water supply time↖ day↗
Conventional operation scheme	average	2.91	14535	615.464	23.6
	minimum	2.03	11118	615.464	18.1
Scheme of reservoir operation level of 3.0m	average	2.78	14029	615.464	22.8
	minimum	2.03	11118	615.464	18.1
Scheme of a new 50m sluice	average	2.09	11324	615.464	18.4
	minimum	1.74	9993	615.464	16.2
Scheme of 1.5 times magnification control	average	2.78	14016	615.464	22.8
	minimum	2.02	11068	615.464	18.0
Scheme of 2.0 times magnification control	average	2.75	13910	615.464	22.6
	minimum	2.02	11068	615.464	18.0

8.2 Analysis of the drainage ability under water pollution incidents in the reservoir

In general, incidents where the reservoir is being evacuated are rare. In the reservoir operation, according to the reservoir water pollution degree, methods can be taken including introducing new water to dilute the contaminated water in order to improve water quality, and duly restore the water supply. In this study, it is necessary to drain the reservoir to the bottom of the reservoir if there is an extremely serious water pollution event, and take the scheduling scheme for drainage from the upstream and downstream sluice at the same time in order to discharge the polluted water in the shortest time. Due to the water level control of the Yangtze River, it is very difficult to drain from the sluice after the water level goes down to 1m.Therefore, on the basis of the upstream and downstream sluice drainage together, assuming that the set flow rate of $100m^3/s$ drainage pump in drainage, the water level process of the reservoir discharged to the dead water level and then back to storage is shown in Figure7. By calculation, in the case of the average typical tide, it will take 25.5 days to empty the reservoir water level from 3.0m, and 13.5 days to the dead water level. After the reservoir was evacuated, the time required for the water diversion and storage of the sluices to 2.00m was about 5 days.

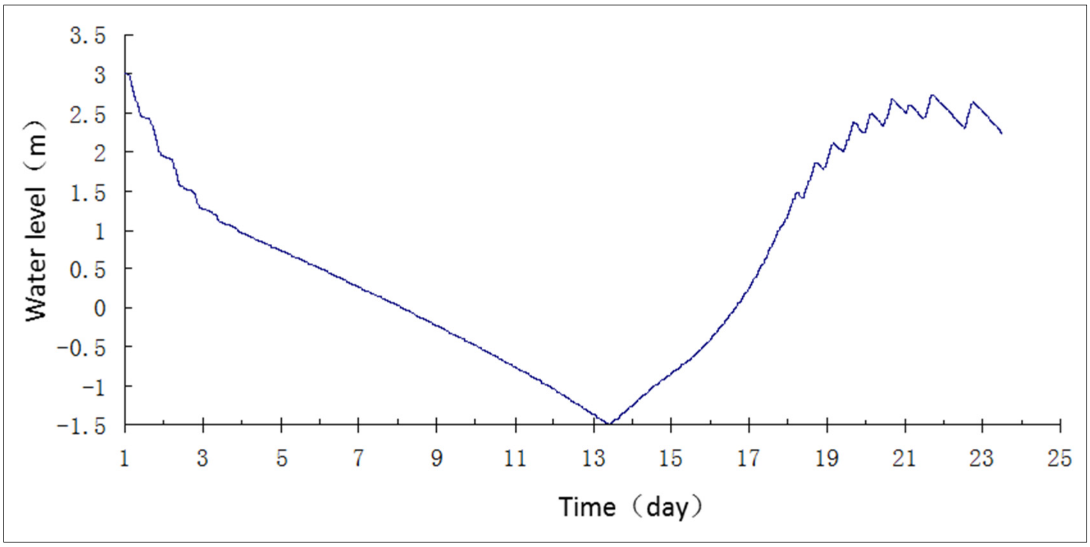

Figure 7. The water level process of the reservoir discharged to the dead water level and then back to storage.

9 SEDIMENT CONTROL & SILTATION PROMOTION MEASURES

The main source of sediment in the reservoir is the sediment deposited from the diversion water and deposit in the reservoir. Therefore, sediment control is mainly about controlling the amount of sediment entering the reservoir, and to promote the deposition of sediment to a certain area of the reservoir, consequently minimizing the deposition to the middle- and down-stream.

9.1 Sand control measures

The sediment concentration in the upstream sluice area of Qingcaosha reservoir is related to the Yangtze River, and also has a close relationship with the tidal changes. The sediment concentration in spring tide is generally greater than the middle and neap tides. According to the analysis of the monitoring data of sediment channel waters near the project area in recent years, the regional average water sediment concentration decreased from the bottom to the surface.

It was exhibited by the hydrological and sediment test in September 2001 that the average sediment concentration during the spring tide was 0.50 kg/m^3, the middle tide was 0.21 kg/m^3, and the neap tide was 0.097 kg/m^3. The average sediment concentration in spring tide was 2.4 times and 5.2 times as much as the middle tide and neap tide. Therefore, in order to effectively reduce the sediment storage in reservoirs, water diversion process should be performed as far as possible during the middle and neap tides, and little or even no diversion during the spring tide.

9.2 Siltation promotion measures

The main approach to accelerate the settlement of sediment is to reduce the velocity of water flow, which can be achieved by enlarging the section. This approach can also be used to promote local siltation. According to a preliminary analysis of the 6 tests in the vicinity of the upstream sluice of Qingcaosha reservoir in April and August 2008, March and August 2009, March and July 2010, the average value of suspended sediment D50 near the upstream sluice was about 0.0121mm. Table 4 lists the results based on the commonly used formula to calculate the sediment settling velocity. The settling velocity of suspended sediment was 0.093~0.131mm/s, and the difference between maximum and minimum was 1.4 times.

Table 4. The calculation results of sediment deposition velocity by formula.

Formula	Storck formula	Zhang Ruijin formula	ShaYuqing formula
Settling velocity(mm/s)	0.131	0.093	0.102

According to numerical calculations, the sediment’s main channel was the South Road The sedimentation in the southern waterway of Qingcaosha reclamation area was greater than that in the North channel. The reservoir sedimentation was mainly in the upstream sluice and on both sides of catch waters, and the southern waterway of Qingcaosha reclamation. However, there was no obvious accumulation in the middle and bottom areas of the reservoir.

For the settlement and control of sedimentation area accelerated sediment, the sediment siltation zone should be arranged in reasonable positions in the upstream of the reservoir, which makes it capable of controlling suspended sediment to the downstream reservoir during transportation. The calculation results showed that the sedimentation trend in the reservoir area was controlled within a certain range after setting up the sedimentation area. The sedimentation was obvious in the settling basin. To the reservoir downstream of the reservoir in the transport range to a certain control, the amount of sediment transport was reduced. The larger the settlement pool area, the deeper the water depth and the more significant the effect. In the front fork through the Qingcaosha reclamation area, local dredging scheme can effectively increase the sediment silting in the reservoir area of the head, and reduce the sediment to the central and tail of the reservoir.

10 WATER AND SEDIMENT DISPATCHING OPERATION SYSTEM

In this paper, based on the analysis of the conventional scheduling scheme, we have proposed schemes such as Scheduling scheme for clean water and control sand, Drainage and self-purification strengthening technology (including engineering measures and nonengineering measures), Emergency dispatching operation scheme and Sediment control & siltation promotion measures , to form a water and sediment dispatching operation system based on eutrophication pre-control, which is of "one frame, three kinds of operation mode, the four measures ". That is to say, the reservoir should be operated under the general framework to meet the water supply, water quality, operation safety, operation economy and operation convenience. Non-salt tide period, combined operation of the upstream and the downstream sluice, and operation mode is divided into three categories: When the water quality in the reservoir is good, the reservoir is operated according to the conventional dispatching mode; When the Yangtze River sediment content of cement is not conducive to the water reservoir, the reservoir is operated by the scheduling scheme for clean water and control sand; When the reservoir water quality shows early warning and control requirements, the reservoir is operated by self-purification strengthening and emergency dispatching mode.

The system has a great innovation in the pre-controlling of the reservoir eutrophication by improving the water quality, ensuring the water supply safety of the reservoir, and has a certain guiding function for the daily operation and management.

THE KEY DESIGN CONCEPTS AND TECHNOLOGIES OF QINGCAOSHA RESERVOIR IN YANGTZE ESTUARY

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ABSTRACT

Shanghai is a typical city with water shortage induced by water pollution. The original water sources from Huangpu River cannot meet the water demand. The fresh water resources of Yangtze Estuary are abundant and water quality is good and stable. The freshwater resources of Yangtze Estuary have great potential for development and utilization. But its direct development is threatened by saltwater intrusion at the intakes. So, a reservoir must be constructed to store fresh water during low salinity and high quality. The construction of Qingcaosha reservoir started began in 2007 after nearly twenty years of research and trial water supply began by the end of 2010. Qingcaosha reservoir is located on the northwest of Changxi Island, namely the diversion area of South Channel and North Channel of Yangtze Estuary. It is the largest single city water supply project in China. Total reservoir area is 66.15km^2. Total reservoir capacity is 0.527 Gm^3. Design daily water supply is 7.19 Mm^3/d. The hydrodynamic processes like the fluvial evolution and freshwater/saltwater interactions, tides and storm surges in Yangtze Estuary are extremely complex. Engineering construction of the coastal reservoir faces a series of technical challenges. The main problems in its design and construction include: water quality management, site selection, intake method, the closure of huge tidal closure gap, long distance dyke structure and implementation on fluvial bed, sluice and pump building on the incomplete consolidation foundation etc. This paper mainly present a comprehensive overview of some key points related to Qingcaosha reservoir design, such as the general arrangement, fluvial process, law of saltwater intrusion, reservoir operation, reservoir water quality management and improvement, hydraulic fill dam in soft soil foundation, exceptional closure gap setting, protection and closure, permeable foundation pit maintenance and foundation treatment etc., providing a practical solution to some water shortage areas affected by saltwater intrusion near estuaries.

Keywords: Qingcaosha Reservoir; Yangtze Estuary; fresh water supply; storing fresh water and avoiding salty tide; saltwater intrusion.

1 INTRODUCTION

Shanghai is a typical city with water shortage induced by water pollution. Shanghai city water supply is mainly from Huangpu River and the rest of the water is taken from adjacent rivers and groundwater before the 1990s. The demand for raw water in Shanghai increased with the continuous development of Shanghai city. But, the water quality of Huangpu River is deteriorated and unstable. The amount of water has reached the limit of desirable water. The original water sources from Huangpu River cannot meet the water demand of Shanghai city. New water sources of good quality are urgently needed to develop. The fresh water resources of Yangtze Estuary are abundant and water quality is good and stable. The gross amount of water resources of Yangtze Estuary accounts for 98.8% of the total water resources in Shanghai. The water quality belongs to class Ⅱ～Ⅲ and has relative high self-purification ability. It is better than surface water in other areas of Shanghai. The freshwater resources of Yangtze Estuary have great potential for development and utilization. Therefore, not only does the incremental raw water need to rely on the development of the Yangtze Estuary, but also properly increasing the proportion of the use of raw water of the Yangtze Estuary in order to improve the quality of raw water in Shanghai.

Shanghai authorities began to organize the relevant parties to carry out long term hydrological and water quality monitoring, research and analytic demonstration on perspective planning water sources in Yangtze Estuary in order to solve the perspective water supply problem since 1980s. But, the direct development in Yangtze Estuary is threatened by saltwater intrusion at the intakes. So, a reservoir with storage capacity must be constructed to store fresh water during low salinity and high quality.

The construction of Qingcaosha reservoir started in 2007 after nearly twenty years of research and trial water supply began by the end of 2010. Qingcaosha reservoir is located on the northwest of Changxi Island, namely diversion area of South Channel and North Channel of Yangtze Estuary. Total reservoir area is 66.15km^2. Total reservoir capacity is 0.527 Gm^3. Design daily water supply is 7.19 Mm^3/d and is accounting for more than 50% of the total raw water supply in Shanghai. The estimated number of beneficiaries is 13.0

million. It is the largest single city water supply project in China. The investment of Qingcaosha reservoir is over 6.0 billion RMB yuan.

2 WATER SOURCE PLANNING PATTERN OF SHANGHAI IN YANGTZE ESTUARY

The research on the planning of Shanghai Yangtze Estuary water source location began in 1980s. It is determined that the ideal waters for water supply reservoirs in Yangtze Estuary are located in Chenhang, Qingcaosha, Dongfengxisha based on long-term investigation and study of water quality, saltwater intrusion, fluvial evolution, intake method and scale, influence etc. The water calorinity in a certain period of time exceeds the requirements of drinking water sources during dry season because of saltwater intrusion. So, a reservoir must be constructed to store fresh water during low salinity and high quality to meet the needs of urban continuous water supply. Figure 1 is a schematic diagram of the location of the Shanghai water sources in Yangtze Estuary.

Chenhang reservoir is the earliest development water source of Shanghai in Yangtze Estuary. It was completed and put into operation in 1992. The design effective capacity is 8.3 M m^3 and the scale of water supply is 1.3 M m^3/d.

Qingcaosha reservoir was completed and put into trial operation by the end of 2010. The design effective capacity is 0.438 G m^3 and design daily water supply is 7.19 Mm^3/d.

Dongfengxisha reservoir is located in the upper reach of the South Branch of Yangtze Estuary, southwest of Chongming Island. It was completed and put into operation in the early of 2014. The design effective capacity is 9.76 M m^3 and the scale of water supply is 0.4 M m^3/d.

The establishment of the Yangtze Estuary water sources of Shanghai represented by Qingcaosha reservoir show the achievement of the strategic transfer of raw water supply from Huangpu River to Yangtze Estuary in Shanghai, formed a new pattern of raw water supply in Shanghai, namely tripartite in Yangtze Estuary and one in Huangpu River.

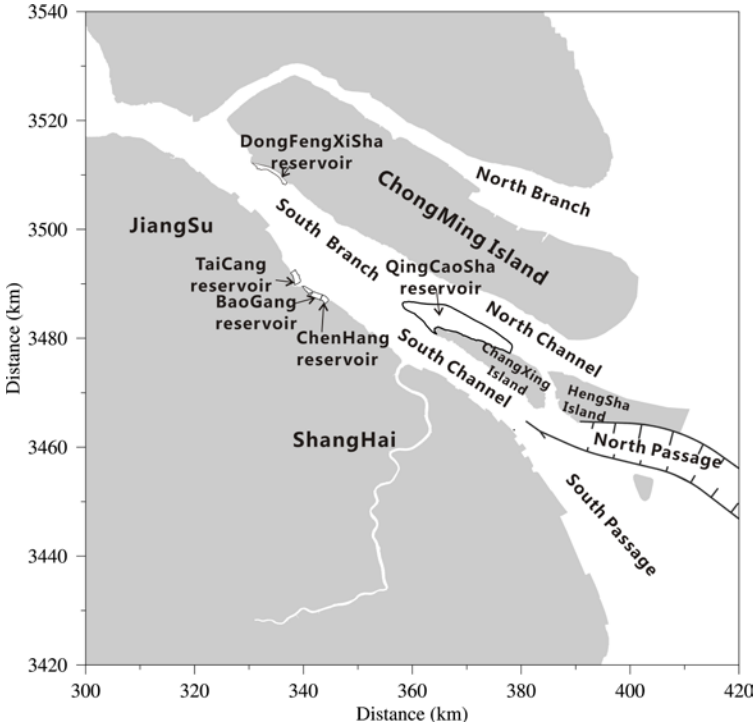

Figure 1. The location of the Shanghai water sources in Yangtze Estuary.

3 PROFILE OF QINGCAOSHA RESERVOIR

Qingcaosha reservoir is located on the northwest of Changxi Island, namely diversion area of South Channel and North Channel of Yangtze Estuary. Figure 2 is the general layout of Qingcaosha reservoir. Figure 3 is the upper water intake system, including upper sluice and pump. The total length of the dyke is 48.4km and newly constructed dyke (IJKLMNOPQRS) is 22km. Total reservoir area is 66.15km^2. The upper gate net width is 70.0m (5X14.0m) and bottom elevation is -1.50m. Maximum high water level of the reservoir is 7.0m (Wusong Datum). The dead water level is -1.5m. Total reservoir capacity is 0.527 Gm^3 and the design effective capacity is 0.438 G m^3. Design daily water supply is 7.19 Mm^3/d. The reservoir still can provide enough raw water for the water receiving area under the circumstances of occurring the longest continuous unfavorable water intake time of 68 days during saltwater intrusion.

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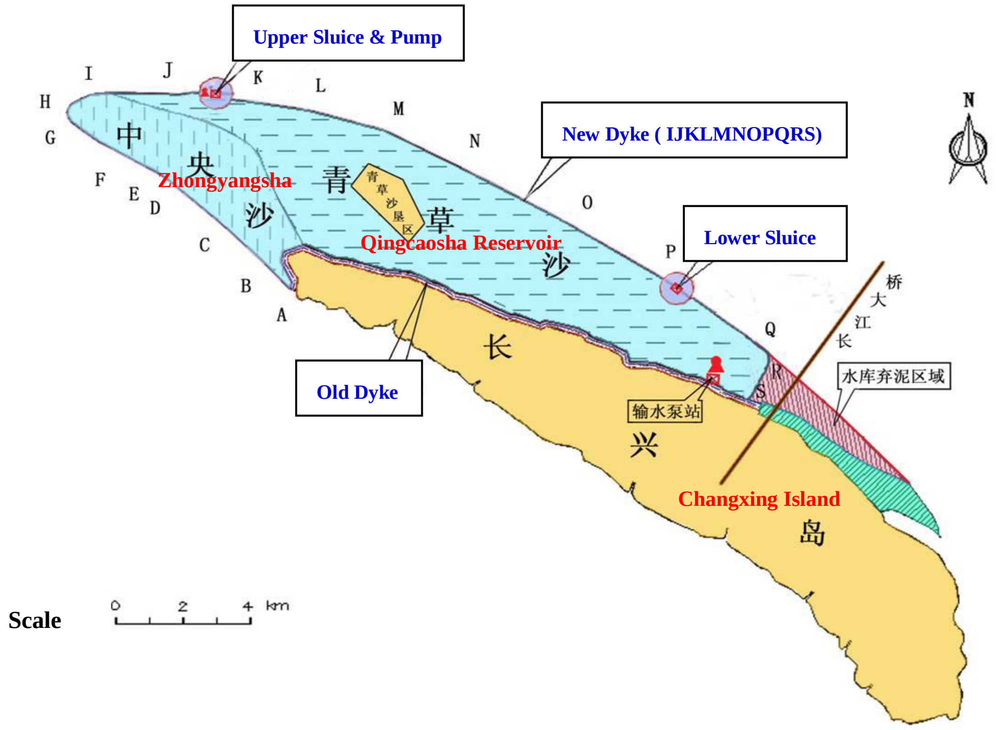

Figure 2. The general layout of Qingcaosha reservoir.

Figure 3. The upper water intake system.

The main function of the reservoir is to store fresh water during low salinity and high quality. The morphological characteristic of the reservoir is long and narrow. It is about 22km long and 3km wide. Combined pump and sluice water intake, upstream and downstream sluice combined operation scheme and general layout were proposed on the basis of comprehensive study of the tide characteristics, saltwater intrusion, fluvial process, flow pattern and water quality evolution in the reservoir, etc. The water intake (including upper sluice and pump) is arranged at the upper end of the reservoir. The water supply system and lower sluice are respectively arranged in the downstream section of the south and north sides of the reservoir. This arrangement can make full use of tide and take water at higher tidal level, reducing operating energy consumption. At the same time, the operation scheme which the water takes from upstream and drain from downstream can control water retention time of the reservoir. Dredging to make flow more smoothly can also reduce the risk of local algal outbreaks.

The water intake is mainly artesian diversion during the flood season. The pre-storage water and grabbed water through sluice and pump is designed to meet the demand of raw water supply in the receiving area. The upper pumping station scale is 200m^3/s and 6 mixed flow pump are chosen. The upper gate net width is 70.0m (5X14.0m) and bottom elevation is -1.50m. The lower gate net width is 20.0m (5.0m+10.0m+5.0m) and bottom elevation is -1.50m too. Raw water out of the reservoir adopts gravity water conveyance method. The net width of water conveyance gate well is 24.0m and bottom elevation is -4.0m. Design water conveyance scale is 0.11 M m^3/d.

Slope type earth rock mixture embankment structure is adopted in new north and east dyke. Measures for strengthening soft foundation with plastic drainage plate are taken in east dyke deep water area. The dyke adopts closed seepage control structure, namely three axis deep mixing pile cutoff wall.

4 THE KEY RESEARCH POINTS

The key technical problems in the planning and construction of Yangtze Estuary reservoir are as follows:

(a) Law of saltwater intrusion and reservoir scale
Law of saltwater intrusion has a direct impact on the estuarine reservoir. It plays a key role in the site selection, the layout of hydraulic structures and the operation of the reservoir. The saltwater intrusion of each estuary has its particularity. Saltwater intrusion from the North Branch of Yangtze Estuary increases the complexity of saltwater intrusion law in the Yangtze Estuary. It is a prerequisite for the construction of the estuary water supply reservoir to study the laws and characteristics of water and salt movement. The longest continuous unfavorable water intake time has decisive influence on the reservoir scale.

(b) Site selection and arrangement of dyke line
The shape of Yangtze Estuary is in the shape of a trumpet. There are three-order bifurcations and four outlets into the sea in the Yangtze Estuary, namely the North Branch, the North Channel, the North Passage and the South Passage. Due to the requirements of water quality and scale, the site of Qingcaosha reservoir is selected in the reach of the bifurcation of the North Channel and the South Channel. The frequent changes of shoal and trough have happened in this reach in the last hundred years. Erosion and deposition is severe. The regime evolution law is very complex. Constructing the reservoir in the South and North diversion area, on the one hand, it needs to consider the impacts of the project implementation on the estuarine fluvial evolution, on the other hand it needs to consider that the regime changes will bring security impacts on the project itself and the corresponding engineering measures should be proposed.

(c) Intake method and operation scheduling
There are three methods of reservoir intake, namely pumping, sluice, and combined pumping and sluice. The changes of water quality, saltwater intrusion and river regime evolution directly influence the reservoir water intake reliability. The rational choice of the position of the water intake and the way of water intake has direct impact on water supply safety, scale of water intake project, reservoir operation cost, getting high-quality raw water, etc.
Because of the large scale of the reservoir water supply, it should study intake tidal characteristics and the law of saltwater intrusion. It needs the reasonable arrangement of the pump and gate structure. It should study the appropriate scheduling operation, reducing operating costs and saving energy.

(d) Water quality protection and reservoir eutrophication prevention and control
The reservoir has the characteristics of shallow lakes. The flow pattern in reservoir also has influence on water quality. After the completion of the reservoir, it has a great risk of eutrophication. It needs to fully consider the reservoir shape, layout of pump and gate, scheduling operation, etc., to make flow more smoothly and to maintain reasonable water residence time and to take algae control measures.

(e) Hydraulic fill dam in soft soil foundation
The beach surface upon which the dike of reservoir is planned to be built generally lies in the elevation range of 0.0m to -10.5m. The dike at the eastern part of Qingcaosha Reservoir is built crossing the deep passage of flood tide channel, where the conditions, such as deep water, fast flow and high waves, are unfavorable for construction. Furthermore, the foundation soil is unfavorable for the stability of dike due to its soft and weak nature and severe settlement. And because of the long dike built on water there is no land supportive condition available for dike works.

(f) Exceptional closure gap setting, protection and closure
The reservoir is formed by building an encircled dike. Therefore, the greatest concern and risky point during construction period is focused on the arrangement and protection of closure gap, as well as the closure design. The design tidal amount in one tide period is about 150 million m^3 and the design flow speed at the closure gap is higher than 6.5m/s. Under the effect of reversing tide at the closure gap, the periodic tidal variation limits the continuous and available working time only to 6 to 8 days in general. Due to shortage of stone material and land riprap condition, the soft and weak soil foundation is easily washed away and difficult to protect. Any scouring occurred will turn out to be an event extremely difficult to control.

(g) Permeable foundation pit maintenance and foundation treatment
The average tidal level at Qingcaosha reach is 2.12m. The foundation base elevation of main pump house of the pumping station is -12.0m. So, it is required to build a cofferdam in the middle of the

river, within the part surrounded by the cofferdam a deep foundation pit needs to be excavated. The soft soil layer underlies the structure is deep and thick, the load of upper structure of the pumping station and sluice is relatively high. However, the connecting embankment is of highly filled soil on two sides. Because of difference in loads, the foundation is required to be treated in consideration of coordination for deformation that may occur between the pumping station and sluice and the connecting embankment on two sides.

5 SOLUTIONS

(a) Law of saltwater intrusion and reservoir scale

The scale of raw water supply of Qingcaosha reservoir depends on the scope of water supply, determined by the demand for water in the reception area. The scale of the reservoir is determined by the scale of raw water supply and maximum number of consecutive not suitable for water intake days during saltwater intrusion. Therefore, the study on the law of saltwater intrusion in the demonstration on the scale of Qingcaosha reservoir is one of the key factors.

To study the law of saltwater intrusion, the Yangtze Estuary salinity auto-monitoring system was established. Full tidal synchronous hydrological and salinity investigations were also carried out during dry season, for example in 1999, 2002, 2006, etc. Systematic analyses were made based on the measured data. Research were mainly focused on the influencing factors of saltwater intrusion in Yangtze estuary, the temporal and spatial variation of saltwater intrusion, the law and influence of the saltwater intrusion from the North branch, the characteristics of saltwater intrusion in Qingcaosha reach.

The saltwater intrusion is affected by the comprehensive effect of runoff, tide, plane form, wind, coriolis force, circulation off the shelf, etc. It has the characteristic of remarkable temporal and spatial variation. Upstream runoff and tide are the main influencing factors of saltwater intrusion in Yangtze Estuary. The saltwater intrusion from North Branch to South Branch increases the complexity of the law of saltwater intrusion in Yangtze Estuary.

The salinity in the South Branch upper waters is mainly affected by the impact from the North Branch. The higher the upstream goes, the higher the salinity is. The salinity in the South and North Channel lower waters is mainly affected by the direct effect of saltwater intrusion from the sea. The nearer the sea goes, the higher the salinity is. The salinity of Qingcaosha waters is affected by both the saltwater intrusion from the North Branch and the saltwater intrusion from the sea. Correlation analysis and mathematical model analysis show that the longest continuous unfavorable water intake time is 68 days during saltwater intrusion period in Qingcaosha waters at the 1978 ~ 1979 design representative typical year.

(b) Site selection and arrangement of dyke line

The impact assessment had been conducted on the basis of some technical means, such as fluvial evolution analysis, mathematical model, fixed bed physical model test, movable bed physical model test. The characteristics and trend of the fluvial evolution at the reach of Qingcaosha waters had been systematically studied on the basis of research and comprehensive summarization of the existing results, combining the analysis of the flow, sediment and underwater topographic data.

The flow fields, influences and river bed changes after the implementation of Qingcaosha reservoir in the typical hydrological conditions are predicted on the basis of the comprehensive research results of the flow and sediment analysis, erosion and deposition analysis, mathematical model and physical model. It was revealed the regime of Qingcaosha waters was relatively stable before 2007. It was in the critical point of erosion and moving down of diversion area of South Channel and North Channel of Yangtze Estuary. It was a good opportunity to build Qingcaosha reservoir. It was no obvious adverse effects on flood control and drainage, navigation channel, fluvial processes, existing engineering and facilities in Yangtze Estuary.

(c) Intake method and operation scheduling

Qingcaosha waters have plenty of fresh water from May to October and the probability of occurrence of fresh water is generally between 44.4%~100% in other months according to the long-term observation and statistics and analysis of saltwater intrusion process during 1978～1979, which is the design typical year (water supply guarantee rate is 97%). The pre-storage water in the reservoir is needed to use when the intake water salinity is not suitable for water intake during the saltwater intrusion period from November to April.

The highest reservoir water level is 7.00m. The mean annual high tide level in Qingcaosha waters is 3.35m and the mean annual lower tide level 0.92m. There is plenty of fresh water in the flood season and the reservoir is in constant water level. We can make full use of tidal power to bring fresh water into the reservoir through the sluice. The water level of the reservoir is filled as high as possible by the sluice, and then the pumping station is used to pump the fresh water into the reservoir during dry season. So, combined sluice and pump method is used in water intake. This method takes into account the hydrological characteristics and the saltwater intrusion characteristics in Qingcaosha waters. Because most of the time in a year is sluice intake, so this intake method reduces energy consumption. Annual savings of electricity is 5.62 million kW•h, compared with the other storage reservoirs in the Yangtze Estuary, only using the method of water intake of the pump.

The operation mode of the reservoir is as follows:

Artesian diversion of sluice is used in high tidal level during flood season. The local area in the reservoir is prone to eutrophication because of higher temperature if you do not change the water in time. Therefore, the sluice in the lower part of the reservoir is arranged and it is used to drain.

Through the upstream and downstream linkage operation mode, the mobility of water in the reservoir is increased and the residence time of water in the reservoir is reduced. The ability of reservoir to resist eutrophication is also enhanced. The residence time of water in Qingcaosha reservoir is controlled in 15 ~ 20 days at present.

The water level in the reservoir maintains as high as possible for energy saving and is generally 3.3m. Reducing the water level operation is needed if increasing the mobility of water to control the water quality is considered.

In order to meet the demand of raw water supply during the saltwater intrusion period, the water level in the reservoir has to be raised through sluice and pump. Reservoir water level is generally 6.2m during saltwater intrusion period. Pumping more fresh water into the reservoir before the advent of serious saltwater intrusion based on prediction. The opportunities for the emergence of interstitial freshwater is also taken, sluice and pump are used to take in water in the time gap available for fresh water in order to meet the safe water supply in next saltwater intrusion circle.

(d) Water quality protection and reservoir eutrophication prevention and control

Qingcaosha waters are located in the middle of Yangtze Estuary which is at the end of the Yangtze River Basin. The quality of water sources is subject to not only the quantity and quality of water from the upper reaches of the basin, but also the water environment and the runoff and tide interaction in the estuary. The water quality in Qingcaosha waters has a large number of influencing factors and the potential environmental risk is greater. The characteristics of the water quality in Qingcaosha waters is long-term, sudden and uncertainty.

At the same time, the reservoir has the characteristics of shallow lakes. The water flow in the reservoir slowed down after the completion of the reservoir and the residence time of water in reservoir are longer. There is stagnant area in some local waters. There is a greater risk of eutrophication, even the risk of algal blooms because of the higher content of nitrogen and phosphorus in the reservoir water. This easily leads to deterioration of water quality in the reservoir and may have a certain impacts on the quality of raw water.

Qingcaosha reservoir is a large water supply reservoir. The only way to prevent eutrophication is to optimize the shape and morphology of the reservoir and select the appropriate layout and optimize the reservoir operation scheme to increase the flow of water with the establishment of a sound ecological system and other measures to maintain and improve the water quality of the reservoir.

A long and narrow reservoir in morphology is formed which is more than 20 km long and the average width is 3km. This feature on the one hand can ensure that the effect on coastal regime is reduced to the minimum, on the other hand, it can ensure that the water body has a certain amount of mobility. The general layout of water intake from upper section and drainage from lower section is adopted by the reasonable layout of the water intake, drainage and water distribution. Dredging is further to optimize the morphology of reservoir and to improve the local flow pattern. The implementation of water ecological construction in stagnation waters near north dyke can reduce the risk of algal blooms. Raising or lowering the water level operation and increasing water flow according to the characteristics of algae growth is also used to prevent algal blooms.

A set of reservoir eutrophication control technology system has been established which combined early warning monitoring, risk assessment, prediction, water and sediment scheduling based on demonstration base construction, measured data analysis, numerical simulation, physical model test.

(e) Hydraulic fill dam in soft soil foundation

(e-1) Sequence of dike construction

Regarding the situation along the long-distance dike in the middle of river, i.e. undulate riverbed channels that are prone to scouring and variation, the overall sequence of dike construction and technical control principles are proposed as follows:

Commencing at full capacity;

Conducting in multi spots;

Promoting construction in a wide coverage;

Starting off with low-beach river-bottom protection followed by thalweg submerged section;

Forming the high-beach outline first;

Plugging the branching channels in sequence for final grand gap closure.

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(e-2)Structural type of deep-water dike

The part crossing the thalweg accounts for one fifth of the newly built dike of the reservoir, including the 2.2km-long eastern section where the maximum water depth is up to 15m, the beach surface lies at the elevation range of -5.0m to -10.5m and dike height ranges from 13m to 19m. The foundation surface layer is of 3m to 5m-thick silt and over 10m-thick highly compressive sludge. And the hydrological features are deep water, fast flow, reversed and variable tide. From the perspectives of soft soil foundation treatment, hydraulic filling in deep water for dike construction, etc., a new dike structure and associated construction technology are formulated. Specific, plastic drainage plates will be used for foundation treatment, and large and high strength geotextile bag with hydraulic filling to form a sloping dike. The cross-section of a dual-prism slopy dike structure is given in Figure 4.

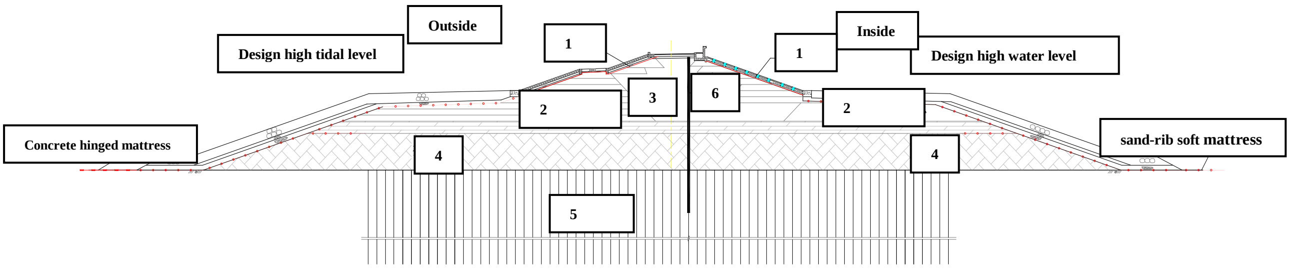

Figure 4. The cross-section of hydraulic filling sloping dike
1) Anti filter geotextiles; 2) Geotextile tube bag filling sand; 3) Hydraulic filling sand;
4) Dumped sand bags; 5) Plastic drainage plates;
6) Anti-seepage walls.

(e-3)Seepage proofing of a hydraulic filling dike

Taking the hydraulic filling dike body, dike foundation of complicated silt and sludge interbeds and bi-direction water retaining requirement of the hydraulic filling dike into consideration, the means as field test, generalized physical modeling of dike section in flume, in-situ testing of adjacent or similar dike's permeability, etc., are used to unveil the permeability and permeable damage mechanism of the new sedimentary soil and hydraulic filling dike in Yangtze Estuary.

The typical dike body structure is selected to perform generalized physical modeling and permeable test in flume, as well as in-situ testing of adjacent or similar dike's permeability. The following laws of permeability are gained. 1) single-layer geotechnical bag structure is close to original sand sample in permeability; 2) multi-layer geotechnical tubular bag structure is generally twice to four times the filling body in permeability, which is mainly caused by connecting seepage of those geotechnical tubular bags; 3) permeable damages are all occurring in connecting seepage of geotechnical tubular bags, and the critical gradient value of connecting seepage is 0.1.

Through the field test of impermeable wall and the improvement and optimization of construction control requirement, the problems such as triaxial mixing pile penetrating geotechnical bags and pile shaping are resoundingly solved. That impermeable wall of triaxial cement mixing piles is successfully applied to the hydraulic filling dike which is totally 30km in length. As for the closure section of the dike, a new type of impermeable wall is built by assembling one row of high pressure jet grouting piles between two rows of triaxial mixing piles. The difficulty of seepage closure by a 2m-thick riprap layer in dike body is also solved. Figure 5 gives a sketch of structural plan of combined impermeable wall.

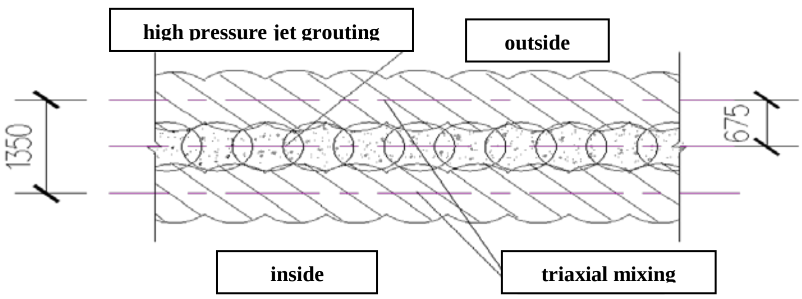

Figure 5. Sketch of combined anti-seepage wall.

(f) Exceptional closure gap setting, protection and closure

(f-1) Hydraulic parameters of closure gap

The study is mainly performed through 2D and 3D hydrodynamic mathematical models, hydrodynamic physical model test for closure gap, box cage wave tank test, cross section test in flume, etc. All these means are mutually combined and complementary. Upon the study results, the evaluation and comparison is conducted in several construction factors and finally hydraulic parameters of closure gap have been gained. To suit the actual conditions in the construction course and based on the tidal and meteorological changes, a short-duration hydraulic forecasting technology of gap closure is developed and used in practice. The design flow speed at closure gap by vertical and plain plugs is 9.5m/s and 7.6m/s respectively. According to technical and economic comparisons, the closure method is finally determined to be plain plug.

(f-2) Protection of closure gap

Through comparison of several schemes, such as setting closure gaps separately in small areas gained by dividing the entire reservoir area, setting multiple closure gaps along the high beach of the entire reservoir area, and setting exceptional closure gap at the deep channels, the scheme of setting the main closure gap, in a width of 800m, at the deep channel section of eastern dike for the entire reservoir is finalized. Within the closure gap range the maximum design flow speed during construction is 7.6m/s, the silty soil and sludge on riverbed and the embankment formed by sand-filling tubular bags are prone to scouring caused by rising and ebb tides. To suit the construction of underwater structures with ship machine, the armor face of closure gap adopts multi-layer composite protection structure (Figure 6), the layers are, from the bottom up, large-sized high-strength geotechnical cloth bags filled with sand (sand quilt), 1300g/m^2 super strong geotechnical cloth soft drainage body of sand ribs, soft drainage body of chained concrete blocks, and 60 tons of string bagged stones or 30 tons of concrete blocks (Zhongmin et al., 2013).

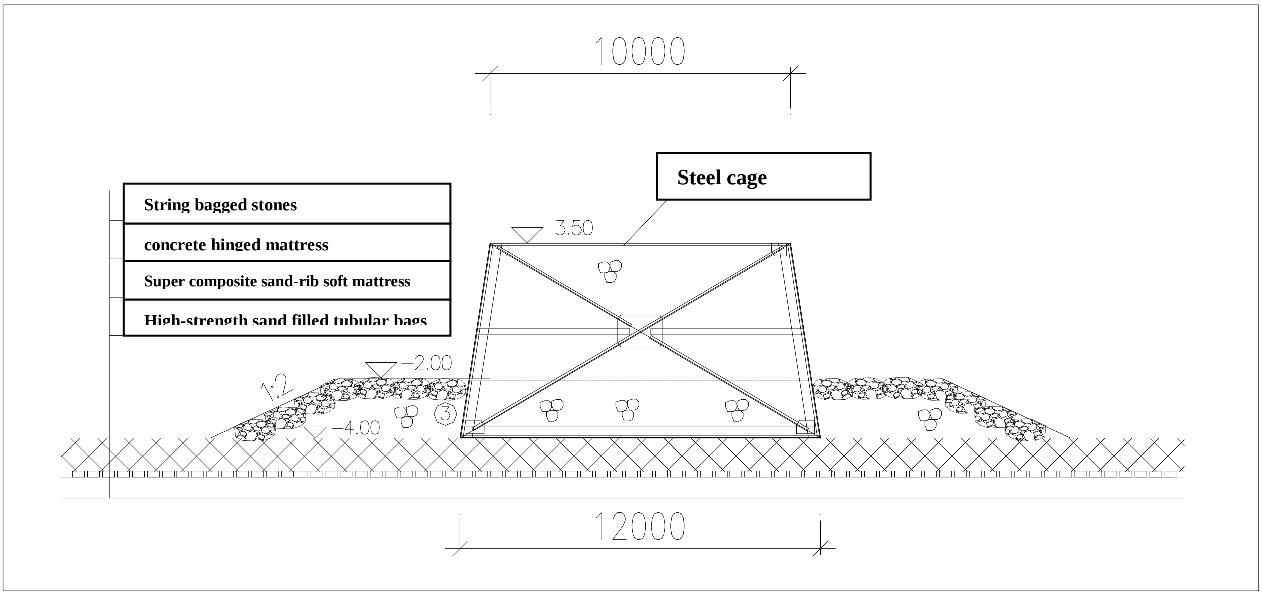

Figure 6. Protection of main closure gap at eastern dike and damming structure of cage.

(f-3) Method of damming

For the damming of exceptional closure gap, the plain plug with steel-caged riprap is used (Figure 6) and the design maximum flow speed for damming the closure gap is 7.6m/s (real-time measured speed is 5.15m/s).

Three problems need to be solved in the design of steel cage, i.e. (1) the stability of cage during initial placement; (2) contacting status of riprap in the cage with the string bagged stones on subgrade; (3) evenness of the cage placed on the subgrade of string bagged stones. Through the testing and analysis of the stability of cages under the effects of various flow conditions, the volume of each steel cage is finalized as about 1000m^3 and the permeable supporting skeleton made by shaped steel is used.

Prior to damming, taking the advantage of small neap tides, the steel cages are placed from the two sides of the 800m-wide closure gap towards the middle, and simultaneously, ripraps are dumped at the bottom and both sides of the cages to add weight against scouring; thus, a permeable skeleton of damming structure is formed. During the damming, pick the duration of next small neap tide and set up a fleet of ships to dump riprap into the cages to complete the damming.

The plain plug method with large-sized steel cages filled with riprap was successfully used in the damming of Qingcaosha Reservoir. The application of the method created the record of damming a 49.8km^2 of water area without separating working places and the discharge of 150 million m^3 through the closure gap in one tide duration.

The closure gap after placement of steel cage is shown in Figure 7.

(g) Permeable foundation pit maintenance and foundation treatment

(g-1)Deep foundation pit maintenance with the combination of permanent and temporary facilities

The water intake pumping station is located on the newly deposit deep beach in the middle of the river, the upper foundation stratum is of permeable sandy soil and the foundation pit is 13m deep; besides, surrounded by water with large internal and external water head difference the foundation pit is faced with difficulty of dewatering. Taking the protection requirements of cofferdam and foundation pit into consideration, the composite protection system formed by combining the cofferdam, slope excavation and underground continuous cutoff wall is used. Consequently, the function and requirements of water retaining, seepage and the construction conditions on dry land are satisfied. In the meantime, the underground protection wall of deep foundation pit is connected to the underwater wall of pumping station. As a result, the construction period is shortened and economic benefits are gained.

(g-2)Foundation reinforcement

The foundation reinforcement is conducted by using the high-pressure jet grouting piles to coordinate the deformation at the connection of dike and gate; thus the hidden danger of leakage caused by the potential uneven settlement at the connection of structures and dike is eliminated. Through the multi-condition analogy of space FEM of fluid-solid coupling of pumping sluice structures and foundation pit and by adopting the deformation coordination foundation treatment measures, the control requirements, i.e. water conveyance gate well sharing the place with the receiving well of shield tunneling machine in water conveyance main and the deformation of structure no more than 15mm under the effect of 15m water head difference inside and outside the gate well are met.

Figure 7. Closure gap after placement of steel cage.

6 CONCLUSIONS AND PROSPECT

Qingcaosha reservoir is a successful example of coastal reservoir in Yangtze estuary. Qingcaosha reservoir began to supply water to Shanghai city in the end of 2010. It has suffered typhoon, saltwater intrusion, oil pollution events. The hydraulic structure, intake and water supply facilities of the reservoir are safe and stable and the water quality of the reservoir meets the requirements of the design standards. It has good performance. The site selecting, intake method, arrangement of sluice and pump, scheduling scheme, deepwater dyke, super gap closure, water quality protection and reservoir eutrophication prevention and control technology, hydraulic fill dam in soft soil foundation, exceptional closure gap setting, protection and closure, permeable foundation pit maintenance and foundation treatment have been proved to be correct and reasonable. It can provide technical reference for similar coastal reservoir study, design and construction.

Qingcaosha reservoir is still worthy of study in the following areas:

(a) The hydrodynamic processes at the reach of Qingcaosha reservoir and its development trend, especially in the waters near west, the upper and north of Qingcaosha reservoir. Beach protection measures must be carried out if necessary;

(b) Study on the increasing the reservoir water mobility to shorten the water body residence time of 7 ~ 10 days and further reducing the risk of a " algal bloom";
(c) Further dredging and optimizing reservoir topography and to carry out the ecological restoration inside and outside the reservoir embankment.

ACKNOWLEDGEMENTS

Shanghai Investigation Design & Research Institute Co. Ltd (SIDRI) is the main designer of Qingcaosha Reservoir. The authors would like to thank all participants for their involvement in this project design and the subject “study and application of key technologies in building large saltwater-avoiding and freshwater-storing reservoir in Yangtze Estuary”.

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RESEARCH OF THE INFLUENCE OF SALINITY INTRUSION ON QINGCAOSHA WATER SOURCE

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ABSTRACT

The Yangtze Estuary has abundant water with strong self-purification ability. It is an ideal water source for Shanghai, a megalopolis along the coast of the Yangtze Estuary. Qingcaosha Reservoir is the world's largest reservoir of avoiding saltwater and storing freshwater and its water supply scale is about 50% of the total water supply in Shanghai. The salinity intrusion in the dry season is a potential threat to the safety of Qingcaosha water source. In this paper, a two-dimensional mathematical model of the tidal current and salinity transport in the Yangtze Estuary is established to study the distribution characteristics of freshwater in the Yangtze Estuary in the dry season and the safety of Qingcaosha water source under the impact of salinity intrusion. In January when salinity intrusion is the most severe in the Yangtze Estuary, the area of freshwater resources is the smallest and the salinity at the water intake of Qingcaosha Reservoir is the highest of the year. However, as the reservoir has a large capacity and under normal circumstances, the intake salinity is only about 2 times higher than the standard value, brackish water drawing can also alleviate the water supply crisis to a certain extent in an emergency. The construction and operation of Qingcaosha water source can provide reference for the construction of other island water sources.

Keywords: Qingcaosha Reservoir; the Yangtze Estuary; salinity intrusion; water source safety.

1 INTRODUCTION

With its upper reaches starting from Xuliujing, the Yangtze Estuary is China's largest estuary of about 182 km long. Its reaches are fan-shaped in plane and in the pattern of three-order bifurcations and four outlets into the sea (Figure 1). Shanghai is a megalopolis in the Yangtze River Delta. Before 2010, its water supply was mainly taken from the Huangpu River, but due to water shortage and poor quality, it became a typical city of pollution induced water shortage. However, the Yangtze River has abundant water and strong self-purification ability, thus the water quality is fine and stable. As the water demand of Shanghai increases with its urban development, to solve the water problem, the water drawing center is transferred to the Yangtze River. At present, Shanghai has formed the water source structure of “two rivers simultaneously and the Yangtze River-based”. The water supply scale of the three major concentrated water sources in the Yangtze Estuary: Dongfengxisha water source, Chenhang water source and Qingcaosha water source (Figure 1) has reached about 80% of the water supply in Shanghai. Among them, the water supply scale of only Qingcaosha water source has reached more than 50%.

Figure 1. The map of the Yangtze Estuary and route of salinity intrusion.

Qingcaosha water source, built beside Changxing Island in the middle of the river, is the world's largest reservoir of avoiding saltwater and storing freshwater in the tidal estuary by far. Its water quality is desirable.

However, as a result of the impact of salinity intrusion (the other name: salt tide) in the dry season, there will be periods when water drawing is unsuitable due to a high content of chlorides, usually over 250mg/L (the same as salinity 0.45‰) at the water intake (DING et al., 2016). Once such periods last long, the city's water supply will be affected (Ruan and Han, 2003). It is generally believed that the saltwater of Qingcaosha water source will be affected by the frontal intrusion of saltwater of South Channel and North Channel and the backward flow of saltwater of North Branch. The two-dimensional mathematical model of tidal current and salinity transport is used in this paper to study the distribution of freshwater resources in the Yangtze Estuary and the influence of salinity intrusion on the water intake of Qingcaosha water source, so as to provide reference for the construction of water sources in other estuaries and islands in the sea.

2 CONSTRUCTION OF QINGCAOSHA WATER SOURCE

2.1 Construction background

Qingcaosha Reservoir is located near the bifurcation of North Channel and South Channel of the Yangtze Estuary and in the northwest of Changxing Island. Its water area reaches up to 66.155km^2. Qingcaosha is an alluvial sandbar of the Yangtze Estuary in China. The construction of Qingcaosha Reservoir was commenced on June 5, 2007, and the raw water system of Qingcaosha water source was comprehensively built and opened in 2012. The planned water supply scale which was 7.19 million m^3/d, accounted for more than 50% of the city and benefited over ten million people. The status quo effective storage capacity is 382 million m^3, while its designed effective storage capacity is 438 million m^3 (Li et al., 2009; Liu et al., 2009).

2.2 Safety constraints of water source

The main restraining factors of water supply in Qingcaosha water source are salinity intrusion, while runoff is the main factor affecting salinity distribution. Zhu et al. (2013) used to make a research: the runoff series is corrected by using the long runoff volume data at Datong Hydrological Station in the lower reaches of the Yangtze River combined with the influence of the Three Gorges Project, the South-to-North Water Diversion Project, the diversion and drainage along the river and other factors. Based on the numerical simulation, the maximum number of days unsuitable for water drawing in Qingcaosha Reservoir is 68 days and the reservoir is designed according to the safe water supply of 68 days. Under the current dispatching mode of Qingcaosha water source, the number of safe water supply days is 35.

3 ESTABLISHMENT OF MATHEMATICAL MODEL

The Flow module in Delft3D was used to establish a two-dimensional mathematical model of the tidal current and salinity transport in the Yangtze Estuary to carry out simulation research of the salinity transport process in the Yangtze Estuary.

The area range and grid of model are shown in Figure 2. The area included the Yangtze Estuary, Hangzhou Bay and adjacent sea. The north boundary was at north latitude 34.67°, the farthest of the south boundary was at north latitude 29.33°, the east boundary was the farthest at east longitude 124.24° and the open boundary in the west was obtained through the harmonic analysis of the main tidal constituents by applying water level boundary conditions. The upstream boundary was taken in Datong, which was the flow control condition, and the hourly measured flow rate at Datong Station was used for validation. The model grids were body-fitted orthogonal grids, with 1431 elements horizontally and 163 vertically. The grid size in the open sea was large, reaching up to 2km × 2km and the grids were locally densified in the Yangtze Estuary area, with the minimum size of 70m × 60m.

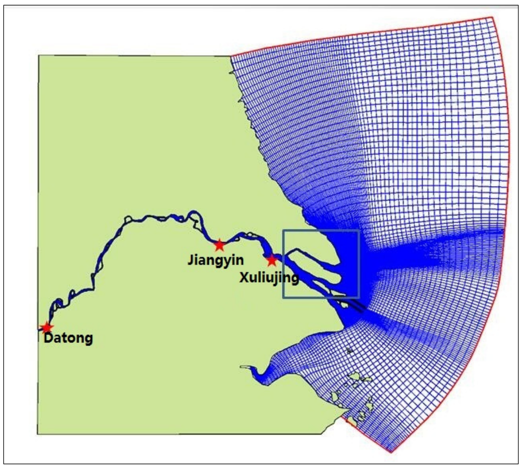

Figure 2. The area range and grid of model.

The terrain from Jiangyin down to the Yangtze Estuary was the measured terrain of 2011 and local terrain was updated according to the Xincunsha improvement project and the land formation project of Hengsha East Beach. The terrain from Jiangyin to Datong was the measured terrain of 2006. The time step was set at 15s. The roughness of the model was provided by Chezy coefficient, and the value varied from 80 to 200m$^{1/2}$/s according to the terrain. The average salinity diffusion coefficient was 250m^2/s. The wind field can be specified pursuant to the measured wind speed. During model calculation, the field after running for 2 months was taken as the initial field, and then the plans were simulated.

The model used the large-scale full-tide simultaneous hydrometry in the Yangtze Estuary in January 2016 to conduct the validation of hydrodynamic force and salinity and validated the water level, velocity, flow direction and salinity at each measuring point. Due to limited space, only the validation results of the spring tide at the measuring point near Chongtou, at the entrance of North Branch and near the Qingcaosha Reservoir were given. As indicated by Figure 3, the model can well simulate the hydrodynamic force and saltwater transport in the Yangtze Estuary.

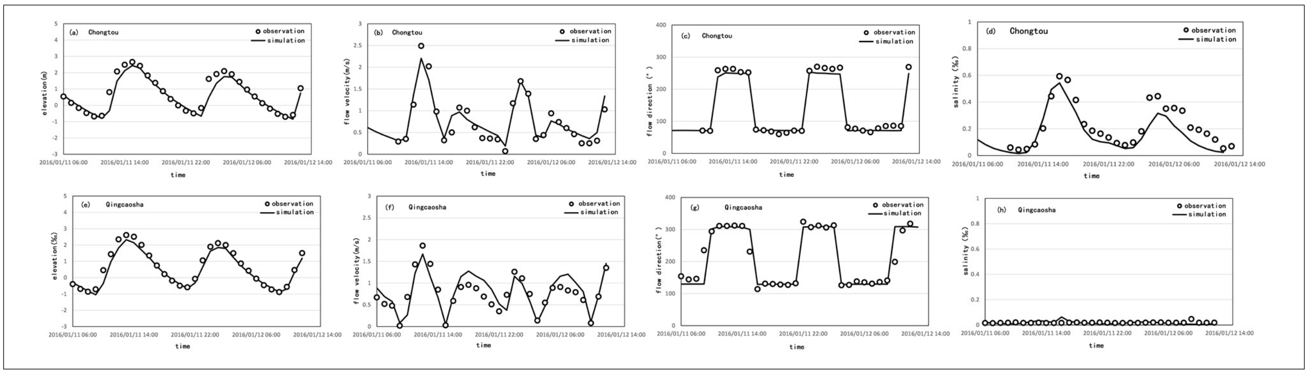

Figure 3. The validation results ((a)~(d) is elevation, flow velocity, flow direction and salinity of Chongtou; (e)~(f) is elevation, flow velocity, flow direction and salinity of Qingcaosha).

4 CALCULATION AND ANALYSIS

4.1 Model setting

Datong Hydrological Station is more than 600km from the upper reaches of the Yangtze Estuary. It is the nearest hydrological station in the lower reaches of the Yangtze River from the estuary, and not influenced by the tidal dynamics. After the completion of the Three Gorges Project, Pearson Type III curve analysis was made for the daily runoff of Datong in each month and the analysis results are shown in Table 1. The runoff volume of 50% frequency can represent the ordinary situation of the runoff in each month.

Table 1. Flow rate of Datong after the completion of the Three Gorges Project (unit: m³/s).

	25%	50 %	75%	90%	98%
OCTOBER	28627	23409	18698	14873	10552
NOVEMBER	21672	17135	13998	12178	10898
DECEMBER	16420	13797	11935	10814	9979
JANUARY	14245	12384	11070	10285	9708
FEBRUARY	14620	13422	12261	11248	10001
MARCH	21867	18225	15149	12817	10399
APRIL	25496	21137	18033	16157	14750

Based on the established mathematical model, the distribution of freshwater in each month of the dry season at runoff volume of 50% frequency and the salinity at the water intake of Qingcaosha Reservoir were studied. At the upper reaches of the model, steady flow was taken according to the month of study. With respect to the tide, the complete semimonthly tidal level period that can represent the ordinary situation in the dry season was taken. To eliminate the impact of wind, the wind speed in the model was zero, and the other settings were the same as during the model validation. After the model ran for 40 days, the salinity near the water intake of the water source was analyzed. The analysis time was a complete semimonthly period (16 days), starting on the 4th day before the occurrence of the maximum tidal range, and ending on the 4th day after the occurrence of the minimum tidal range. When the salinity was below 0.45‰, it was deemed as freshwater.

4.2 Distribution of freshwater resources

According to the model calculation results, the plane distribution of freshwater in the Yangtze Estuary was analyzed. Due to limited space, four typical moments in the semimonthly period only in January were analyzed. They were the flood and ebb slacks of spring tide and the flood and ebb slacks of neap tide. For the large range of the Yangtze Estuary, there were variations in the flood and ebb phases in different regions. The flood and ebb slacks mentioned in this paper referred to the state of Chongtou tidal level of North Branch.

In January, the runoff was relatively the smallest and the runoff at 50% frequency was 12384m³/s. At this time, the areas with freshwater were the smallest of the year (Figure 4) in the Yangtze Estuary. At the flood slack of spring tide (Figure 4(a)), 0.45‰ isohaline had crossed the bifurcation of North Branch and South Branch, and traced to the vicinity of Sutong Bridge. The Yangtze Estuary waters below Xuliujing were occupied by saltwater. At the ebb slack of spring tide (Figure 4(b)), the isohaline moved towards the lower reaches and appeared in the downstream of Baimaokou. The whole Yangtze Estuary was still basically occupied by saltwater. The freshwater distribution area during neap tide was larger than that during spring tide. At the flood slack of neap tide (Figure 4(c)), the isohaline of South Branch appeared at about 7km in the upper reaches of Liuhekou and North Branch was still full of saltwater. At the ebb slack of neap tide, the isohaline was near the Liuhekou and the isohaline of North Branch was near Chongtou. In the whole semimonthly period, freshwater appeared in the upper reaches of Liuhekou of South Branch only when the tidal range was small. In the case of large tidal range, nearly the whole Yangtze Estuary was saltwater. The water intake of Qingcaosha Reservoir was surrounded by salt water at these four moments

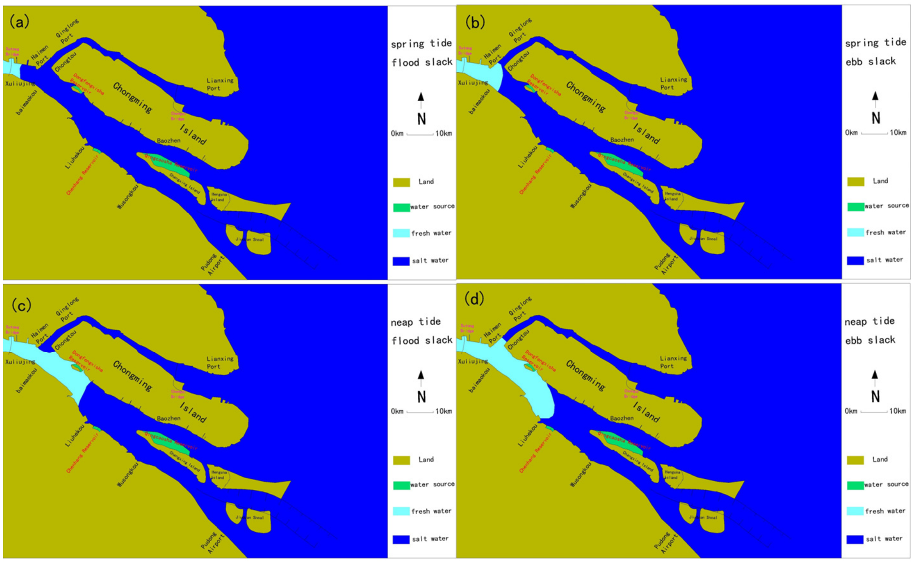

Figure 4. Freshwater distribution of the Yangtze Estuary in January at runoff volume of 50% frequency ((a)~(d) is the distribution at the moment of flood and ebb slacks of spring tide and the flood and ebb slacks of neap tide, respectively.)

The analysis of the distribution of freshwater showed that in January, salinity intrusion was the most serious in the Yangtze Estuary and the freshwater distribution area was the smallest. The bigger the runoff was, the larger the area of freshwater resources will be. The area of freshwater appearing during neap tide was larger than that during spring tide. According to the simulation of other months, under normal circumstances, the water intake of Qingcaosha water source was surrounded by freshwater without the influence of salinity intrusion from March to November each year and the higher the runoff of the month was, the larger the freshwater area will be.

4.3 Salinity process of water intake

The semimonthly salinity process of Qingcaosha water intake at runoff volume of 50% frequency in each month of the dry season in the Yangtze Estuary is shown in Figure 5. The figure clearly showed that the higher the runoff was, the lower the salinity will be. In December, January and February, salinity at the water intake exceeded the standard value at severe moments, while the salinity was always lower than 0.45‰ in other months.

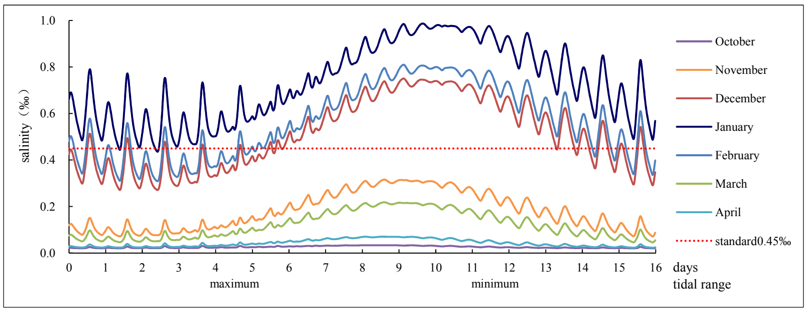

Figure 5. The semimonthly salinity process of Qingcaosha water intake at runoff volume of 50% frequency in each month of the dry season in the Yangtze Estuary

There is a different definition of the days unsuitable for water drawing in the event of salinity intrusion in the water source. Zhu et al. (2013) thought that, if in a day, the time for continuous water drawing is not less than 4 hours, then water drawing can be done this day; otherwise, this day is unsuitable for water taking. The longest 68 successive days unsuitable for water drawing for Qingcaosha Reservoir was obtained according to this calculation method. A more stringent definition of the impact of salinity intrusion on Qingcaosha Reservoir is given in Article 10 of *Reply to the Response Plan of Salt Tide in the Yangtze Estuary* issued by the National Flood Control and Drought Relief Headquarters in 2015. For Qingcaosha Reservoir, “generally when the chloride concentration outside the gate in its upper reaches is more than or equal to 250mg/L for two consecutive hours, it will be taken as the basis for the beginning of the salt tide; when the chloride concentration outside the gate in its upper reaches is lower than 250mg/L for 2 consecutive hours and the chloride concentration is not more than or equal to 250mg/L for 2 consecutive hours within a monitoring period of 12 consecutive hours, it will be taken as the basis for the end of salt tide”. The days unsuitable for water drawing defined by Zhu is regarded as Plan A. That on the basis of *Reply to the Response Plan of Salt Tide in the Yangtze Estuary* as Plan B. Exploring the maximum number of days unsuitable for water drawing in a semimonthly period in each month of the dry season was executed with different water intake plans. In the meanwhile, the proportion of exceeding standard time to the total time is defined as the salinity exceeding rate.

As shown in Table 2, in January, the highest salinity of the Qingcaosha water intake was 0.99‰, 2 times higher than the standard, while the lowest was 0.44‰, close to the water drawing limit of 0.45‰. The exceeding standard rate was up to 99.1%, indicating that the salinity at runoff volume of 50% frequency was almost higher than the water drawing standard value in January. Regardless of whichever plan, the entire semimonthly period was not suitable for water drawing. In December, the salinity at the water intake was 0.27 ~ 0.75‰, and the exceeding standard rate was 58.9%. The maximum number of days unsuitable for water drawing was 8 days according to Plan A and 9 days according to Plan B. In February, the salinity at the water intake was 0.31 ~0.81‰, and the exceeding standard rate was 69.9%. The maximum number of days unsuitable for water drawing was 9 days according to Plan A and 11 days according to Plan B. Therefore, the maximum number of days unsuitable for water drawing based on Plan B was less than that on Plan A, and the method of Plan B was stricter and safer.

Table 2. Salinity, the exceeding standard rate and the maximum number of days unsuitable for water drawing.

Month	salinity（‰）		the exceeding standard rate	the maximum number of days unsuitable for water drawing	
	maximum	minimum		Plan A	Plan B
October	0.03	0.02	0	0	0
November	0.32	0.07	0	0	0
December	0.75	0.27	58.9%	8	9
January	0.99	0.44	99.1%	16	16
February	0.81	0.31	69.9%	9	11
March	0.22	0.05	0	0	0
April	0.07	0.02	0	0	0

Qingcaosha Reservoir has a design safe water supply period of 68 days and 35 days under the current conditions. According to analysis, in January when salinity intrusion was the most severe, water cannot be drawn in the entire semimonthly period analyzed, but as the reservoir has a large capacity, if the saltwater is well forecast, thus water storage is done in advance, serious water supply crisis will not occur and the safety of water source can be guaranteed. Moreover, as the highest salinity in January was only about 2 times of 0.45‰, brackish water drawing is feasible under extreme circumstance. The salinity is diluted by the freshwater in the reservoir, thus it can still be guaranteed that salinity at the outlet complies with the national standards, and the water taste will not be affected.

5 CONCLUSIONS

i. Qingcaosha water source is located in the Yangtze Estuary. It is the world's largest estuary and river central reservoir of avoiding saltwater and storing freshwater. Salinity intrusion in the dry season is a main threat to the water source safety;

ii. In January, the runoff is the smallest, the salinity intrusion is the most severe and the area of freshwater in the Yangtze Estuary is the smallest of the year. What is more, the freshwater appearing during neap tide is larger than that during spring tide. Under normal circumstances, the water intake of Qingcaosha water source is surrounded by freshwater from March to November each year;

iii. The runoff at 50% frequency of each month is used to represent the ordinary situation of the month. In January, the semimonthly period is not suitable for water drawing at the water intake of Qingcaosha Reservoir. However, as the reservoir has a large capacity and the highest salinity is only about 2 times higher than the standard value, if the salinity intrusion is forecast accurately and water storage is done before the saltwater approaches, generally the safety of water source can be guaranteed. In an emergency, the measures of brackish water drawing can also further alleviate the water supply crisis.

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RESEARCH ON SEASONAL STRATIFICATION OF IRON AND MANGANESE IN RESERVOIR IN THE KARST WATER SHORTAGE AREA

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ABSTRACT

Because of the characteristics of soil and sediment in reservoir inundation area, the problem of excessive iron and manganese is common in karst area， where insufficient resources and low water quality are the main causes of water shortage. Using A'gang reservoir as an example, monitoring the status of iron and manganese in reservoir watershed, conducting the release experiment of iron and manganese in the reservoir sediment and soil, and combining the estimation of the source in watershed and the simulation of the seasonal concentration in reservoir, research on seasonal stratification of iron and manganese in reservoir in the karst area is carried out. The concentration of iron and manganese in the bottom of the reservoir is even higher than that of the water quality, due to high content of iron and manganese in Karst area, meanwhile reservoir thermal oxygen stratification enhances the weak acid and reductive environment at the bottom of reservoir.

Keywords: A'gang reservoir; thermal stratification; endogenous; Fe Mn concentration.

1 INTRODUCTION

Trace amount of iron and manganese are necessary for the human body, too much iron and manganese in drinking water will cause great adverse effects on the human body, namely ferrum exceeding the standard impact on the heart, and excessive manganese will affect the central nervous system. Criterion of iron and manganese of surface water in centralized drinking water source are prescribed as 0.3mg/L and 0.1mg/L respectively. The research on iron and manganese pollution in thermal stratified reservoirs show that the distribution of iron and manganese in reservoirs changes seasonal, affected by the temperature gradients of reservoirs, showing obvious vertical distribution. High concentrations of iron and manganese pollutants mainly occur in the reservoirs middle and bottom when water temperature stratification, closely related to hypoxia and pH decreased in the reservoirs bottom, as well as the secondary pollution caused by the release of iron and manganese pollutants from the sediments. In the karst area, insufficient resources and low water quality are the main causes of water shortage, drinking water reservoirs are affected by the external pollution of solid wastes in the upper reaches of the reservoir area and endogenous pollution of soil in submerged region. The problem of iron and manganese exceeding the standard is common. Exogenous pollution can be achieved through comprehensive management measures to improve water quality, the endogenous pollution existed in the reservoir after impoundment, and the red soil and iron and manganese nodule in the karst area strengthened the release of endogenous. Taking A'gang Reservoir in Yunnan Province as an example, research on seasonal stratification of iron and manganese in reservoir in the karst water shortage area, can enrich the theory of environmental hydraulics, also can provide the theory evidence for stratified water-taking measures of water supply reservoirs.

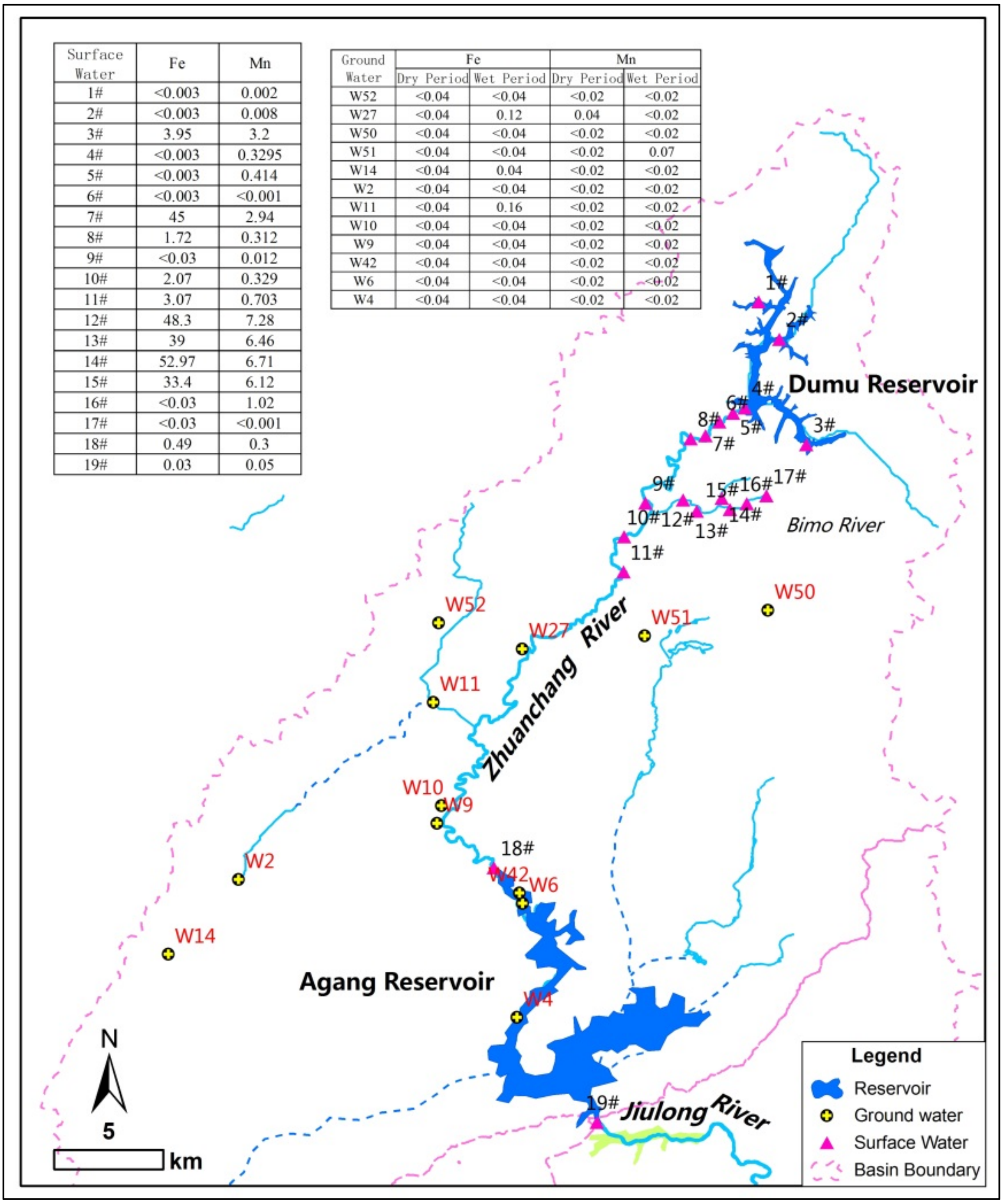
2 THE SURVEY OF RESEARCH REGION

A'gang reservoir is located in the northwest of Luoping County, Qujing city of Yunnan province, on the Zhuanchang river upstream of Jiulong River. The geographical coordinates of the dam site is 104º0'20" east longitude and 23º34'0" north latitude, as shown in Figure 1. The dam site controls the runoff area of 1142 km^2, the normal water level of the reservoir is 1866m, the total storage capacity is 1.2907 billion m^3; the dead water level is 1838.20m, and the corresponding dead storage capacity is 765 million m^3. The main tasks of A'gang Reservoir are urban and rural life water supply, industrial water supply and agricultural irrigation supply, the average annual total water supply amount is 135.37 million m^3. The present industrial parks in the reservoir watershed are concentrated in coal mining and washing industries, food enterprises and coking industries. Among them, the coal mining enterprises are not equipped with sewage treatment facilities or are not in use. In addition, the drainage water from the mines is irregularly drained, would cause pollution to the upper reaches of the reservoir water environment.

3 STATUS MONITORING IN A'GANG RESERVOIR WATERSHED

According to the results of monitoring of iron and manganese in 21 surface water monitoring points within A'gang Reservoir watershed in 2015, the concentration of iron and manganese exceeded the standard, and the concentration in water from the upstream to the downstream was slowed down. In the main stream between Dumu reservoir dam and Bimo River in Dongshan town, iron and manganese exceeded the standard in different degree. Among them, ferrum exceeded 0.6 times in tail of A'gang Reservoir, manganese exceeded 2 times; iron and manganese is not exceeded in A'gang Reservoir dam site; ferrum exceeded more than 100 times in tributary, manganese exceeded more than 30-60 times. The iron and manganese pollution sources in the whole watershed are concentrated in the Dongshan Bimo River Basin.

The monitoring results of 12 groundwater monitoring points in the A'gang reservoir watershed indicate that all monitoring points during the dry season and wet period should not exceed the standard of iron and manganese, the groundwater in the A'gang reservoir watershed with the features of high quality and not easy polluted. The disposition of surface water monitoring sections and groundwater monitoring points, and the evaluation of iron and manganese are shown in Figure 1.



Surface Water	Fe	Mn
1#	<0.003	0.002
2#	<0.003	0.008
3#	3.95	3.2
4#	<0.003	0.3295
5#	<0.003	0.414
6#	<0.003	<0.001
7#	45	2.94
8#	1.72	0.312
9#	<0.03	0.012
10#	2.07	0.329
11#	3.07	0.703
12#	48.3	7.28
13#	39	6.46
14#	52.97	6.71
15#	33.4	6.12
16#	<0.03	1.02
17#	<0.03	<0.001
18#	0.49	0.3
19#	0.03	0.05

Ground Water	Fe		Mn	
	Dry Period	Wet Period	Dry Period	Wet Period
W52	<0.04	<0.04	<0.02	<0.02
W27	<0.04	0.12	0.04	<0.02
W50	<0.04	<0.04	<0.02	<0.02
W51	<0.04	<0.04	<0.02	0.07
W14	<0.04	0.04	<0.02	<0.02
W2	<0.04	<0.04	<0.02	<0.02
W11	<0.04	0.16	<0.02	<0.02
W10	<0.04	<0.04	<0.02	<0.02
W9	<0.04	<0.04	<0.02	<0.02
W42	<0.04	<0.04	<0.02	<0.02
W6	<0.04	<0.04	<0.02	<0.02
W4	<0.04	<0.04	<0.02	<0.02

Figure 1. A'gang reservoir watershed and the disposition of surface water monitoring sections and groundwater monitoring points.

Six sampling points set in the upper reaches of Dumu Reservoir, Dumu Reservoir downstream, A'gang Reservoir dam site, monitoring the status of iron and manganese of the sediment in river and reservoir region, detailed in Table 1. The coal mine contains manganese ore, which is related to the pollution from the surrounding coal mining plants. In the process of coal preparation, the manganese ore can't be collected completely and efficiently, so that the wastewater containing manganese is discharged into the water body, and the manganese is adsorbed and enriched, leading to a high manganese content in the sediments.

According to the results about the soil background value of iron and manganese in the A'gang Reservoir watershed, the contents of iron and manganese in the soil of A'gang reservoir watershed were 99933mg/kg and 794mg/kg, detailed in Table 1. Judging from available data, the background value of soil iron and manganese in A'gang Reservoir watershed is in the medium high level of Yunnan province and the whole country. The concentration range of soil iron and manganese pollutants is 1200-125000 mg/kg and 42-3000 mg/kg. The mean concentrations were 29,700 mg/kg and 540 mg/kg, respectively.

Table 1. Monitoring of iron and manganese in sediments and soils in the catchment area of A'gang reservoir Unit: mg / kg.

Sediment monitoring			Soil monitoring		
Monitoring points	**（Fe）**	**（Mn）**	**Monitoring points**	**（Fe）**	**（Mn）**
A'gang Reservoir dam site	5.72×10^4	1.82×10^3	01#	107500	739
A'gang reservoir area	4.17×10^4	1.05×10^3	02#	137600	1156
Dumu reservoir area 1#	7.5×10^4	406	03#	104600	1427
Dumu reservoir area 2#	8.03×10^4	861	04#	84600	469
Dumu reservoir area 3#	8.51×10^4	93.5	05#	99800	529
Dumu Reservoir downstream	3.57×10^4	1.52×10^3	06#	65500	446
average value	6.25×10^4	958.4	average value	99933.3	794.3

From the monitoring results of surface water and groundwater in the watershed, iron and manganese in the main stream of the Zhuanchang River above the dam of site exceed the standard. The main cause is the Bimo River basin upstream of the dam site; the external pollution load of iron and manganese in the A'gang Reservoir watershed also concentrated in the basin. Based on the monitoring results of iron and manganese contents in soil and sediments, the background value of iron and manganese in the soil of A'gang reservoir watershed is in the medium high level of Yunnan Province, and the content in the sediments is almost the same as that in the soil. The ferrum content in the sediments was slightly lower in the soil, the manganese content in the sediment is slightly higher than the soil. The contents of iron and manganese in the watershed of A'gang reservoir were higher than those in the groundwater monitoring sites, which indicate that the contents of iron and manganese in the groundwater are not exceeded, and also indicate that leaching precipitation of iron and manganese content of the soil in the A'gang reservoir watershed is limited.

4 SEASONAL VERTICAL DISTRIBUTION OF IRON AND MANGANESE CONCENTRATIONS IN A'GANG RESERVOIR

4.1 Loading estimation of iron and manganese in A'gang Reservoir

After the completion of the A'gang Reservoir, the iron and manganese pollution in the reservoir mainly come from endogenous and exogenous cause. The exogenous estimate is based on the actual monitoring data, the direct emission concentration of iron and manganese is 30 mg/L and 6mg/L, and the post treatment concentration is 7 mg/L and 4 mg/L. There are a total number of 91 existing industrial enterprises above the dam site in A'gang Reservoir, whose industrial pollution of iron and manganese emissions were 61.46 t/a and 8.06 t/a. Based on the status of sewage and background conditions, after years of completion, the average annual runoff at A'gang dam site is $6.55 \times 10^8 m^3$, the annual amount of iron and manganese into the reservoir through the surface runoff is 196,500 t/a and 327,500 t/a.

Endogenous estimates are based on the dissolution limit values of test and the reservoir inundated area. The test results of iron and manganese dissolution (immersion) of soil and sediment samples in the reservoir area are shown in Table 2. The results of dissolution test show that the average dissolution value of iron and manganese was 10.63mg / L and 0.19mg / L, and the dissolution rates are 0.12% and 0.14%.

Table 2. A'gang Reservoir soil sampling points of iron and manganese dissolution value of sediment.

Sample Category	pH	Ferrum content (mg/kg)	Ferrum dissolution value (mg/L)	Ferrum dissolution rate %	Manganese content (mg/kg)	Manganese dissolution value (mg/L)	Manganese dissolution rate%
soil	7.9	92064	20.12	0.227	1628	0.128	0.09
Sedimentation	7.3	98604	2.49	0.03	1298	0.234	0.19
average value	7.6	95586	10.63	0.12	1450	0.19	0.14

Based on the results of the above tests, the iron and manganese release limits of soil and sediment in A'gang Reservoir area were estimated. The inundation area of A'gang Reservoir is 155540 mu ($10.36 \mathrm{km}^2$), with 0.2m as the thickness of dissolution substrate. According to the Eq. [1], the total amount of iron and manganese released from the bottom of the reservoir into the water body in the reservoir area can be estimated. The results are shown in Table 4. The total amount of iron and manganese released from the reservoir bottom into the water of the reservoir are 695.7t and 6.5t respectively.

$$M = S \times H \times m \times \eta \times \rho \qquad [1]$$

In the formula: M is the limiting dissolution of soil and sediment, t; S is reservoir bottom area, km^2; H is the average thickness of soluble soil and sediment, m; m is soil and sediment iron and manganese content, mg/kg; η is dissolution rate, %; ρ is unit volume of soil and sediment to form a dry basis weight, take 2.8 t/m³.

Table 3. Limit release estimation of iron and manganese in soil and sediments of A'gang Reservoir.

Normal water level submerged area（km^2）	Substrate release thickness (m)	Substrate Iron and Manganese content (mg/kg）		Substrate dry weight（t）	Dissolution rate		Limit release /t	
		Fe	Mn		Fe	Mn	Fe	Mn
10.36	0.2	99933.3	794.3	5.8×10^6	0.12%	0.14%	695.7	6.5

4.2 Seasonal concentrations forecast of iron and manganese in A'gang Reservoir

Under the status of the sewage and background conditions, the total amount of ferrum entering the A'gang Reservoir through external and internal sources is 715.35 t/a, of which the external source is 19.65 t/a, the endogenous source is 695.7 t/a. The total amount of manganese is 39.25t / a, the external source is 32.75 t/a and the endogenous is 6.5 t/a. With $6.55 \times 10^8 m^3$, annual runoff at the dam site, vertical concentration of iron and manganese is closely related to water temperature, pH value and DO. Under the hydrological and meteorological conditions, the monthly water temperature and the concentration of iron and manganese in A'gang Reservoir are shown in Figure 2, reservoir surface monthly iron and manganese concentration as shown in Figure 3.

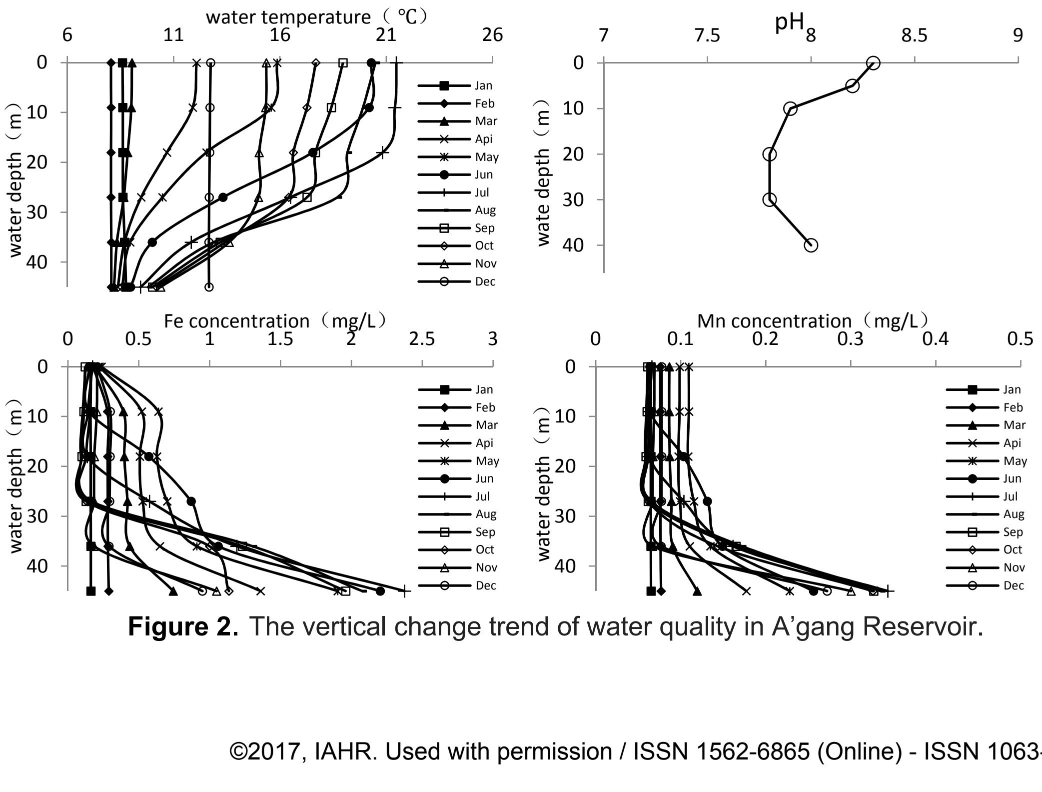


Figure 2. The vertical change trend of water quality in A'gang Reservoir.

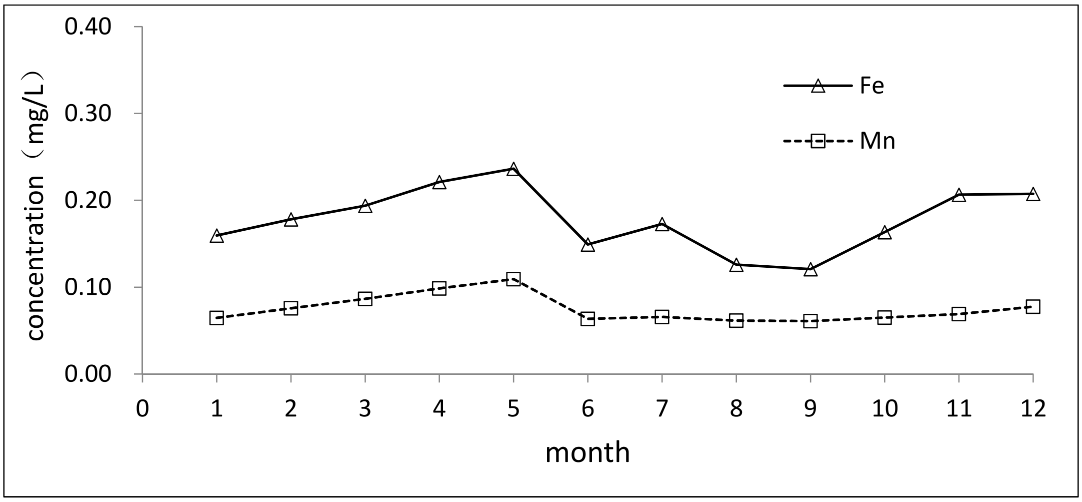


Figure 3. Monthly average concentration of iron and manganese in A'gang reservoir surface water.

In this paper, the endogenous release limit value is based on the test results of water-solubility, which is too large for the worst case. The purpose is to analyze and to quantify the effect of iron and manganese release from soil and sediment on reservoir water quality stratification. True natural condition, which is the release of iron and manganese in the sediments, is the process of slow release from surface sediments.

4.3 Analogy analysis of reservoir water quality influence

In order to further analyze the effect of endogenous sources on the concentration of iron and manganese in A'gang Reservoir, this paper adopts the analogy analysis method, which is analogous to the Mudi River reservoir in Dehou river watershed of Yunnan province. The limit of release of iron and manganese from Mudi Reservoir is about 167 t/a and 2.95 t/a, respectively. Through monitoring the content of iron and manganese in the water of the Mudi River Reservoir, the average monthly concentration of iron and manganese on the surface of Mudi River Reservoir monitored by Wenshan environment monitoring station in 2013 is shown in Figure 4. The water quality of iron and manganese meets the water quality standard Ⅲ. Figure 5 shows the results of the stratified sampling of water quality of the Modi river reservoir in April 2015. Except for the excess iron and manganese in the bottom water, all the other water bodies can meet the water quality Ⅲ standard of surface water.

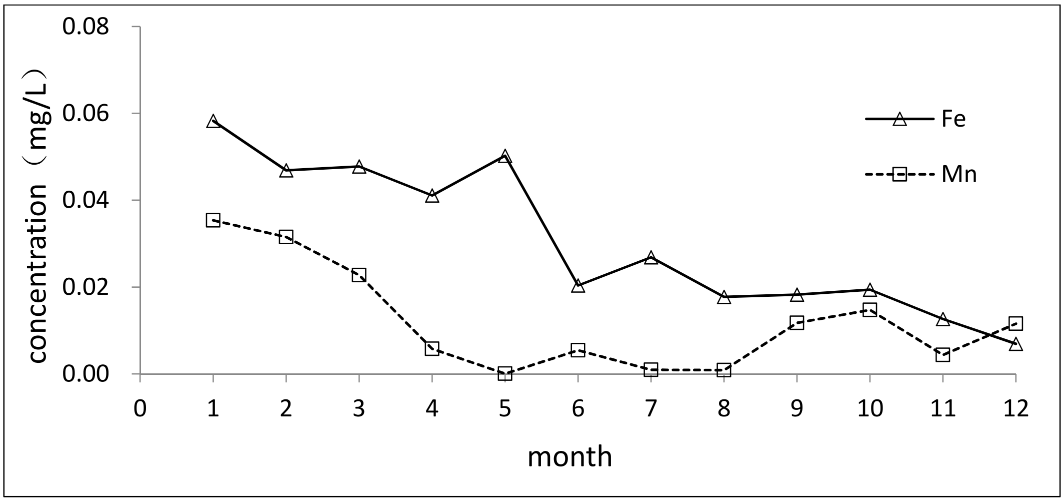


Figure 4. Mean concentrations of iron and manganese in the surface water of the Mudi River reservoir.

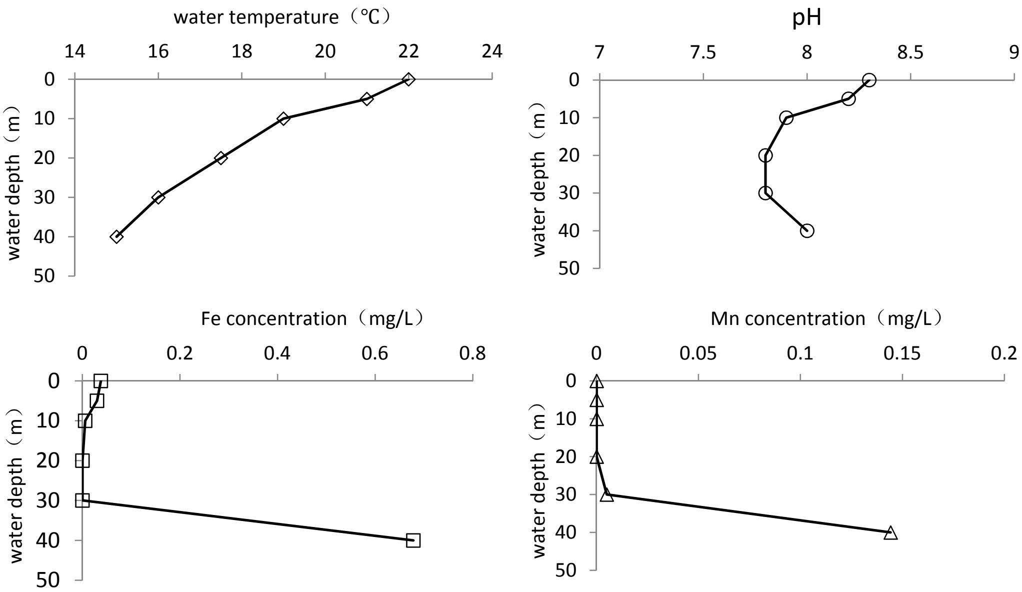


Figure 5. Vertical variation trend of water quality of the Mudi River reservoir.

4.4 Seasonal vertical distribution of iron and manganese concentrations in A'gang Reservoir

The distribution of iron and manganese in reservoirs changes with the seasons and the temperature gradients of reservoirs, showing obvious vertical distribution. High concentrations of iron and manganese pollutants mainly occur in the middle and lower reservoirs of the stratification stage of water temperature, and are closely related to the bottom of the hypoxia and pH decreased, as well as the secondary pollution caused by the release of iron and manganese pollutants from the sediments. In karst area, the characteristics of red soil and ferrum manganese nodules at the bottom of reservoir strengthen the endogenous role of ferrum manganese release.

In summer and autumn, the water temperature of the reservoir is distinctly stratified, the upper and lower water bodies are separated by thermocline and lack of convective movement, leading to the reservoir surface oxygen difficult to enter through the thermocline into the bottom, the dissolved oxygen in the bottom of the reservoir is consumed by the benthic organisms, organic matter decomposition and reductive pollutants, and the dissolved oxygen in the bottom layer continues to decrease. At the same time, the pH value decreases, resulting in the release of iron and manganese in the sediment at the end of the reservoir to increase, and also the concentration of iron and manganese in water significantly to increase. According to the results of simulation and analogy analysis, the ratio of iron and manganese concentration at bottom, middle and surface of reservoir are 16:4:1 and 5:2:1, respectively.

In the winter and spring, the water temperature of the upper and lower reservoirs tends to be isothermal or the temperature difference is small, and the dissolved oxygen and pH of the reservoir water are high, and the whole water body is oxidized. Under the oxidizing environment, the iron and manganese with very low migration ability is in the high valence state and forms insoluble compound. Gradually, the compounds are deposited on the surface of the sediments. The iron and manganese contents in the sediments increase and the concentration of iron and manganese in the water is reduced accordingly.

5 CONCLUSIONS

The water body of A'gang reservoir area is poor in fluidity and exchange time is long, which leads to the stratification of the water temperature in the vertical direction and the formation of the thermocline. The reservoir surface oxygen is difficult to enter the bottom, and carbon dioxide and organic acids produced in the bottom of the library make the pH drop, eventually leading to the bottom of the reservoir iron and manganese in the weak acid and reducing environment was released into the water body, resulting in the end of the water quality of iron and manganese concentrations higher, or even exceeded. However, after taking stratified water measures, through the use of surface water, for downstream water, iron and manganese can be avoided excessive water quality problems.

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ANALYSIS ON RESPONSE CHARACTERISTICS OF WATER QUALITY TO THERMAL STRATIFICATION IN DAHUOFANG RESERVOIR

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ABSTRACT

According to the design parameters of Dahuofang Reservoir, the water temperature structure of the reservoir is thermal stratification. In order to study the correlation between stratification and water-quality variance, vertical water temperature and water-quality monitoring in front of the dam was carried out in May, July and September 2010~2012. The result showed that water-quality of surface water was good and stable in the reservoir and could reach Grade II of the National Surface Water Quality Standards. Since the reservoir was operated under a low water level during 2010~2012, thermally stratified period only occurred in summer. The steady temperature gradient could control the water environment of the reservoir, which effectively restricted oxygen transfer and exchange among the vertical water layers. In summer, dissolver oxygen (DO) in surface water was high and over 7mg/l, even to its supersaturation. DO in bottom water was even lower than 4mg/l, which could not meet Grade III water quality. In autumn, the cold water on surface settled down which strengthened the vertical mixture of the reservoir, so DO in surface water reached the lowest all over the year. If the reservoir is operated in a high level for a long time, the time of thermal stratification in Dahuofang Reservoir will increase, thus leading to further decrease of DO in bottom water. It may lead to the formation of hypoxic environment for bottom water which will cause pollutants such as Fe, Mn, H2S to release from sediments. Then, with the strengthening of the vertical mixture of the reservoir in autumn, the pollutant in bottom water will pollute the whole reservoir and cause abrupt water pollution accident which will have a direct threat of the water supply security.

Keywords: Dahuofang Reservoir; thermal stratification; water quality; dissolved oxygen.

1 INTRODUCTION

With the increasing of human water resources regulation and control ability, more and more countries and regions in the world attach importance to the role of reservoirs in the development of human society. Since reservoirs are the critical infrastructure to provide water safety and security for economic and social development, the construction of reservoirs has become one of the essential topics (Jia, 2004). Now China is in the critical period of economic development, but due to the uneven distribution of water resources in time and space and the shortage of water resources, a large number of reservations need to be constructed urgently, which are also the best way to provide enduring guarantees for flood control, water supply, food security, energy security, ecological security and optimization disposition of water resources. Also, the reservoir has become an important source of drinking water in China (Jia, 2013; Jin, 2008). The construction of the reservoir changes the hydrological and hydrodynamic conditions in the river and the original river ecosystem has been evolved into the reservoir ecosystem. For example, the water flow velocity in the reservoir area is slowed down, the water depth increases, the water self-purification capacity decreases, and the water temperature distribution is stratified in vertical. The thermal stratification controls the process of water environment evolution and leads to water quality stratified in the reservoir water (Deng, 2003; Wang, 2005). Studies have shown that even with good upstream water quality, thermal stratification reservoirs may cause abrupt water pollution accident when reservoir stratification is unstable (Lu and Li, 2014). Therefore, it is vital to strengthen the investigation and research on the change rules of water quality in reservoirs which are usually the drinking water source.

Dahuofang Reservoir is a large reservoir in the northeastern mountainous area of Liaoning Province, and the reservoir has various functions such as flood control, irrigation, water supply, power generation, fish farming, tourism, and others. It is the important drinking water source for 22 million people in Shenyang, Fushun, Anshan, Dalian and other seven cities, Liaoning Province (Wang, 2015). Dahuofang Reservoir has been the ninth most important drinking water source area for urban water supply in China, and water-quality protection is becoming increasingly important. At present, researchers have done a great deal of research in the reservation about numerical simulation of reservoir thermal stratification, the investigation and analysis of reservoir water-quality and sediment (Wang, 2015; Luo et al., 2011; Shi et al., 2003). Studies have shown that thermal stratification reservoirs strongly affect evolution of water environment (Wetzel, 2001; Wang and Dai, 2009), however, few studies of the response relationship between water environment and thermal stratification have been done. In this paper, detailed monitoring of vertical water temperature and water-quality in front of Dahuofang Reservoir

Dam is carried out in order to analyze thermal stratification state and explore the impact of water pollutant transport and transform in thermal stratification of the reservation. The research can offer a reference for the changing rule of water quality in similar reservoirs and provide a scientific basis and reference to water quality protection and pollution prevention of reservoirs for drinking water source.

2 MATERIALS AND METHODS

2.1 The overview of the study region

Dahuofang Reservoir, built in 1958 is located in the middle and upper reaches of the Hun River Basin, which is a multipurpose large-scale reservoir, mainly serving as flood control, urban water-supply, irrigation, power generation as well as fish farming (Figure 1).

The area of upper Dahuofang Reservoir catchment is 5437km^2, and the perennial mean air temperature is 5~7°C. The average annual precipitation in the area is about 650 ~ 800mm, mainly concentrated in July and August, of which makes up 50%. The height of the reservoir dam is 49.8m; the total reservoir capacity is 1.94 billion m^3. When the reservoir is in normal water lever, the reservoir storage capacity is 1.43 billion m^3, the length of reservoir backwater is about 35km, the maximum cross-section width is about 4km and the water surface area is 91.2km^2 (Wang et al., 2015). Since the running of the reservoir, the minimum and maximum water depth are 17.19m and 46.46m respectively. The average runoff at the dam section is 1.47 billion m^3, and the average annual flow is 46.61m^3/s.

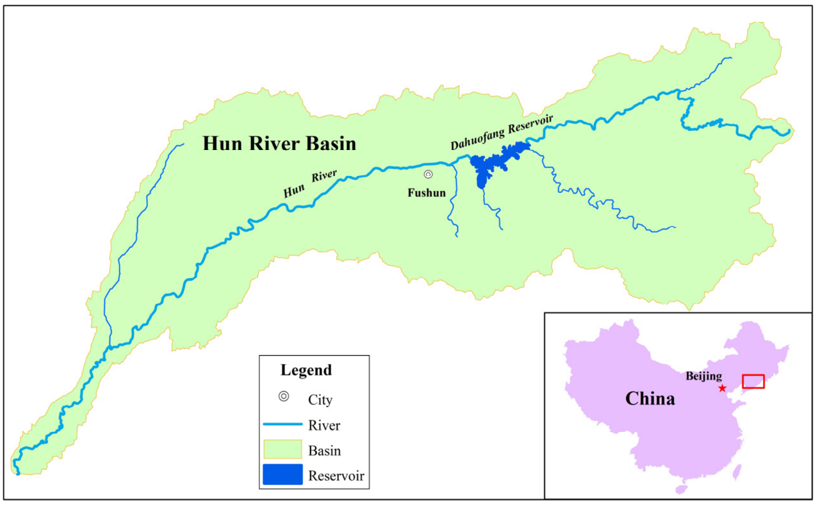

Figure 1. The location map of Dahuofang Reservoir.

2.2 Sampling and analysis methods

Vertical water temperature and water-quality monitoring in front of the dam were carried out in May, July and September during 2010 to 2012, mainly including water temperature, pH, dissolved oxygen (DO), total phosphorus (TP), permanganate index (COD_Mn), five days' biochemical oxygen demand (BOD_5) and others. The surface samples were collected from 2m below the surface, and the bottom bed samples were collected from 2m above the sediment. Meanwhile, the water temperature, DO and pH were carried out in-situ monitoring, and TN, TP, COD_Mn and BOD_5 were carried out by lab examination.

3 DETERMINATION FOR WATER TEMPERATURE STRUCTURE AND ANALYSIS ON DISTRIBUTION CHARACTERISTICS OF DAHUOFANG RESERVOIR

For the reservoir, the velocity of flow is slower and the water depth increases, running water environment has become quiescent water environment and the water convection is weakened, which results in a stratification of the water temperature in vertical. According to the reservoir scale, depth, geographical location, climatic conditions and other factors, reservations can be divided into thermal stratified, seasonal stratified and mixed based on vertical structure of water temperature (Deng, 2003).

3.1 Determination for water temperature structure

At present, the most popular methods for reservoir water temperature structure identification include the inflow and the storage capacity ratio method (also known as α method), the density Froude number method, cross-section and water depth ratio method and others. In this paper, the first two methods were chosen to judge the water temperature structure of Dahuofang Reservoir.

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3.1.1 α method

α method of computation references 'Hydrology computing specification in water resources and hydraulic engineering (SL278-2002)'. The formula for calculation is as follows:

$$\alpha = \frac{\text{annual average annual runoff}}{\text{total reservoir capacity}} \qquad [1]$$

When α <10, the water temperature structure is thermal stratified; when 10 <α <20, it is seasonal stratified; when α> 20, it is mixed. The average annual runoff of Dahuofang Reservoir is 1.47 billion m³, and the total reservoir capacity is 1.43 billion m³. Then, the value of α is equal to 1.03. The water temperature structure of the reservoir is thermal stratified.

3.1.2 Density Froude number method

Calculation formula of Density Froude number method is as follows (Wang, 2009):

$$F_r = 320 * \frac{LQ}{HV} \qquad [2]$$

where, Fr is the density Froude number, L is the length of reservoir's backwater (m), Q is the average annual flow (m³/s), H is the average water depth (m), and V is the reservoir storage capacity (m³). When Fr <0.1, the water temperature structure is thermal stratified; when 0.1 <Fr <1.0, it is seasonal stratified; when Fr> 1.0, it is mixed. Fr in Dahuofang Reservoir is less than 0.1 by calculation, so the water temperature structure of the reservoir is thermal stratified.

According to the methods above, water temperature structure of Dahuofang Reservoir is decided to be thermal stratified. Considering the monitoring of vertical water temperature in front of the dam, the maximum temperature difference is 9°C between the surface and the bottom, which was carried out in July, and the reservoir is thermally stratified.

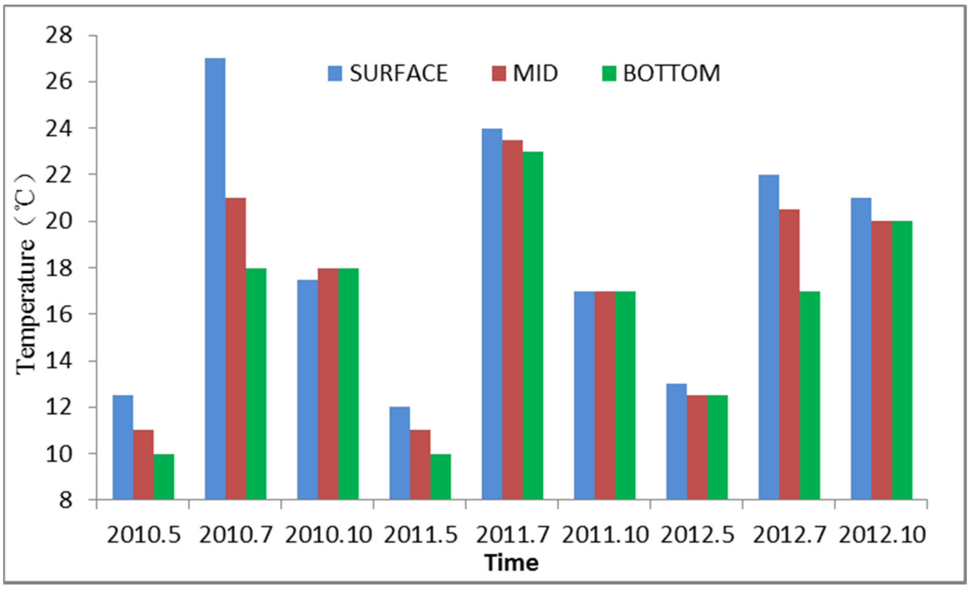

Figure 2. The monitoring of vertical water temperature in front of the dam in Dahuofang Reservoir during 2010 to 2012.

3.2 Analysis on water temperature distribution characteristics of Dahuofang Reservoir

The above analysis and the monitoring show that Dahuofang Reservoir is a thermal stratified reservoir, and the temperature difference between the surface and the bottom is largest in summer. The maximum temperature differences in front of dam from 2010 to 2012 are as follows: 9°C, 1°C and 5°C, all in summer. Strong solar radiation in summer leads to a rapid increase of the water temperature in surface in summer, and the water in bottom is less influenced by solar radiation. Due to the long water residence time in large reservoirs, water convection between surface layer and bottom layer is poor. Then, the reservoir appears stratified. However, vertical water temperature in the summer of 2011 is not stratified, mainly due to the low operating water level of the reservoir during 2011. Water depth was only 16m in the summer 2011, and the reservoir water volume was less than 200 million m³, which was less than 15% of the reservoir storage capacity. At the same time, the water residence time was short and water convection in the reservoir was sufficient. Then, thermal stratification was not significant.

In the spring and autumn, the maximum temperature difference of Dahuofang Reservoir was about 1°C, and the reservoir basically presented an equal temperature distribution. Then, thermal stratification was not significant. In the summer, the reservoir was thermal stratification. Into autumn, with the dropping air temperature, the water temperature on reservoir surface decreased and the water density increased when the water temperature was greater than 4°C (Figure 3). As the density of the surface water increased, it sank down and water convection between surface layer and bottom layer was strong which caused water to mix well in the reservoir. Then in winter, surface water and the bottom water were closed to the freezing point and 4°C respectively, and the reservoir was inversion thermal stratification. With the increasing temperature in the spring, the temperature and density of surface water increased, and the surface water sank. Then, water was well-mixed. Therefore, the maximum temperature difference of the reservoir was tiny in the spring.

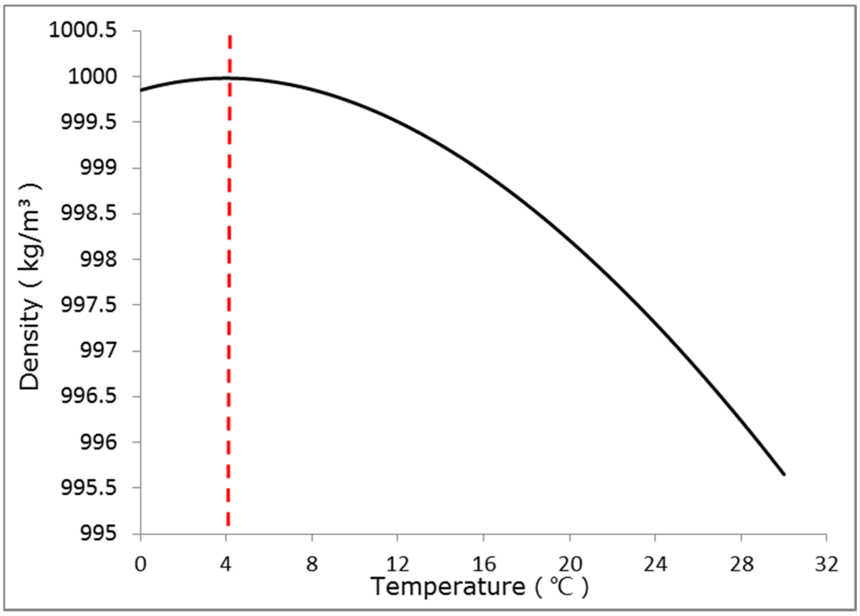

Figure 3. Curve of water temperature~ density.

4 RESPONSE CHARACTERISTICS OF WATER QUALITY TO THERMAL STRATIFICATION

4.1 Vertical distribution of water quality

The water temperature, DO, TP, COD_{Mn}, BOD_5 etc. were also monitored in the reservoir. Monitoring work shows that the content of TP, COD_{Mn} and BOD_5 could be consonant with Grade I water quality, and pH and the content of DO in the spring and autumn could meet Grade II water quality. The vertical content distribution of DO was in a similar stratification to the distribution of water temperature in the summer. The content of DO in surface water was high, which met Grade II water quality. However, the content of Do in bottom was lower than 4, only to meet Grade IV water quality, which could not meet Grade III water quality for drinking.

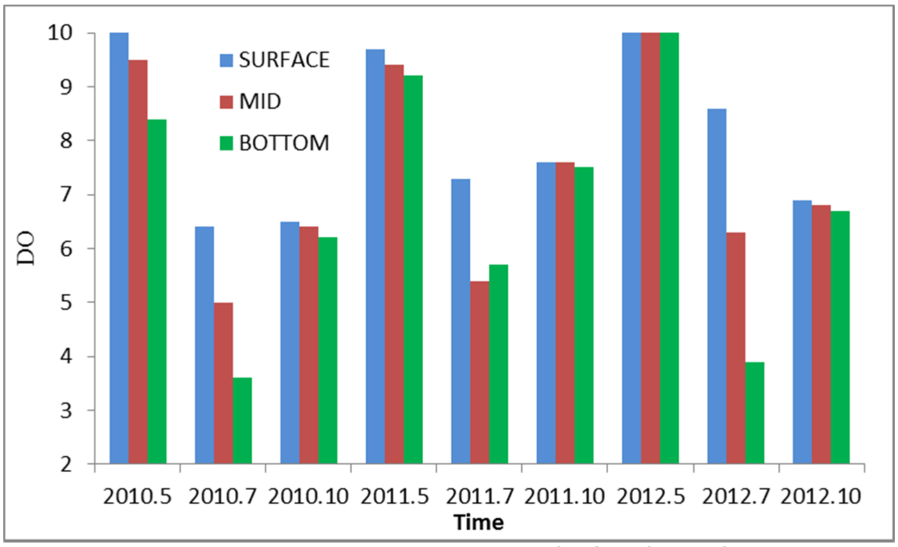

Figure 4. The vertical content distribution of DO in front of the dam in Dahuofang Reservoir during 2010 to 2012.

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4.2 Response characteristics of water quality change

In the spring and autumn, water convection is strong and water is well-mixed in the reservoir. The content of DO is not stratified in vertical. When the water temperature in the reservoir is thermal stratification in the summer, the content of DO in surface water is high because of the supply DO from the upper air and phytoplankton photosynthesis; for the bottom water, since the poor water convection causes no DO supplies, and the respiration of aquatic organisms and organic matters degradation consume oxygen, the content of DO decreases gradually. Then, the bottom gradually develops into anoxic environment and the water quality deteriorates. In the autumn, with water convection enhancing, the water is mixed vertically and the content of DO is also well-mixed. The content of DO in surface water is lower and DO in bottom water increases, which leads to the surface water being polluted.

In general, the hypoxic environment is formed at the bottom of the reservoir due to the thermal stratification, which may cause pollutants such as Fe, Mn, H2S to release from sediments. Then, the water quality in the bottom will be further deteriorated. In recent years, due to the low operating water level of the reservoir, the stratified stratification occurred only in the summer and was of short duration. Therefore, the content of DO in the bottom was consumed limitedly, and water quality deterioration was not serious. However, if the reservoir is operated in a high-water level for a long time, the thermal stratification will be more stable and the stratification time will be prolonged, which will cause the DO concentrations to be further reduced and water quality in the bottom to be worsen. By strengthening the vertical mixture of the reservoir in autumn, the pollutant entering bottom water will pollute the whole reservoir and cause abrupt water pollution accident and have a direct threat of the water supply security.

The upper Dahuofang Reservoir catchment belongs to mountain area and hill, and distributes extensive forest vegetation. So far, the ecological environment is maintained well, and water quality of upstream rivers into Dahuofang Reservoir is good, but enrichment of pollution in sediments is poor. When the hypoxic environment is formed at the bottom of the reservoir, only a few of the pollutants in sediment will be released into water, which does not lead to water pollution in the reservoir. Therefore, in order to protect the water quality in Dahuofang Reservoir, it is necessary to strengthen the controlling of the sources of pollution in the upper reservoir catchment.

5 CONCLUSIONS

In this paper, the water temperature structure of the reservoir was judged according to the design parameters of Dahuofang Reservoir. In order to investigate the correlation between stratification and water-quality variance, vertical water temperature and water-quality monitoring in front of the dam were carried out in May, July and September in 2010~2012, including DO, TP, CODMn, BOD5 and others. The study found that the structure of water temperature in the reservoir was thermal stratification and the maximum temperature difference was 9°C. Since the reservoir was operated under a low water level during 2010~2012, thermally stratified period only occurred in summer.

The steady temperature gradient could control the water environment of the reservoir, which effectively restrict oxygen transfer and exchange among the vertical water layers. Water quality of surface water was good and stable in the reservoir and could reach Grade II water quality, but DO of bottom water was even lower than 4mg/l which could not meet Grade III water quality. In autumn, by strengthening the vertical mixture of the reservoir, DO of surface water reached the lowest all over the year. Thermal stratification of the reservoir could lead to the formation of hypoxic environment for bottom water.

During the study period, due to the low operating level of the reservoir, the stratified stratification occurred only in the summer and was of short duration. Then, water quality deterioration was not serious. If the reservoir is operated in a high-water level for a long time, the thermal stratification will be more stable and the stratification time will be prolonged, which will cause water quality to deteriorate severely. It could cause abrupt water pollution accident and have a direct threat of the water supply security.

ACKNOWLEDGEMENTS

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ALTERNATIVES ANALYSIS FOR REDUCING ENVIRONMENTAL RISKS IN BURULUS LAKE

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ABSTRACT

The North of Egypt contains five coastal lagoons; these lakes represent economically important terms of fish production with more than 11% of Egypt's production. After adding production of farms that are located in these lakes, the total production becomes about 75% of total production in Egypt. The lakes are exposed to various challenges in this area and also to pollution problems. Burulus Lake is one of these Northern lakes and it is the second largest natural lake in Egypt. It has a current production of 60 thousand tons of fish annually, and when adding fish farms inside and along the perimeter, the total production becomes about a third of fish production in Egypt. Burulus wetland is one of the disposal areas for agricultural drainage water. It receives most of the drainage waters of the Nile Delta region through the drainage system. Recently, the marine ecosystem in the lake has deteriorated due to unbalanced water resources. To re-establish the pre-deterioration environmental case, water balance of the lake has to be investigated. Furthermore, all activities in and outside the wetland have been studied and a hydrodynamic model that can simulate Burulus Lake has been developed, including tidal behavior, freshwater inputs, water balance, mixing, exchange with the Mediterranean Sea, density current, geomorphological characteristics and sediment movement. This study aims to find the optimal solution for decreasing the lake pollution by studying four options: (i) Digging group of wells at the Southern part of the Lake, (ii) Dredging the lake Bottom, (iii) Construction of a new strait, and (iv) Change Drains direction to the Mediterranean Sea directly. Iber software has been used for each option to calculate water velocities and water circulation in the lake. Finally, the study has presented a matrix of the four options which could be used as a tool for decision makers.

Keywords: Coastal lakes; environmental impacts; hydrodynamic models; alternatives analysis; Burulus Lake.

1 INTRODUCTION

The Mediterranean basin in the North of Egypt contains five lakes and arranged from West to East (Marriut, Edco, Burulus, Manzalah, and Bardawil) (see Figure 1), these lakes represent economically important terms of fish production more than 11% of Egypt's production. When adding production of farms that are located in these lakes, the total production becomes about 75% of total production in Egypt. The lakes are exposed to various challenges in this area and also to pollution problems.

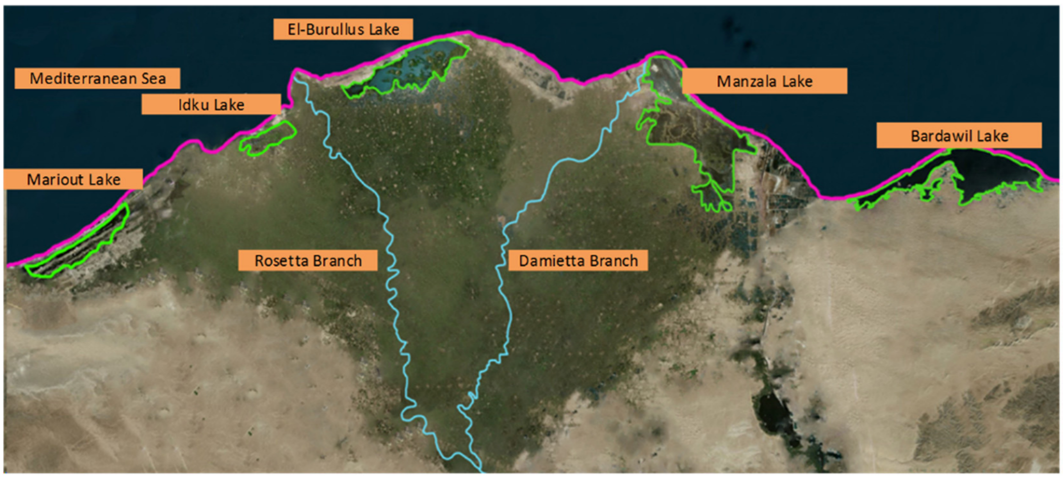

Figure 1. Natural lakes in the North of Egypt

Burulus Lake is one of these northern lakes, and it is the second largest natural lakes in Egypt. It has a current production of 60 thousand tons of fish annually, and when adding fish farms inside and along the perimeter, the total production becomes about third of fish production in Egypt.

Lake Burulus was predominantly saline in the Northern zone and brackish in the Southern zone, with a salinity gradient between both zones. Following the completion of the Aswan High Dam on the Nile River in 1965, the fresh water resources became fully regulated and both the intensity of agricultural irrigation and synthetic fertilizer consumption has been increased. This dramatic change leads to a rise in the amounts of agricultural drainage received by the lagoon before they are discharged to the eastern Mediterranean Sea through a small breach-way. It is now almost brackish throughout the entire basin (CoRI 2005 and Awad, 2011). The Catchment area of Burulus wetland is located between latitudes (30^0 22' 02'' - 31^0 36' 16'' N) and longitudes (30^0 29' 00'' - 31^0 21' 19'' E), Figure (1). The catchment altitudes vary from zero level at the Mediterranean Sea in the north to about 20 meters at the most southern edge. The surface slope in the catchment is northwards with an average slope of 0.0015 m/m. The catchment area covers most of the Nile Delta region. It has an area of about 4988 km^2 that equals to about 1,190,000 fed excluding the wetland area. Including Burulus wetland, the total area is 1,300,000 fed. The total area of the Nile Delta, including Burulus Lake area, is about 1,750,000 fed. The catchment area covers about 74.3% of the total area of the Nile Delta region.

Water resources in the catchment area are the irrigation water from the Nile, drainage water, and the Nile Delta groundwater aquifer. The main source that affects the wetland is the drainage water. The irrigation water has an indirect impact on the wetland except Prempal canal that discharges about 5% of the annual discharges to the lake. In this concern, irrigation water case has been considered qualitatively. The drainage system discharges an annual water volume of about 3.905 billion cubic meters through 8 drains excluding Prempal discharges.

The mean monthly and the mean annual volumes of water that were discharged into the lake through each drain are presented in Table (1). The amounts presented in Table 1 represent the monthly mean values (El-Shinnawy, 2003-A). Drainage water is discharged into the lake through a group of pumping stations at the end tail of the drains except Al-Gharbia drain that discharges its water freely without pumping.

Table 1 Mean monthly drainage inflows to the Lake (million m^3)

Month	Therah	Burulus	D #7	D #11	D # 8	Bur/W	D # 9	Gharbia	Prempal	Total
Jan	32.93	4.89	27.77	45.08	29.75	7.44	65.00	32.22	13.70	258.78
Feb	36.83	4.56	31.75	39.91	28.58	7.37	65.00	21.37	5.70	241.07
Mar	40.11	5.74	32.23	56.71	29.64	10.45	65.00	36.41	16.75	293.04
Apr	41.83	4.86	39.07	51.20	28.55	9.01	65.00	33.13	14.42	287.07
May	55.64	5.03	36.64	65.52	32.68	12.66	65.00	31.50	16.35	321.02
June	60.64	4.40	44.53	78.16	37.29	16.62	65.00	48.53	15.46	370.63
July	72.59	5.87	51.32	85.00	48.46	18.19	65.00	60.21	16.99	423.63
Aug	72.34	6.30	52.00	77.62	49.55	17.35	65.00	52.37	18.02	410.55
Sep	64.14	6.79	48.18	71.87	41.90	14.14	65.00	60.01	23.32	395.35
Oct	46.65	5.80	39.48	56.67	33.12	9.83	65.00	44.02	19.12	319.69
Nov	42.89	5.55	36.60	53.75	33.18	9.86	65.00	32.36	20.30	299.49
Dec	43.08	5.96	36.53	41.49	32.97	6.83	65.00	33.63	18.80	284.29
Annual	609.67	65.75	476.10	722.98	425.67	139.75	780.00	485.76	198.93	3904.6

This study aims to improve environmental conditions by studying the following four options for reducing pollution and increase lake salinity: (i) Group of wells, (ii) Dredging the lake Bottom, (iii) Construction of a new strait, and (iv) Diversion of drains to the Mediterranean Sea directly.

For this purpose, Iber software (Iber, 2011) will be used. Iber is a numerical model for simulating turbulent free surface unsteady flow and environmental processes in river hydraulics. The ranges of application of Iber cover river hydrodynamics, dam-break simulation, flood zones evaluation, sediment transport calculation and wave flow in estuaries. Iber has been implemented successfully for modeling Burulus Lake for the baseline case (Awad, 2011) and that model will be used in this paper to study the effect of the proposed four options.

Iber has three main computational modules: a hydrodynamic module, a turbulence module and a sediment transport module. All of them work in a finite volume non-structured mesh made up of triangle or quadrilateral elements. In the hydrodynamic module, which constitutes the base of Iber, the depth averaged two-dimensional shallow water equations are solved (2D Saint-Venant Equations). The turbulent module allows including turbulent stresses in the hydrodynamic calculation, in this way allowing its use for different turbulent models for shallow waters at different degrees of complexity. The most recent version of Iber also includes a parabolic model, a mixing length model and a k-ε model. The sediment transport module solves the bedload and the turbulent suspended load transport equations, based on the sediment mass balance evolution at the bed.

2 GROUP OF WELLS

Digging group of wells at the Southern zone of the Lake for pumping saline water is proposed in order to increase the salinity. Fresh water extends from ground surface to level (- 30) meters below the ground surface. Salty water extends from level (-30) to level (-190) m below the ground surface, underneath this the Delta confines aquifer which extends with depth 800 m of fresh water (Elshinnawy, 2003-A). The salinity of seawater is 36,000 ppm and in drains is 600 ppm, whereas medium salinity in the lake is 6600 ppm (Elshinnawy, 2003-

B). By proposing using wells of 80 m depth and 45 cm in diameter and in order to pump 2 billion m^3/year, the number of wells is estimated at 8500 wells (Awad, 2013). Capital cost of that solution will reach 1,300 million EGP, while the operational annual cost had a figure of 2,540 million EGP. (Awad, 2013).

3 DREDGING THE LAKE BOTTOM

Increasing Burulus Lake depth by 1 m has been studied and detailed calculations are presented by Awad (2013) based on actual Bathymetric leveling of lake (CoRI, 2005). Lake area including islands equals 432.60 km^2, the total area of islands = 48.35 km^2, and net lake area without islands (i.e., dredged area) = 384.25km^2. Capital cost of that proposal was estimated at 7,685 million EGP. Figure 2 shows the location of islands inside the lake.

4 NEW STRAIT CONSTRUCTION

The proposed new strait between the Mediterranean Sea and the Lake is located 29 km at the West side of the existing strait as shown in Figure 3. Two straits widths have been studied and their construction costs have been estimated by Awad (2013). The total strait length is 2815 m and strait channel depth equals 3 m. Marine protection works and cost of the bridge over the strait had also been analyzed. For both straits widths of 100 m and 200 m, capital costs were 91.16 and 115.18 million EGP, respectively.

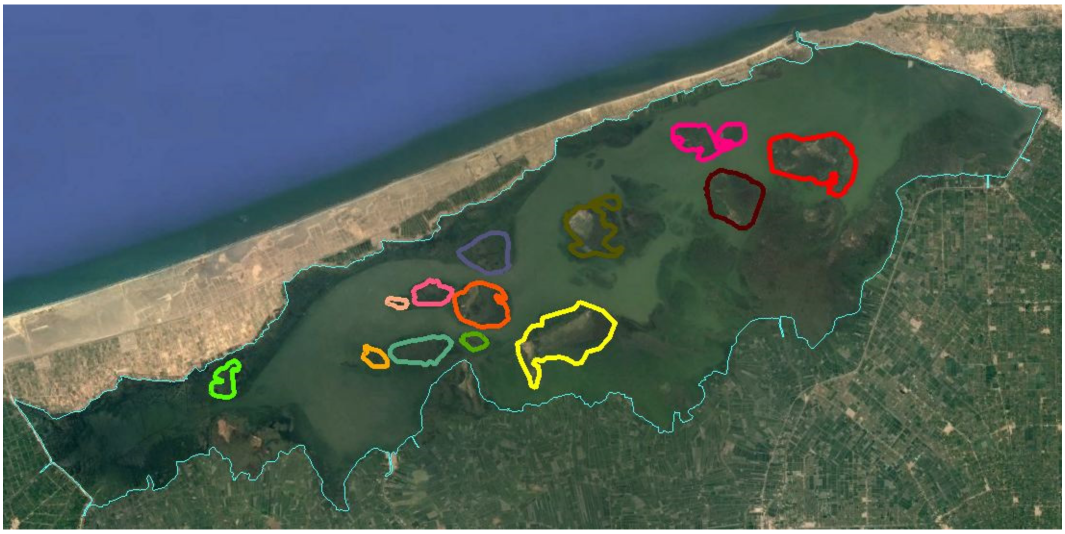

Figure 2. Islands in Burulus lake

Figure 3. Location of the proposed new strait

5 DIVERSION OF DRAINS

Two paths of the drains have been analyzed by Awad (2013). The Eastern and Western drains diversion routes are shown in Figures 4 and 5, respectively. Economical analysis includes the cost of excavation and filling, construction of four bridges, land allocation, and construction of two pumping stations. Capital cost estimated for that option was 669.64 million EGP, while the operation cost was 83.02 million EGP/year (Awad, 2013).

Figure 4. Eastern path of drains diversion to the Sea directly

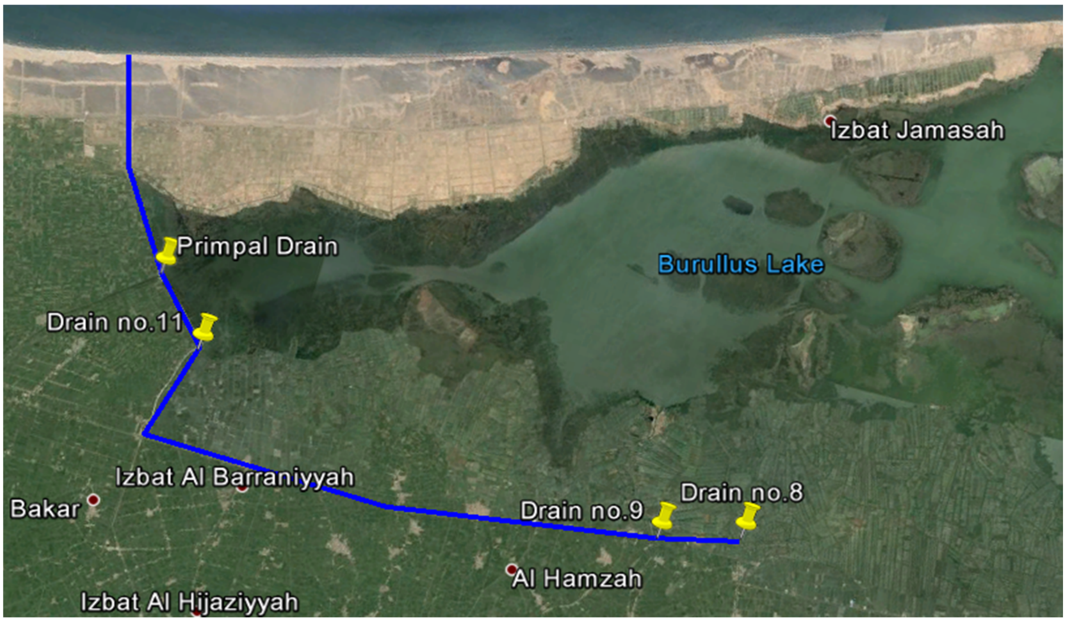

Figure 5. Western path of drains diversion to the Sea directly

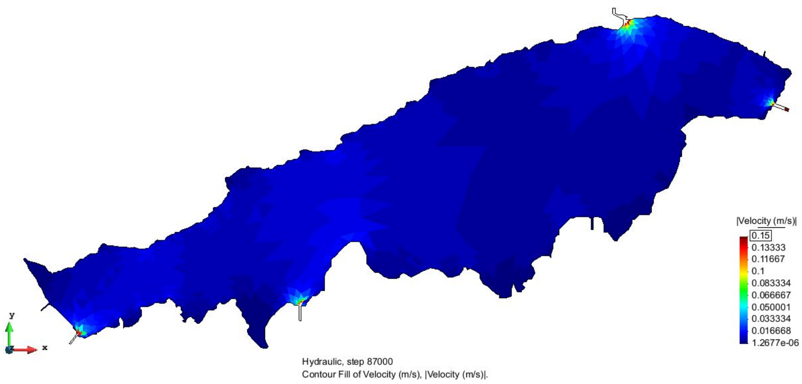

Figure 6. Baseline case (January – LWL)

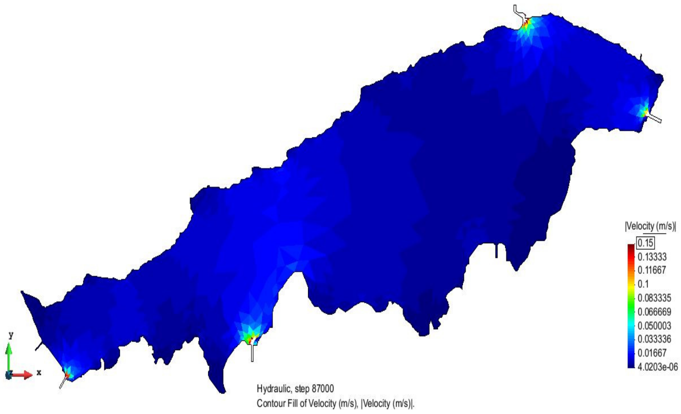

Figure 7. Using group of wells

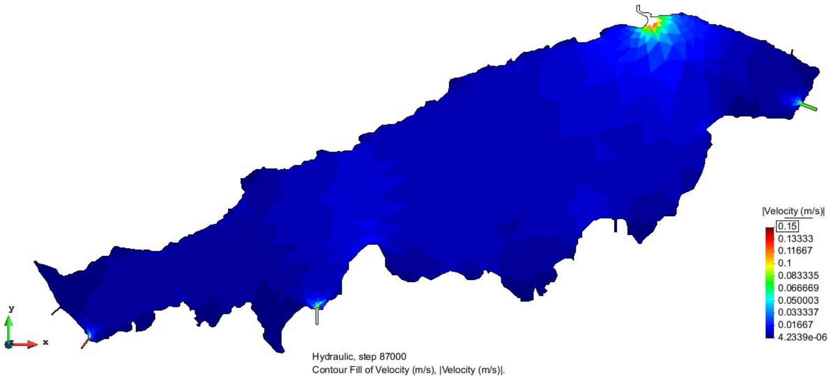

Figure 8. Increasing depth (JanuaryLWL)

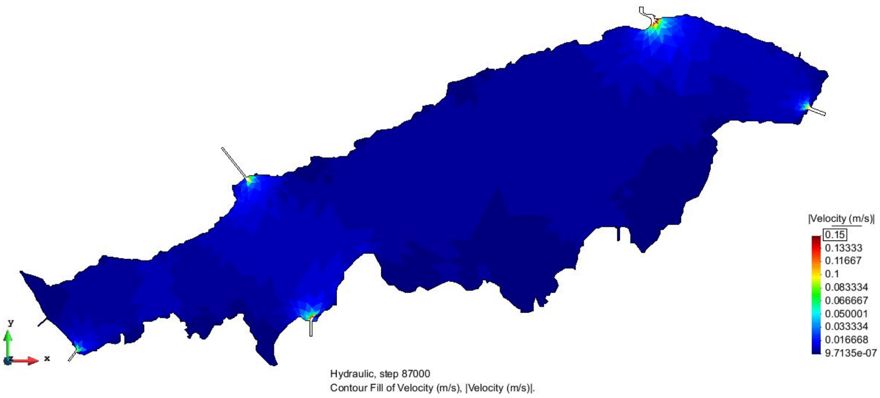

Figure 9. New Strait with 100 m width lJanuary-LWL)

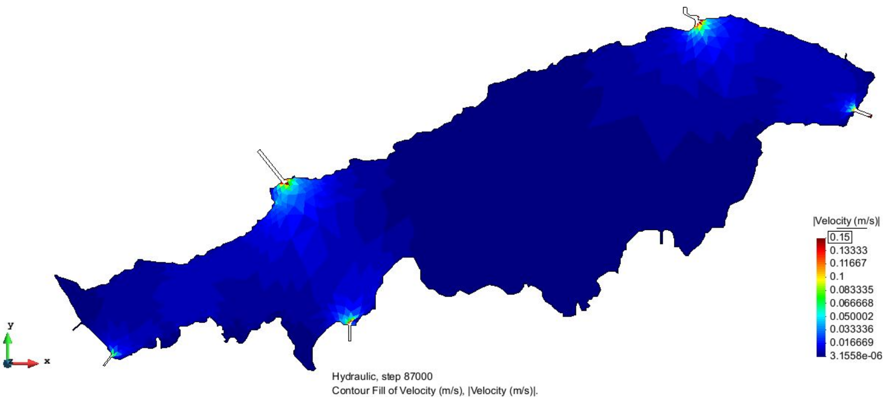

Figure 10. New strait with 200 m width (January – LWL)

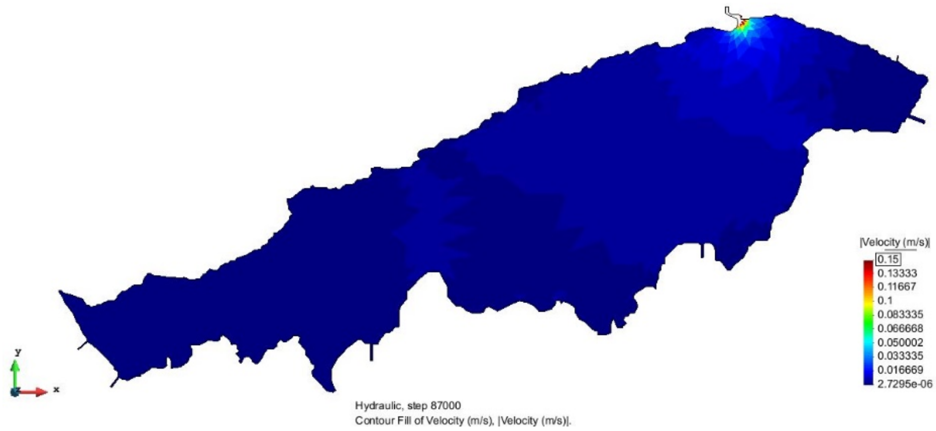

Figure11. Diversion of drains (January – LWL)

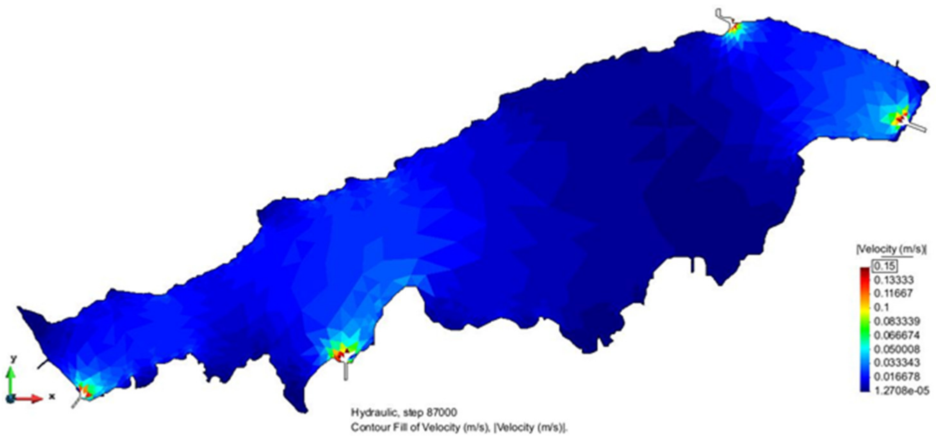

Figure 12. Baseline case (July –HWL)

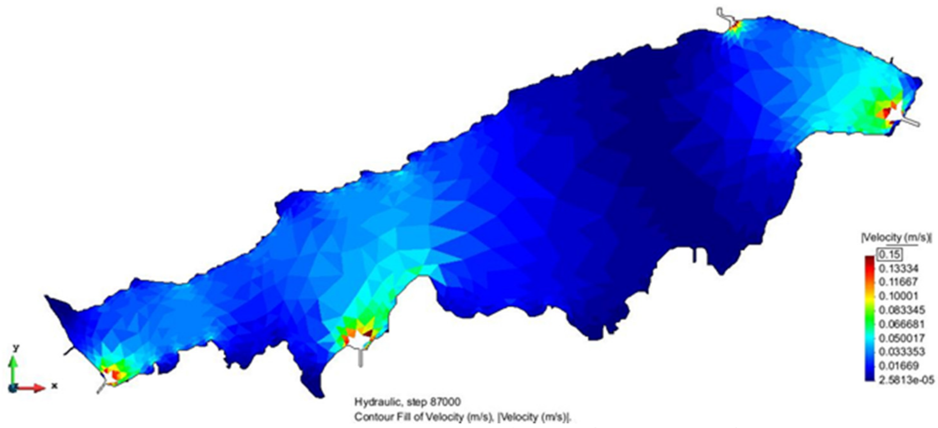

Figure 13. Using group of wells (July – HWL)

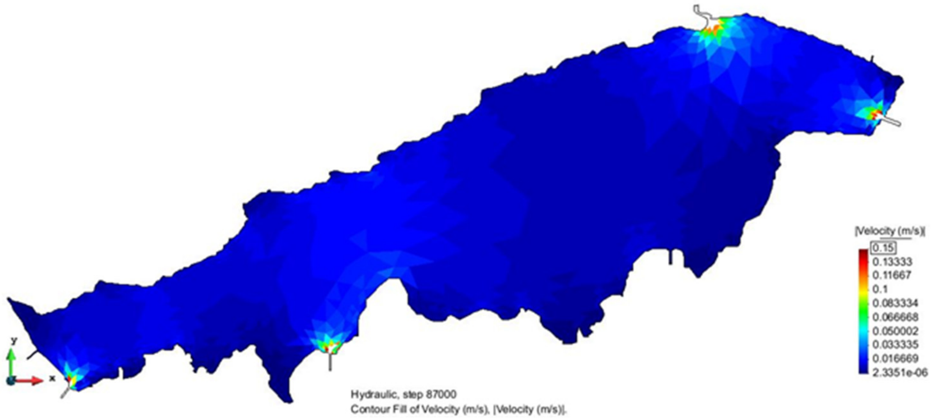

Figure 14. Increasing depth (July –HWL)

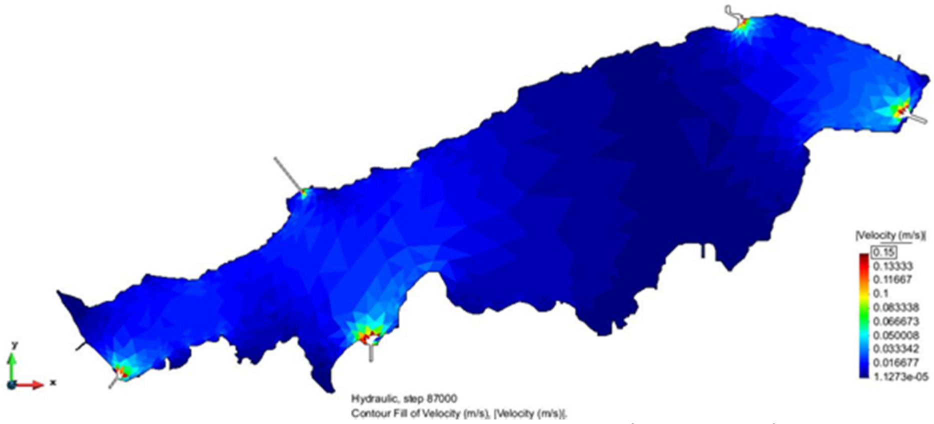

Figure 15. New strait with 100 m width (July – HWL)

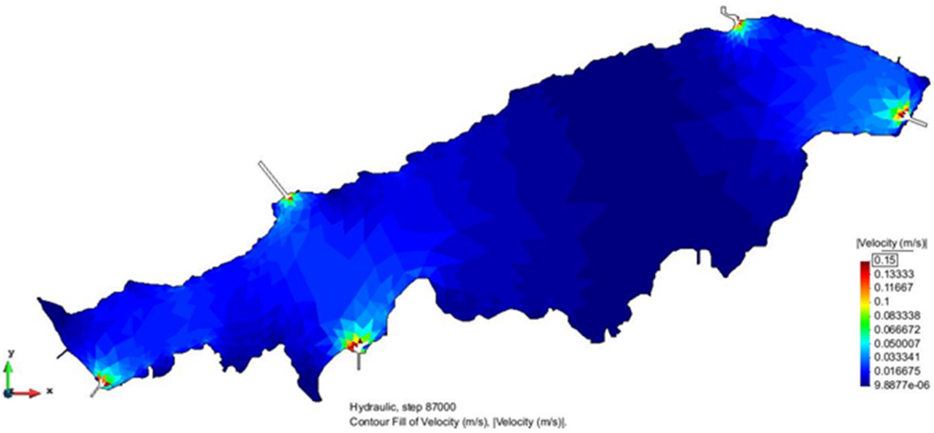

Figure 16. New strait with 200 m width (July – HWL)

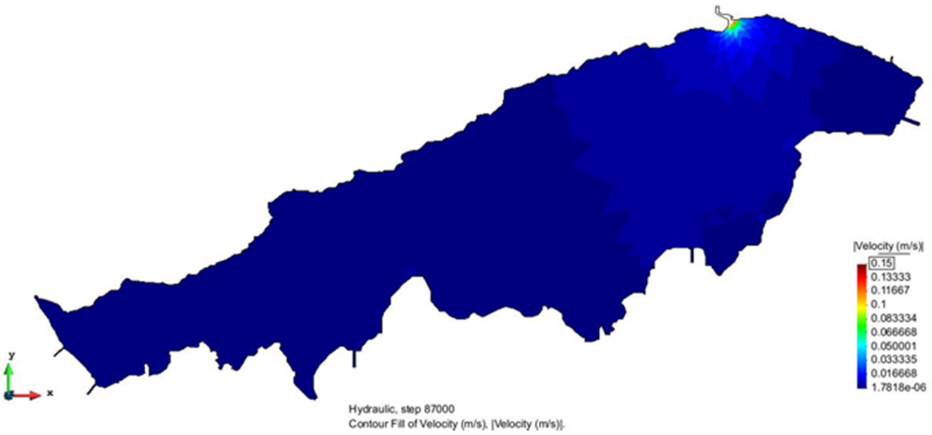

Figure 17. Diversion of drains (July – HWL)

6 HYDRAULIC MODELING AND RESULTS

Figures 6 to 11 show the velocity distribution of all proposed options in January for the case of low tide, while Figures 12 to 17 have been plotted for the case of high tide in July. All 2D hydraulic models had been developed using Iber software as described in Awad (2011). Table 2 shows a summary of all main results and comparison of each proposal capital and annual costs. Construction of a new strait with 100 m width is the option with the minimum investment and strait velocity could increase by 20% in January allowing better water circulation. Increasing lake water depth has the most capital investment requirements which are more than 80 times the construction of a new strait. Despite clear benefits for implementing that option but its capital investment could be a main constraint for its feasibility. Diversion of drains to the sea will improve the water quality of the lake but its capital investment could also present a main constraint. Digging group of wells at the southern part of lake seems to be infeasible due to both high operational and capital costs.

Table 2. Velocities, capital cost and annual cost for all proposals

Simulation Case	Sea Low Water Level (January)		Sea High Water Level (July)		Total Cost	
	Strait Velocity (m/sec)	Min Velocity (m/sec)	Strait Velocity (m/sec)	min Velocity (m/sec)	Capital cost million EGP	Operating cost million EGP/year
Baseline Case	0.501	0.017	0.612	0.033	NA	NA
Group of wells	0.610	0.041	0.800	0.460	1,300	2,540
Dredging The lake	0.775	0.035	0.969	0.039	7,685	NA
New Strait 100 m	0.593	0.036	0.622	0.048	92	NA
New Strait 200 m	0.601	0.039	0.625	0.048	115	NA
Drains Diversion	0.489	0.016	0.551	0.019	670	84

7 CONCLUSIONS

As Burulus Lake suffers from serious environmental problems, this paper presents an evaluation and assessing of engineering measures to minimize the existing impact. The study presents four options for reducing pollution: (i) Digging group of wells, (ii) Dredging the lake Bottom, (iii) Construction of a new strait, and (iv) Diversion of drains to the Mediterranean Sea directly. Hydraulic analysis has been performed with the assistance of Iber hydraulic modeling software package. Based on that analysis, in addition to economical analysis, construction of a new strait located 29 km at the western part from the existing strait seems to be the most feasible suggestion. Total construction cost of that strait varies between 92 and 116 million EGP based on its width. Diversion of drains is ranked as the second feasible option and its main feasibility constraint is its required capital investment. Both options of increasing lake depth and digging group of wells at the southern zone are considered infeasible options in current time due to their highly needed capital cost investment and/or their operational costs. It is expected that with the outcomes of this research if it will be implemented that quality and quantity of marine production from Burulus Lake will be improved, existing environmental problems will be reduced, and local society will gain additional financial benefits.

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JINGTANG PORT SITE SELECTION AND PLANNING

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ABSTRACT

The present paper introduces the site selection and planning study for the Jingtang Port in Tangshan, which has rapidly grown from a local minor port into one of the key ports along the coast of China. Starting from the largest dredged-in harbor basin, then in China, the harbor has undergone continuous development and improvement through planning, design and construction while overcoming key technical problems such as layout of dredged-in basin, structure of underground diaphragm sheet pile walling, and the protection of approach channel along silty seabed. The planning of the harbor has given full attention to the advantages but avoided the disadvantages of the natural conditions to the maximum extent, thus having led to the successful construction of a large general port. All three aspects of the growth of the throughput of the port, the categories of cargoes and the sizes of ships that can be handled at the port have justified the feasibility of the planning.

Keywords: Port planning; dredged-in harbor basin; diaphragm walling sheet pile; sand dike.

1 INTRODUCTION

Jingtang Port was planned and designed in the 1980's and the construction was officially commenced in 1989 and was open to calling ships on the 28th of August 1991. By the end of 2008, there were 28 berths constructed in the harbor, with the largest one capable of accommodating ships up to 100,000dwt, and with the total berth line in length of 6633.8m. In 2008, the port handled 76.5 million tons of cargoes. The history of the port development in two decades has proven that the port should be developed in association with the requirement for social and economic development in the hinterland, and the port planning should be based on reasonable utilization of natural resources and be appropriately advanced in time.

The progress of the port from a local minor port to a major port along the coast has been led by a series of comprehensive and careful planning and studies. Starting from the largest dredged-in harbor basin, then in China, the harbor has undergone continuous development and improvement through planning, design and construction while overcoming key technical problems such as layout of dredged-in basin, structure of underground diaphragm sheet pile walling, and the protection of approach channel along silty seabed. The planning of the port has given full play to the advantages but avoided to the maximum extent the disadvantages of the natural conditions, thus having led to the successful construction of a large general port. The growth of the throughput of the port, the categories of cargoes and the sizes of ships that can be handled at the port have all justified the feasibility of the planning.

2 SITE SELECTION

Jingtang Port was originally named as Wangtan Port, as it was located at Wangtan Village of Laoting County, 80km to the southeast of Tangshan of Hebei Province, on the north coast of Bohai Bay, between two estuaries of Luanhe River and Daqinghe River. It is 119km to Qinhuangdao Port on the east and 130km to Tianjin Port on the west. In the 1980's, the shipping cargoes from or to the eastern Hebei Province and Tangshan area were mainly handled at Tianjin Port and Qinhuangdao Port, which were so busy that demurrage of ships and cargoes happened very frequently. From a strategic point of view of zonal economic development, the government of Tangshan City decided to build a port in its own territory to promote the local trade import and export. The selection of the site of Jingtang Port was based on the factors of the requirement of the hinterland economy, the potential in leading the zonal development, and the local natural conditions.

2.1 Requirement from the zonal economy

Tangshan is one of the major industrial cities along China's coast and was then the most developed economy zone in Hebei Province, with its foreign trade value taking up one third of that of the whole province. Many large and moderate enterprises such as Kailuan Coal Mine, Tangshan Steel, Eastern Hebei Cement Plant, Daqinghe Salt Yard and others were located in the hinterland of the port, which were busy handling the cargoes of coal, steel, cement, and raw salt, in large quantities. According to the forecast for cargo traffic in 1987, the cargoes from the direct hinterland of Tangshan city itself in the year of 2000 would reach 4.31

million tons. Therefore, it is necessary and urgent to construct the local port to meet the requirement for the domestic trade.

On the other hand, as a general trend of port development, especially from the emerging port cities, it can be seen that the port, as the infrastructure facility for trading and shipping, has a very important role in leading the urban construction and zonal economy development. The construction of port at the site of Wangtan would give impetus to the economic development in Tangshan City, and the port and its vicinities would gradually develop into a development zone of port economy. The actual fact of the port development in twenty years has proven that it is true.

2.2 Natural conditions of the port site

2.2.1 Topographical conditions

Jingtang port is located in the middle of the Luanhe River Delta. From the 1970's, many dams and reservoirs have been constructed on the upper stream of Luanhe River, causing 70% of the river water regulated, with great deduction of sediment brought down into the sea. Such phenomenon has a great impact on the coast evolution, which features a general regression of coast line in landward direction.

Judging from topographical conditions, the coast line from the Luanhe Estuary on the north to the Daqinghe River Estuary on the south can be divided into four sections as follows:

(1) The delta front edge at Luanhe River Estuary – Due to sharp reduction of sediment source, and shortage in sand supply, the front edge of the delta is regressing annually as a result of the corrosion from wave scouring. This section of shoreline is very unstable for the site of port construction;
(2) The section of shoreline from the delta to Hulinkou on southwest – In this section of shoreline, the developed sand bars and lagoons are present and the shoreline is located at the downstream of sediment transport from the Luanhe River Delta. It is also unsuitable for the port construction;
(3) The section of shoreline from Hulinkou to the eastern end of Dawanggang – a section of shoreline in length of about 6 km. Here, the slope of seabed is steep, and there is no sandbars and lagoons in the shoreline area. The deposition rate of the sediment is nearly zero, and the shoreline is slightly eroded. The sediment transport is mainly driven by wave actions, moving in the direction from NE to SW, in insignificant quantities. This section of shoreline is comparatively stable, and suitable for the construction of port;
(4) The section of shoreline from the eastern end of Dawanggang to the estuary of Daqinghe River – The river is greatly affected by the tidal actions, and there are many delta beaches, sandbars and tidal channels at the estuary of the river, therefore the area is not suitable for the construction of port.

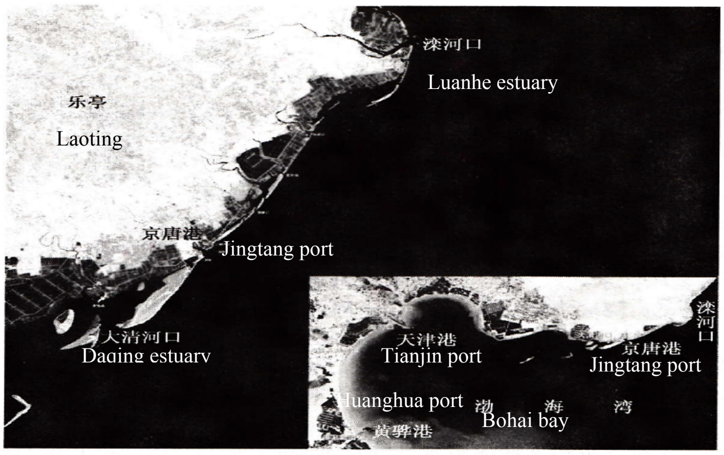

Figure 1. Shoreline of Jingtang Port.

From the analysis of topographical features of the section of shoreline from Hulinkou to the eastern end of Dawanggang, it is found that the shoreline near Wangtan Village is stable and suitable for the construction of port. The area is free from impact of fault band near the Luanhe River Delta, with wide flat land behind the shoreline, with ground level at about 2.0m, which is easy to be excavated and filled. Therefore, it is concluded that the shoreline at Wangtan is an ideal choice for the port construction. For details of the shoreline from the estuary of Luanhe River to the estuary of Daqinghe River, please refer to Figure 1.

2.2.2 Oceanography and meteorology

In the area of Jingtang Port, wind from north prevails in the winter, and wind from south is prevalent in the summer, with strong characteristics of monsoons. From the statistics from June 1993 to May 1995, it is seen that the prevailing wind is from SSW and the next prevailing wind is from WSW, while the strong wind is from NE and the next strong wind is from ENE.

The tide at the site is of irregular semidiurnal tide, with the following characteristic values:

- Highest high tide: 2.91m
- Lowest low tide: -1.39m
- Design high water level: 2.02m
- Design low water level: 0.27m
- Extremely high water level: 3.62m
- Extremely low water level: -1.53m

High waves in the water area of Jingtang port mainly come from the directions of ENE and EN, with wave heights higher in spring and summer than in autumn and winter. The prevailing wave is from SE direction and the next prevailing wave is from ESE; the strong wave and next strong wave are from ENE and NE respectively. The wave parameters for design high water level with 50-year return period are shown in the following Table 1.

Table 1. Design wave parameters at Jingtang Port.

Main wave directions	**$H_{1\%}$ (m)**	**$H_{1/10}$ (m)**	**T (s)**
ENE - ESE	4.9	4.22	7.6
SE - S	4.5	3.87	7.4

The currents in the sea of Tangshan area are mainly tidal currents that obviously reciprocate in directions parallel with the shore, flooding in SW direction and ebbing in NE direction. The velocity of near shore currents is smaller than that of deep water offshore. The velocities are distributed along the vertical line in the pattern that the velocity decreases with the water depth, with the largest value at the surface and the smallest at the bottom of the water. However, when current with maximum velocity occurs, the velocities at surface and at bottom are basically the same. The velocity of current at spring tide is remarkably greater than that at neap tide.

2.2.3 Geology

The seabed is overburdened by a fine sand layer in thickness of 1 to 2 meters. The under lying layers are silty loam, loam, sand, clay and hard sand (with SPT N>50).

From the analysis of the natural conditions, it is concluded that the shoreline at Wangtan is suitable for the construction of port.

3 PORT PLANNING

3.1 Wangtan port planning and initial stage construction

Jingtang Port was started from Wangtan Port, a local small port as it was defined. According to the Master Plan of Wangtan Port 1987, it was forecast that the throughput of the port would reach 4.31 million tons in the year of 2000. The port was planned to finally accommodate ships up to a maximum size of 20,000 DWT, and initially constructed with two berths for ships up to 5,000dwt (with berth structure designed for ships up to 10,000dwt), with throughput capacity of 880,000 tons per year.

The port site was selected at the beach near Wangtan Village. Two port layouts were compared and the dredged-in layout in comparison with the constructed-out layout can save the investment by 30 percent in the initial stage construction. The ensuing works of this layout are also economic and cost effective. Therefore, it is recommended in the port plan that dredged-in type of port layout is to be used. For details, refer to Figure 2.

The initial port layout takes the shape of the letter F, arranged with two rectangular harbor basins. It was planned that 8 berths for ships from 5000dwt to 15000dwt would be constructed in No. 1 Basin, with total annual throughput capacity of 4 million tons. The approach channel was designed for ships of 5,000dwt at the initial stage, in total length of 2.6km, with bottom width of 7.3m and water depth of 7.3m. Finally, the channel would be deepened by dredging to allow for navigation by ships of 20,000dwt. The sand dike in total length of 2450m was constructed with the east end located at a location with water depth of -5.0m and with the west end at water depth of -3.0m. As the initial stage of port was constructed in limited time with tight budget, without the backing up from sediment transport experiment, taking into account the complexity of the sediment transport along silty beach, a philosophy of “constructing, observing, while adjusting the construction plan, in pursuit for development” was then proposed.

The initial plan of Wangtan Port is the first step of the Jingtang Port development, having played the important leading function for the expansion of No. 1 Basin, No. 2 basin, the approach channel and the sand dike. Twenty years of the port development has proven the dredged-in layout and the port site selection was correct and successful.

3.2 Interim adjustment of the port master plan

Jingtang port was constructed starting from 1989, and its first berth was completed and open to ships in 1991. In July 1993, the port formed a joint venture with Beijing to greatly expand the development space for the port. The port's hinterland has extended to cover Beijing, the northern and middle regions of Hebei, Shanxi, Shaanxi, Ningxia, Inner Mongolia and other areas. The hinterland has good conditions for transportation, with well established networks of highways and railways, having supported and promoted the development of the port. The traffic forecast made in 1994 estimated that the cargoes handled through the port would reach 12 million tons in 2000, 22.1 million tons in 2010, and 35.8 million tons in 2020. The nature of the port would be changed, and it would be no longer the local minor port but be promoted to the modernized key port in the Bohai Bay Port Cluster with multiple functions, handling fuels, bulk cargoes, containers and many other categories of cargoes. In order to adapt to the development trend, the first major adjustment was made in the port master plan in 1994.

The adjusted master plan covers a total shoreline of about 13km, starting from Xiaohezi on the west, ending at a location 4km to the east of the second drainage canal. The existing two harbor basins would be used for commercial ships. The third basin, extended 3km westward by dredging from the vicinity of the second basin, would be used for serving the port neighboring processing industries and logistics entities. The forth basin in total length of about 5km, would be formed by dredging the land on the north and filling the artificial island on the south, and would be used for handling bulk cargoes in large quantities and serving the industrial park. The sand embankment and the lagoon on the west of the West Sand Dike would be the waterfront area for residence and tourism.

The maximum size of ships calling at the port was increased to 50,000dwt. The approach channel would be widened and deepened to allow for two-way navigation by ships up to 20,000dwt and one-way navigation by ships up to 50,000dwt.

The first and second harbor basins would be developed by 2020, with bulk cargo berths constructed in Basin 1, and container berths, general cargo berths and passenger terminals constructed in Basin 2. The first batch of 15 berths in Basin 1 and Basin 2 would be constructed by 2000, increasing the throughput capacity of the port to 12mtpa (million tons per annum). By 2010, 20 berths would be completed to increase the port throughput capacity to 22.1mtpa. By 2020, construction of 30 berths in total would be completed in Basin 1 and Basin 2, increasing the port throughput capacity to 35.8mtpa. For general layout of master plan of 1994, please refer to Figure 3.

3.3 Re-adjustment of the port master plan

Since the port was put into operation in 1992, it has been developing at an accelerating speed, with its throughput growing from 0.45mtpa in1993 to 33.2mtpa in 2005. Especially since 1998, the port development has run on a fast drive, with average growth in throughput at 30.6% for 5 consecutive years, having played a great roll in promotion of the economic development in Tangshan area and the port hinterland.

In 2006, Caofeidian Economic Zone was initiated for development. For rational utilization of resources of shoreline and land, Tangshan City government prepared Tangshan Port Master Plan, requiring definition of functions of Jingtang Port and Caofeidian Port, both under Tangshan Port Authority. On the other hand, the construction of Dawangtan power plant has constrained the extension of Basin 3 to the west. Owing to these reasons, it is necessary to readjust the port master plan. The new master plan covers an area along a shoreline of 12km starting from Hulinxinhe River Estuary on the west to the east boundary of the development area.

The widths of existing Basin 1 and Basin 2 are respectively 404m and 431m. Basin 3 is 700m wide and 150m long, with enough space for container carriers up to 30,000dwt to maneuver and navigate in and out of the harbor basin. The turning circle in diameter of 600m for 50,000dwt container carriers is arranged at the junction part between Basin 2 and Basin 3. Basin 4 is 1200m wide and 6000m long, capable of allowing ships up to 100,000dwt to freely enter and exit the basin even when berths are being constructed on the South Quay. Basin 5 will provide berths for handling of liquid chemical products; it is 700m wide and about 1700m long, meeting the requirement for ships of 20,000dwt to 50,000dwt to access and turn in the basin. A turning circle in diameter of 1.5 times the length of design ship is arranged near the shore on the west side of the approach channel but not in the channel. The planned port land area is about 40km^2 and water area is about 12km^2. For details of the Jingtang Port Layout adjusted in 2006, please refer to Figure 4.

To meet the requirement for economic development of the region and adapt the port to the ever-increasing sizes of the calling ships, the port master plan is incessantly adjusted for expansion works. In 2009, a new round of modification of the port master plan was made as shown Figure 5.

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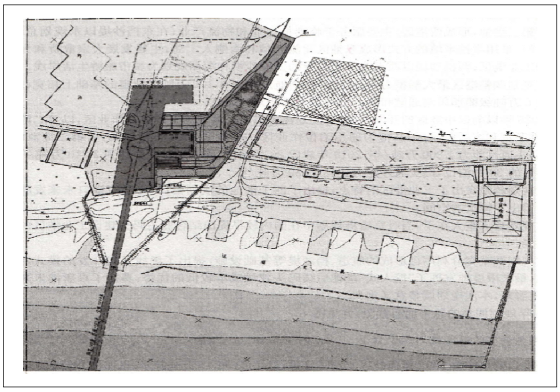

Figure 2. Planning of Wangtan Port in 1987.

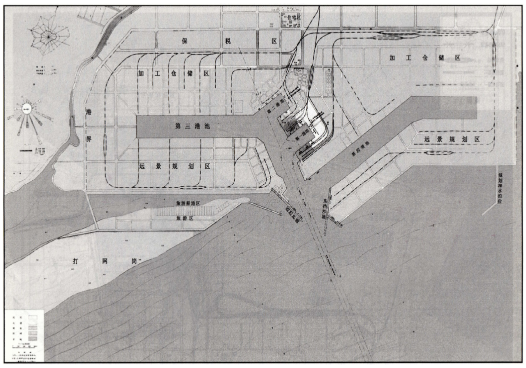

Figure 3. Plan of Jingtang Port, 1994.

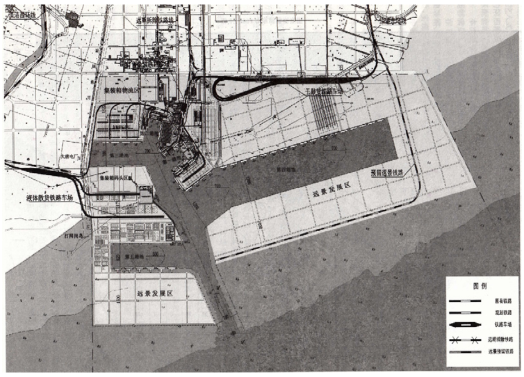

Figure 4. Plan of Jingtang Port, 2006.

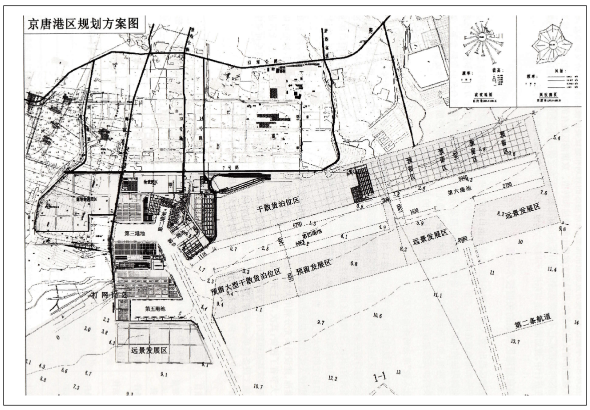

Figure 5. Adjusted Plan of Jingtang Port, 2009.

4 CRITICAL TECHNICAL ISSUES WITH IMPACTS ON THE PORT PLANNING

Jingtang Port has been developed successfully and rapidly due to its layout design of dredged in-shore harbor basin. The dredged-in basin, with the berths built in shore, has avoided the disadvantages of straight shore lines that cannot provide enough sheltering conditions. The dredged materials from the basin can also be used in filling up the reclaimed land area. The comparison between layout options has proven that the dredged-in harbor basin layout is the most cost effective and feasible plan. However, to construct the dredged-in basin, the construction of sheet piled berth with underground diaphragm walling is the prerequisite condition, whereas the study on sediment transport along silty shore and the research on the techniques for construction of sand dike and the channel are the key to guaranteeing the successful operation of the constructed port facility.

4.1 Layout of Dredged-in harbor basin

In the very beginning when the port site was selected, the dredged-in-shore and built-on-shore layout options were compared in detail. The disadvantages of built-on-shore layout are very obvious. For one reason, the shore line of Wangtan is very straight, and the berths need to be sheltered by a long breakwater, which will still be very costly even if it were to be constructed in stages. For another reason, the shore area of Wangtan is low in level, close to the ground water level, the backup land area behind the berths will be filled up with tremendous quantities of soils. Additionally, with the local construction capability, the built-on-shore port facility will require long construction time and high cost.

The dredged-in option has just shown the obvious advantages the other way round. Firstly, the berths are well sheltered in the dredged-in harbor. The sand dike is mainly used for stopping sediment transport and can be built at basic standard to save the cost. The dredged-in operation will generate large quantities of dredged materials that can be used as filling materials for the reclaimed land, thus solving the problem of shortage of filling materials. In addition, dredged-in harbor can be constructed on land operation basis with simple construction plant, with the construction operation unaffected by wind and wave actions from the sea, so that effective construction operation time is increased and the total construction time is shortened.

The two options of layout for the Initial Stage of Port Construction Work were compared as shown in the following Table 2.

Table 2. Comparison between port layouts.

Layout	Dredge-in-shore	Built-on-shore
Major work quantities	Berth 320m，Sand dike 2 450m，filling 3.22million m^3，dredging 19.38 million m^3	Berth 360m，Breakwater 1 930m，filling 1.37 million m^3，dredging 12.80 million m^3
Capex	9 9.93 million yuan	13 2.74 million yuan
Sheltering condition	Excellent	Poor
Construction flexibility	The sand dike can be constructed in stages and be modified in the process of construction while the construction is being monitored. The Capex can be invested in phases.	The breakwater must be built once for all, with large value of initial investment
Construction conditions	Land based operation unaffected by sea climate, with less construction cost.	Large quantities of on water construction works, requiring large quantity of works for transportation of precast members, construction operations affected by sea states, with higher construction cost.
Source of filling materials	Short haulage distance	Long haulage distance, and high transport cost
Land area	510,000m^2	150,000m^2

The above table has shown that the dredged-in layout has the advantages of low cost, better sheltered operation conditions, convenient construction, available filling material, flexible sand dike construction, but it occupies more land area. However, the marginal shore land is generally of saline and alkali soil, so that no farm land will be used. When funds are short in the initial stage of the port construction, the dredged-in layout is the best choice from all aspects. The dredged-in layout of Jingtang.

4.2 Sheet piled berth with underground diaphragm walling

The geological conditions of Wangtan Port are suitable for construction of a number of types of berth structures, such as gravity structure, sheet piled structure, deck structure on piles etc. However, it is the sheet piled structure with underground diaphragm front wall that can give full play to the advantages of the dredged-in layout. The berth structure with diaphragm front wall with high rigidity and good integrity is suitable for large berth in deep water. It consists of front wall, rear anchor wall, steel tie rod, breast wall and other members. It is constructed by forming the slot with drilling machine operated on land, and casting the reinforced concrete in the slot to form the front wall and the rear wall, which are linked by tie rods. When the front wall is constructed, it can serve as retaining structure for dredging in front of the front wall, and also as the berth face when the harbor basin is formed. Thus, it has avoided the dredging and filling in large quantities as required by the construction of other types of berth structures.

The diaphragm front wall was used as the quay wall for 15,000dwt ships for the first time in China at the time. The successful application of the structure has laid good foundation for the development of the port. Recent years have seen the construction of the berth structure with single diaphragm wall for ships of 35,000dwt in Jingtang Port, the upgrading of berth for ship of 20,000dwt to the berth for 50,000dwt by using semi-curtain piled structure, and the innovative construction of berths for ships of 70,000dwt to 100,000dwt with total curtain piles and separate load-relieving diaphragm wall. The experiences gained in construction of Jingtang Port has been applied in the construction of Caofeidian Port. The structure of diaphragm front wall berth is shown in Figure 6.

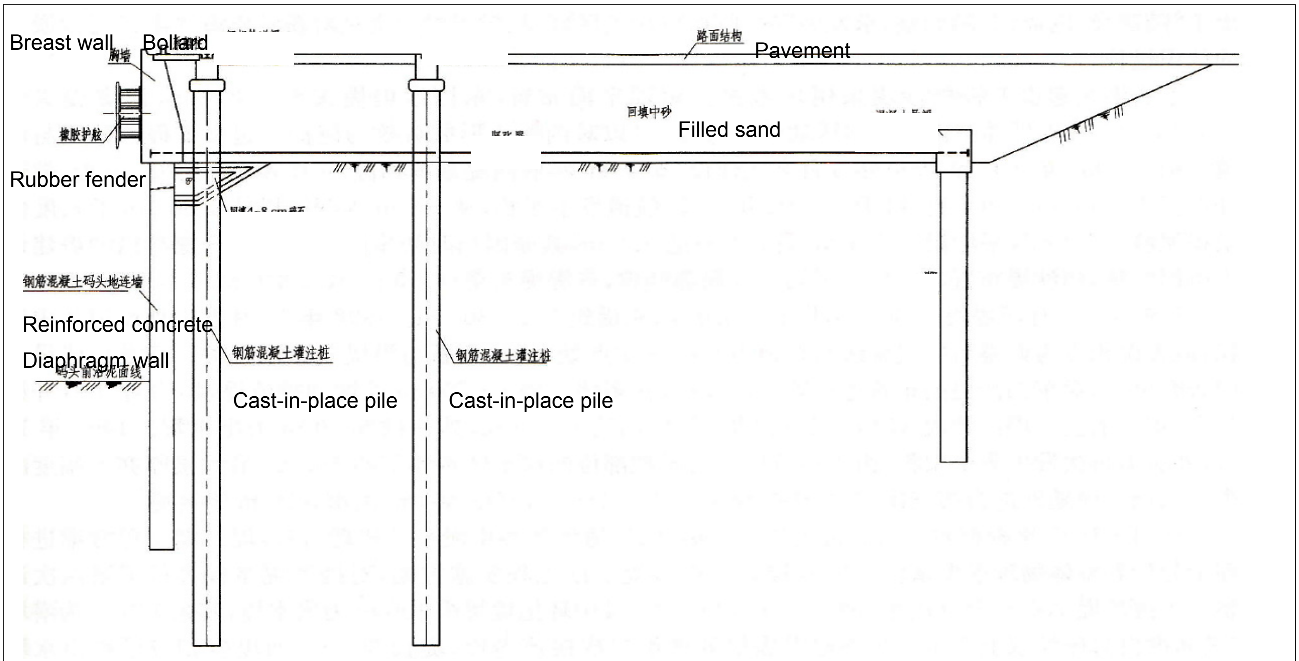

Figure 6. Berth structure on sheet piled berth with diaphragm walling sheet piles.

4.3 Approach channel in silty seabed and sand dike

Jingtang Port is located on silty sand beach with flat slope, with wide sediment active band where the seabed load is prone to being disturbed. The construction of a dredged-in port in such circumstances relies on the successful construction of the approach channel and the sand dike.

4.3.1 Features of sediment transport in waters in the vicinity of the port

The sediment in the sea waters of Jingtang Port come from two sources, one is the supply from the upper stream of current in the vicinity of Luanhe River Estuary, and the other is the supply from the erosion of the local shores. Sediment movement is remarkable along the coast close to the port site, and is especially severe at the wave breaking band near the shore during high waves. According to the results of analysis on the dynamic conditions of wind generated waves in the sea area of Jingtang Port, the net sediment transportation along the shore close to the port is along the direction of SW-NE. Two years' observation has led to the calculation with the result showing the total sediment transported in the period amounted to 380,000m^2 to 620,000m^2, at the rate of 200,000 to 400,000m^3 per year.

The particle size of seabed materials at the beach in Jingtang Port area is that between fine sand and silt. According to the analysis on samples of seabed materials, at the surface of seabed is a layer of fine sand and silty sand in thickness of 1m to 2m. The underlying layer is silty loam with particle size in the trend of turning smaller as it goes toward the open sea. The deposits in the wave breaking band within 1km from the shore (between contour lines of 0.0m and -3.0m) are fine sand mainly in particle size of 0.1 to 0.2mm. The deposits 1km to 3km offshore are finer sand in particle size of 0.06mm to 0.09mm. The deposits 3km offshore (beyond contour line of -8m) are mainly clayey silt. The deposits in the channel are of mean particle size of 0.06mm to 0.09mm.

The water depth at which the beach sediment is disturbed to start moving reflects the limit of beach evolution. In general, the sediment disturbance under wave actions is related to wave height, wave length and the sediment particle size. The sediment disturbance water depth in the port area was calculated with the modified Liu Jiaju formula, with the input of mean particle size of 0.075mm of the deposits beyond the wave breaking band. When the wave height is 1.0m to 2.0m, and the wave length is 35m to 90m, the sediment disturbance water depth is 7.37m to 17.63m. Under the action of normal waves, the sediment on seabed at level of -6m to -10m is disturbed in the port water areas. The water depth, at which the near shore beach sediment is disturbed under the coactions of waves and currents, is deeper than it is when wave dynamic alone is considered.

4.3.2 Construction of sand dike and its effect in stopping the sediment

In the initial work of Jingtang Port construction, the sand dikes were designed as embracing arms on the plan layout, with one short arm and one long arm. The head of east dike is located at the location with water depth of -4.0m, while the head of west dike is at water depth of -3.0m, basically having reached the edge of the active sediment movement band, thus capable of providing protection to the inner channel. In the period from November 1990 to March 1991, sediment siltation occurred in the approach channel with about 190,000 m^3 of muddy sand building up along a section of channel of 1800m. The average siltation thickness was 1.4m and maximum was 4.2m. The cause of the siltation was at first decided to be the non-coordination between the dredging of channel and the construction of the sand dikes. Accordingly, the arrangement of the sand dikes was partially modified for the first time, with the east dike head extended to the water depth of -5.0m, elongating the dike to 1840m length.

Approaching the end of 1992, the west dike was built to the length of 600m, with dike head at location with water depth of -3.0m; the east dike was constructed to the location of 1+300m. In November 1992, another concentrated siltation occurred in the outer channel of the port, and it was determined to be due to the action of current along the dike. Based on conclusion of studies, the port authority decided to adjust the arrangement of the sand dike for the second time, by adding a groin at location 1+500m of the East Dike. The construction of the groin was started in July 1993 and completed by the end of the same year. The groin of 340m length was partly submerged with top level at -2.0m, but the section at the root in length of 50m was out of water. In December 1993, sediment siltation occurred once more in the outer channel. Due to the function of the submerged groin, the siltation section shifted 400m way toward the deep-water area, and the siltation thickness was also reduced to a remarkable extent. Following the siltation event, the third-time adjustment was made on the East Dike, by extending the groin length to 750m, with 300m section out of water, and 450m section submerged.

In the period from 1994 to 1995, analytic studies and physical model simulations were performed for understanding the patterns of sediment movement in the port water area and the mechanism of the concentrated siltation in channel. The study work has led to the proposal of 2nd Stage of the Sand Dike Project, and according to this proposal, the fourth adjustment was made for the arrangement of the sand dikes. The east groin would be made all out of water, and a new embracing dike in total length of 920m (150m out of water, 770m submerged) would be added. The second groin in length of 300m would be built at the root of the embracing dike. Meanwhile, the West Dike would be extended by adding 500m out-of-water dike and 800m submerged dike. For as-built layout of the sand dikes of 2nd Stage Project, please refer to Figure 7.

In the same period of time, the approach channel of Jingtang Port was upgraded from 5000dwt ship grade to 20,000dwt ship grade. The monitoring in the channel has recorded serious siltations in autumn and winter in the initial three years since July 1991 when the port facility was first put into operation. Table 2 shows the siltation in the channel in the period of time from 1992 to 1994. From Table 3, it can be seen that the siltation in the channel is in the trend of reducing from year to year.

By the end of 1998, the upgrading of the channel was completed, with the channel bottom widened to 110m, and the depth dredged to 10.5m. From the maintenance dredging of the channel in March-June 2000 to the pre-dredging scanning on 20 September 2001, no dredging work was done and no disastrous climate was recorded, so the comparison between the maps of surveys on the two occasions can present the representative state of siltation in the channel in a normal year with ordinary sea states. From the distribution of the siltation, it can be seen that siltation seldom occurs in the channel section from 0+100m to the edge of the harbor basin, and in the outer channel beyond 4+250m, but is evenly distributed in the channel section between 0+1 000m and 4+250m, in average thickness of about 0.45m, in total quantity of about 195 000m^3. The maximum thickness of siltation occurred at the location of 2+000m, where the West Dike head is located.

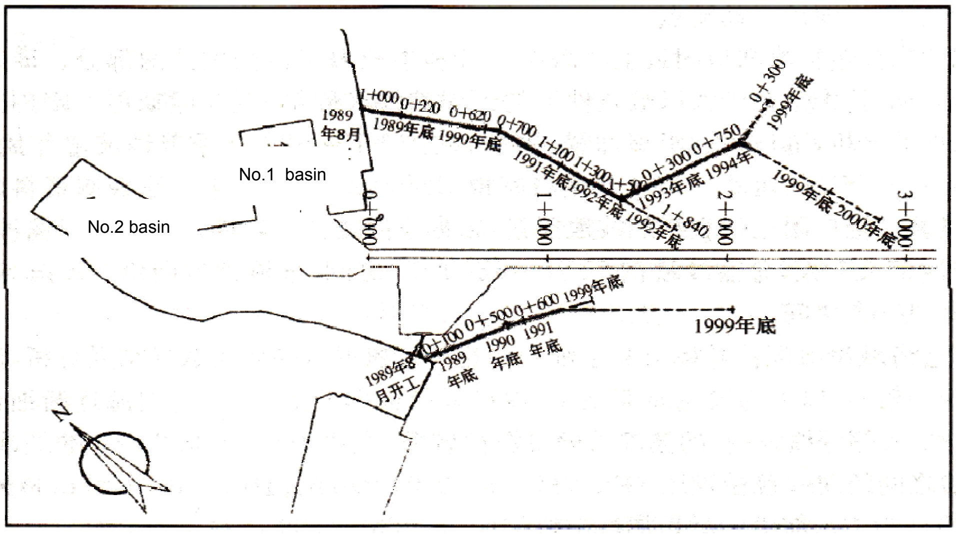

Figure 7. Construction of sand dikes of Jingtang Port.

Table 3. Variation of siltation in the channel of Jingtang Port.

Year	Channel length	Total siltation quantity	Average thickness of siltation	Maximum thickness of siltation	Remarks
1992	3 000 m	470,000m^3	1.56 m	3.70 m	No groin was constructed. East Dike head at -3.5 m water depth. West Dike head at -3.0 m water depth
1993	3 300 m	290,000 m^3	2.50 m	2.50 m	The East and West Dikes of 1st Stage Project were completed in place. 300m submerged groin was added to the East Dike.
1994	3 300 m	180,000 m^3	0.54 m	1.10m	Groin improved on East Dike. 300 m groin raised out of water, 450m submerged groin added.

The above-mentioned siltation pattern indicates that, under normal wave actions, the East Dike has better sheltered the approach channel. The sediment enters the channel mainly through the opening between the West Dike and East Embracing Dike. The built-up materials of the most serious accretion come from the sediment carried by the ebbing tide current that passes around the West Dike head.

5 CONCLUSIONS

From the early 1980's, Jingtang port started the long journey of development from the beach of Wangtan Village through several representative port planning and adjustments. The planning has laid a good foundation of the rapid growth of the port that features cost effectiveness, smooth traffic flow, and adaptability to changes. Through many years of involvement in the planning of the port, the author has acquired a few notions to be shared with colleagues in the port engineering as follows:

(1) A port or a harbor cannot be constructed or planned in isolation with the requirement for development of hinterland economy. Meanwhile, the construction of a port can provide transportation infrastructural conditions for the development of the neighboring areas. The scope of the port development is determined by the total economic value of the region of the port;

(2) A good plan for port development must integrate the advantages of local natural conditions with the port type, scope and requirement, avoiding the disadvantages to the possible extent. In the planning of Jingtang Port, the philosophy of "Composite development" and "Building deep water port in shallow waters" has been expressed. The major engineering problems of shortage in land resources and high cost for construction of large breakwaters in deep waters have been successfully solved. These advantages are especially remarkable in the initial works for construction of the port;

(3) The key technical issues in planning the port must be sufficiently addressed for successful solutions. Great efforts have been made in the studies on dredged-in port layout, the berth structure with diaphragm walling sheet piles and the protection of the approach channel through silty-sand beach;

(4) A port planning cannot be made in isolation with the features of local industries and the magnitude of economic development in the region. Meanwhile, it is also closely related with the types of ships that call at the port and the development of the handling equipment used on the berths. While addressing the present status of the fleet and the level of handling equipment, the port planning must take into account the adaptability and flexibility to the ship size growth, specialization of dedicated berths and

terminals and automation of handling equipment, and reserve the possibilities for development and changes;

(5) The port planning mainly consists of two stages, *i.e.* the port general layout plan and port detail plan. The port detail planning is relatively macroscopic in relation to detail design works, but it is the streamlining of the port general layout plan. To make a good port planning, importance must be attached to the details of port construction, especially to the solution of critical technical problems. It can be said that tackling of technical details is the key to the successful engineering plan;

(6) The planning thought and strategies applied to Jingtang Port shall serve as the major methods being used for the port planning in future, which are recommended by the author. In particular, it is emphasized to carry out a detailed investigation of natural data and the argument for relevant experimental study during the port planning;

(7) Many investigation and study means adopted in the site selection and planning of Jingtang Port can be applied in the planning research of coastal reservoir, including more survey and study on the coastal geology and topographic feature of relevant port site, the investigation study and utilization of meteorology, tide, current and wave, the analysis and simulation test of sediment movement along mealy sand coast. The research achievements on channel, breakwater and berth structure will support the study, planning and design of marine reservoir project to a varying extent. Meanwhile, those strategies apply to similar projects located at common boundary between foreland and ocean.

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STUDY ON ABATEMENT OF SILTATION IN PORT AND CHANNEL BUILT ON SILT-SANDY BEACH

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ABSTRACT

The present paper discusses on effective engineering measures for abatement of siltation in port and channel built on silty sand beach, through analysis and study on coast development, sediment movement and sediment siltation mechanism in the sea area near Jingtang Harbour Area of Tangshan Port. These measures have been proven effective by model tests and application in engineering practice.

Keywords: Jingtang Harbour Area, sediment, sand retaining, offshore breakwater, sand immobilization.

1 BRIEF INTRODUCTION

Silt-sandy beach is a special form of beach that falls between silty beach and sandy beach with very active sediment movement. Under the actions of waves and currents, the sediment on silt-sandy beach is very easily disturbed and settled, rendering much complicated patterns of sediment movement. The problem of sudden siltation and scouring at locations of silt-sandy beach in this area presents a severe challenge to construction of port and development of coast in this area.

Jingtang Harbour District of Tangshan Port is located on the north coast of Bohai Bay between the estuary of Daqing River and the estuary of Luan River. It is Chinas first a large dredged-in port built on typical coast with sand bars and lagoons, also the first one built on silt-sandy beach with very active sediment movement. The construction of Jingtang Harbour was commenced in August 1989 and the port was put into operation and received its first ship in February 1991. The approach channel and Phase 1 sand breakwater were also completed in the same year. The construction of Phase 2 sand breakwater started in 1995. Ever since its establishment, severe siltation in short period of time (sudden siltation) has occurred for three times in the approach channel, respectively in November 1992, December 1993 and October 2003, with the one in 2003 being the most severe event. Ensuing the sudden siltation in port caused by strong storm in 2003, to facilitate the construction of the navigation channel for ships up to 100,000 DWT, study on siltation in port and channel had been started in 2004 in reference with the experiences gained in the Phase 1 Sand Breakwater construction and the Phase 2 port development project. The study had helped the reform of Phase 2 sand breakwater and the design of Phase 3 construction of the port.

In the last two decades, extensive works have been done in observation, analysis and experiment on the silt-sandy beach of Jingtang Harbour district; a number of tests and studies have been performed on siltation abatement in the port and channel by sand breakwater and sand immobilization; and three phases of sand breakwaters have been designed and constructed. The present paper has summarized the effective measures for abatement of siltation, which are the precious result of 20 years' engineering activities and have important significance in the construction of port on silt-sandy beach. It is owing to the support by the results of the study works that the port has, in only 20 years, become a large port with 25 berths ranging from 10,000 DWT to 100,000 DWT and with throughput capacity of 100 million tons of cargo per year.

2 COAST EVOLUTION, COAST SEDIMENTATION AND SEDIMENT MOVEMENT FEATURES

a. Coast evolution

Luanhe River used to be a sediment-laden river second to Yellow River in the area of Bohai Bay. In history, the river estuary had migrated forth and back from north to south, having formed the delta plain with Luanxian at its apex, Changli at its north corner, and Caofeidian at its south corner. The delta front between the two estuaries feature sand bars and lagoons, and Jingtang Harbour is just located between the two estuaries in the middle part of the coast.

Since the 1970's, reservoirs have been built up in the upper and middle reaches of Luanhe River, and 70% of the river water running into the sea has been in the control, and the quantity of sediment carried by the river into the sea has been reduced greatly, which has much impact on the sediment movement in this sea area and evolution of coast by erosion and siltation. After 1970's, the coast has featured the retrogression by erosion, and the bathymetric lines have moved toward the shore (see Figure 1). Therefore, it can be concluded that the coast in the vicinity of Jingtang Harbour before the port construction was in the status of slight erosion in a macro point of view. After the construction of the port, owing to the existence of the port, the erosion pattern of the coast has changed significantly. From comparison of survey maps of different times, it is observed that coast features erosion in the inner part and siltation at the outer part under the action of waves in the normal years, i.e. the beaches at both sides of the East Sand Breakwater and West Sand Breakwater, where the waters are shallow, are in the status of siltation, whereas the area with relatively deep waters are slightly eroded. During strong storm, the coast behaves in the pattern of erosion in the inner part and siltation on the out part, with obvious variation of the coast profile. After the advent of the strong storm in October 2003, comparison of the survey maps have revealed the transportation of sediment in the direction from shore to deep sea; and the beaches within the bathymetric line of -6m was eroded and the sea beds beyond -6m line were silted up. In the most severely silted channel section, the channel was leveled with the seabed.

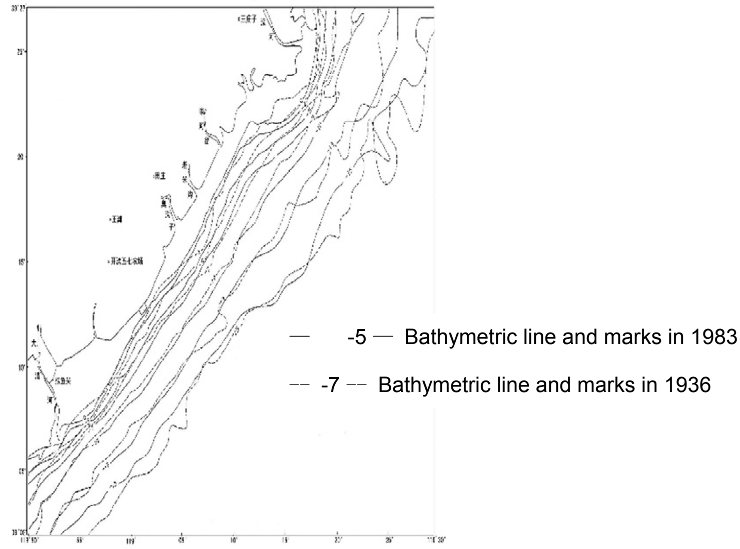


Figure 1. Variation of Bathymetric lines along coast between Estuary of Luanhe River and Estuary of Daqinghe River in time from 1936 to 1983

b. Sedimentation of coast

In the process of the construction of Jingtang Harbour, a number of investigation have been made into the deposits on the coast. As the samples were taken in different times at different locations, the seabed materials are different in distribution. Generally the sediment in this port area is between fine sand and silt. The analysis of the samples has shown that the sediment in the near-shore range of wave breaking band (within bathymetric line of -3m) is coarser, composed of fine sand in particle size of 0.1-0.2mm; the sediment in the range of 1-3km offshore (between bathymetric lines of -3m and -8m) is finer, composed of silt in particle size of 0.06～0.09mm; Beyond the line 3km from shore (beyond -8m bathymetric line), the sediment is mainly of clayey silt. The sediment silting the channel is in the size of 0.06～0.09mm. Figure 2 shows the medium value particle sizes of the seabed materials based upon the samples taken in 2000 and 2004.

c. Sediment movement

Obvious sediment movement in the direction along the coast exist in the sea area of the port. The sediment movement is most active in the wave breaking band near the shore especially in the conditions of wind generated high waves. Calculation with different formula has shown that the volume of sediment movement along the shore of Jingtang Harbour is not of great magnitude, with total sediment transportation in the range of 380,000 to 620,000 m^3 per year. The net sediment transportation is in direction from NE to SW and in volume of 200,000 to 400,000 m^3. After the strong storm hit the port area in October 2003, survey work was performed in the channel and on the beaches near the port, and the results were used in comparison with the survey maps before the storm (see Figure 3) and in the calculation of the volume of sediment transportation during the storm. Taking into account only the actions of the waves, the volume of sediment transportation along the shore was calculated to be about 300,000 to 700,000 m^3. It can be seen that the volume of sediment transportation during one strong storm can be equivalent to that of a year with normal wave conditions. The storm surge has not only played a very important role in the formation of the local beach patterns but also greatly impacted on the sudden siltation in the navigation channel. Taking into account the factors of wind, wave and current during the storm period (for about 6 days), the calculated volume of sediment transportation along the shore in direction from NE to SW during flood tide will amount to 1.656 million m^3, which is in net increase of 936,000 m^3 from the 720,000 m^3 of sediment transportation calculated taking into account the wave action only. In addition, during the ebbing tide period, much volume of sediment transportation also occurs in the direction from SW to NE. Therefore, the actual volume of sediment transportation during storm surge will be much more than that calculated by taking into account the wave actions only.

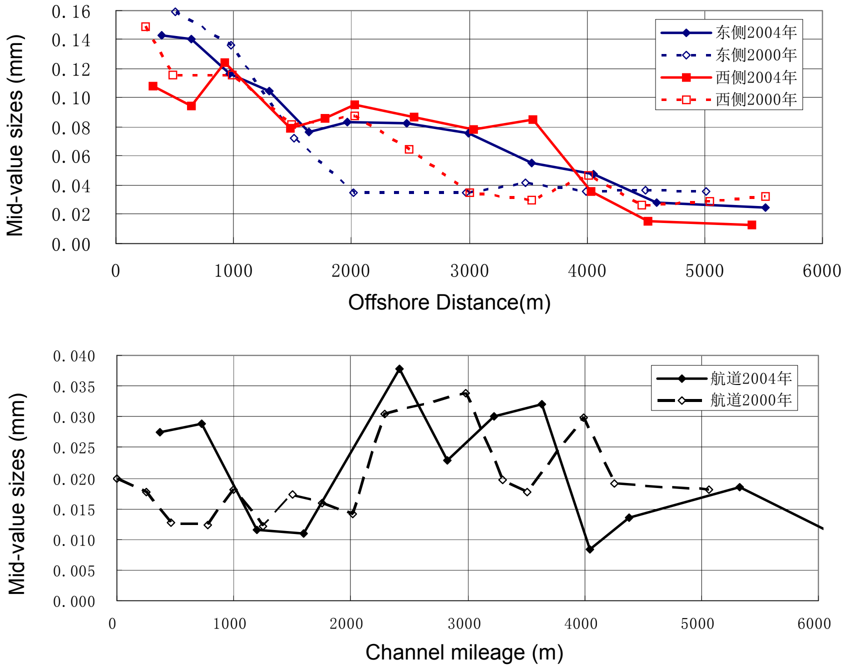


Figure 2. Comparison of distribution of mid-value paritle sizes of bed load material on bottom of channel and beaches in 2004 versus that in 2000

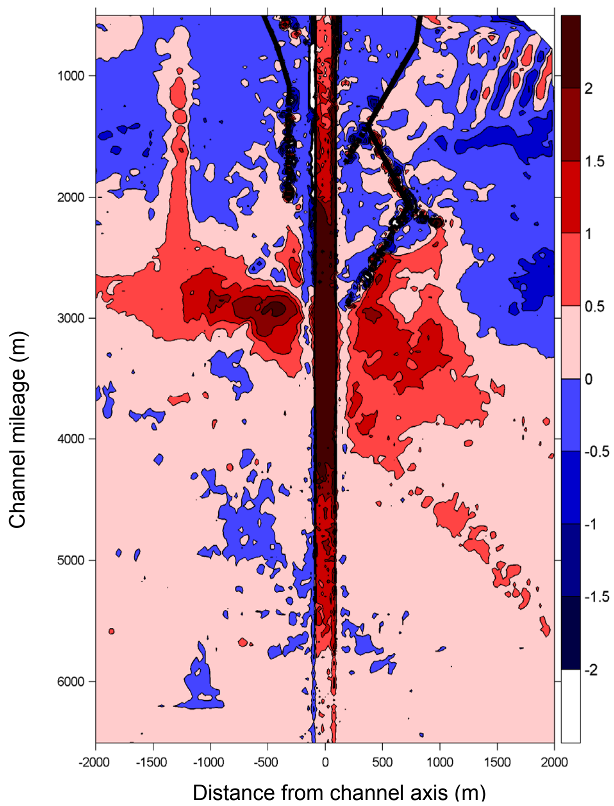


Figure 3. Variation of beaches due to erosion and siltation in period of time bewteen August and December of 2003

d. Sudden siltation in the channel during a typical storm surge

The storm surge in October 2003 caused the siltation in the channel in maximum thickness of 5.5m, at the location of the intersection point of the extension line of the embracing breakwater and the centre line of the channel, near the corresponding mileage of 3+200. The total volume of siltation in the 35,000 DWT channel amounted to 1.5 million m^3 (not including the volume of siltation at the channel side slope).

From the analysis on the variation of the beaches on either side of the channel by erosion and siltation during the storm surge, it is concluded that the diversion groins and submerge embracing breakwater of the East Sand Breakwater had played not much role as expected in the retaining of the sediment. The groins had failed to shift outward the concentrated siltation area, and the east embracing submerged breakwater had not remarkably reduced the magnitude of siltation in the channel section within its protection range. The effect of sand barrier of the West embracing submerge breakwater is neither very clear, although the volume of sediment transportation in the direction of SW to NE has been much less than that in the direction of NE to SW, its absolute volume cannot be ignored.

Before October 2003, concentrated siltation in the port used to happen in a period of time after the passing of the storm surge (for instance, following the storm surge in September 1992, a sudden siltation in the channel occurred in November 1992). However, sudden siltation in the channel happened in the same period as the storm surge passed the area in October 2003, further proving that the sediment that silted up the channel is supplied by the erosion of the upper reach coast. Under normal conditions of storm surge, as the sediment generated by erosion of upper reach of coast will not be transported immediately to the channel, but will be relayed from upper reach to next reach of coast, therefore the time of siltation is relatively delayed behind the storm surge. When the duration and magnitude of the storm surge are sufficient, the sediment will be directly transported to the channel to cause siltation. After the storm surge in October 2003, when the channel was cleared, many cages for cultivation of scallops were discovered. Investigation showed that fishery cultivation activities only existed on the east part of the port. It is obvious that under the conditions of rough seas, sediment from the area including the modern estuary of Luanhe River can be directly transported to the port area.

From the above analysis the mechanism of sudden siltation in the navigation channel of Jingtang Harbour during the process of a typical storm surge can be derived as follows: On the beaches in the vicinity of the breakwaters, the sediment of fine particle size will be deposited under normal wave actions. One part of the sediment will be transported laterally away from shore to the deep water area, causing significant variation in the profile of the beach. Other part of the sediment, also of fine particle size, from the beach on the north of the sand breakwater, will be carried by the strong along-shore current (compound of wave generated current and wind generated current) in the direction of East embracing breakwater to the channel. Meanwhile, the sediment, which is deposited on the beach under normal wave conditions on the outer side of the East breakwater, will be disturbed under the co-action of the strong reflected waves in front of the breakwater and the current running along the breakwater, and be carried and transported along the breakwater, and will be deposited when the current crosses the channel. The co-action of these two parts of sediment causes the sudden siltation in the channel. This process involves two parts of sediment, one being the sediment that has deposited near the breakwaters under normal wave actions and can be defined as locally transported sediment, the other being the sediment carried by current from the upper reaches of coast that can be defined as transit sediment. Strictly speaking, the locally transported sediment is also from the upper reach coast, but the transportation is completed under normal wave actions. Therefore, tracing back to the root, the sediment to silt up the channel mainly sources from erosion of the sea coast on the northeast of the port. To put it more simply, the sediment that silts up the channel under the action of storm surge is supplied from the beaches near the port as result of the sediment transportation along the shore, with the one from beaches in the northeast as the major component, and the one from the beaches in the southwest as the secondary component.

3 ALONG-SHORE SAND BARRIER WORKS

a. Phase 1 and Phase 2 Sand Breakwaters

Phase 1 Project of Development of Jingtang Harbour was started with the construction of sand breakwaters in configuration of embracing arms in plain view. The head of the east breakwater used to be located in the water area with water depth of -4.0m and the head of the west breakwater was located where the water depth is -3.0m. The breakwaters were basically extended to the margin of band of active activities of sediment, providing effective protection to channel for ships up to 5,000 DWT. The construction of the sand breakwaters was commenced in August 1989, and in the process of the construction, the layout of the breakwaters had been modified for a number of times in order to tackle the problem of siltation in the channel. As result of the design modification, the bead of the east breakwater was extended to the location of -5.0m water depth, elongating the breakwater to total length of 1840m. At the location of 1+500m of the east breakwater, a diversion groin was added. The groin is 750m in length, composed of a merged sections of 300m length and a submerged section of 450m length.

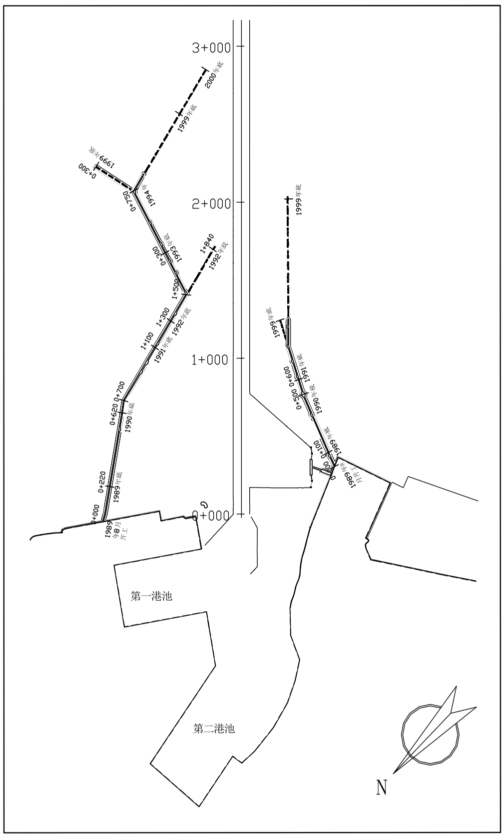


Figure 4. Construction of sand breakwaters in two phase at Jingtang Harbour

Phase 2 Project of sand breakwater included the construction of east diversion groin which is 750m long and totally emerged. An embracing breakwater in length of 920m was also added, of which the root section in length of 150m is emerged and the rest part in length of 770m is submerged and dynamically balanced (with its top over 3m above seabed). A secondary groin in length of 300m was added to the root part of the embracing breakwater. The west breakwater was elongated by 500m of emerged section and 800m of submerged section. Sea Figure 4 for the breakwater construction if Phase 2 Project. In the period of construction of Phase 2 Project, the channel was upgraded for ships up to 20,000 DWT with bottom dredged to 110m width and 10.5m depth by the end of 1998.

In September 2003, the construction of the channel for ships up to 35,000 DWT was completed, with bottom dredged to width of 160m and depth of 12m. Affected by the storm surge that happened from 10th August to 12th August 20003, the channel was seriously silted up. The total quantity of sediment that deposited in the channel amounted to 1.5 million m^3, and the average thickness of deposited sediment over the complete length of the channel was about 1.9m, with the maximum sediment thickness reaching to 5.5m at the location of the intersection point of the extension line of the embracing breakwater and the centre line of the channel, near the corresponding mileage of 3+200. It is found that the diversion groins and submerged embracing breakwater of the East Sand Breakwater constructed in Phase 2 Project had played not much role as expected in the retaining of the sediment. The groins had failed to shift outward the concentrated siltation area, and the east embracing submerged breakwater had not remarkably reduced the magnitude of siltation in the channel section within its protection range.

3.2 Phase 3 Project of Sand Breakwater Construction

In view of the problem with Phase 2 Project revealed by the storm surge in October 2003, in order to ensure safe navigation by ships in the 100,000 DWT channel and provide protection to the channel and port, it was very essential to take engineering measures to improve the sand breakwaters so as to abate the magnitude of sudden siltation in the channel. On basis of extensive studies on the siltation mechanism and large number of model tests for improvement of sand breakwaters, a solution for reform of Phase 2 breakwaters and construction of Phase 3 breakwater was proposed.

To enhance the effect of sand breakwater, it was preliminarily considered that the existing sand breakwaters should be extended to deeper water area. In view of the fact that the submerged breakwater head is only about 260m from the channel axis, the sand breakwater to be extended in Phase 3 could only be arranged either in parallel with the channel or set off in direction away from the channel. The set-off option would entail the widening of the existing entrance of the channel, causing the formation of backflow in certain area in the vicinity of the entrance during flooding tide or ebbing tide, thus having adverse effect in channel siltation. Therefore the parallel option was used in Option 3 for the extension of the breakwater into deeper water area. According to the arrangement of the existing breakwater, three representative options for selection of locations to start the extension of breakwater were simulated in model tests. In Option 1-1 the distance from east sand breakwater to the channel axis is 397m; in Option 1-2 it is 594m; and in Option 1-3 it is 1006m (See Figure 5, Figure 6 and Figure 7). The three options are different in entrance width and the length of west breakwater. According to analysis on current field patterns, under the conditions without the existence of waves, narrow entrance would provide better current patterns. In Option 1-3, backflows in large magnitude are already excluded outside the double breakwaters. In option 1-2, though the function of diversion is more obvious, the velocity of current has been further increased at the location of the breakwater head, thus erosion will be caused to the beaches near the breakwater head, which is unfavorable to the abatement of siltation in the channel. Model tests have also been conducted on current field patterns in case of waves, with results showing that narrow entrance is also more favorable than wide entrance. Therefore the design for the project adopted Option 1-1 for the extension of the parallel breakwater into deep water area. The corresponding current field patterns are shown in Figure 8.

According to the results of model tests and studies on siltation in the channel, through comprehensive analyses on the impact of different width of entrance on the siltation in the channel and on current field patterns at the breakwater entrance, and in consideration of a number of factors such as the scale of port future development, finally the optimized option for general layout of sand breakwaters was worked out. In this option of general layout design, the east breakwater consists of 646m emerged embracing breakwater connected with 700m of emerged diversion breakwater, with the breakwater head extended to water area of -8.0mn depth. The west breakwater is 2402.6m long emerged breakwater with its head located at location with water depth of -9m. The entrance is 700m wide and capable of meeting the standard for construction of double way channel for bulk cargo carriers up to 100,000 dwt in the future.

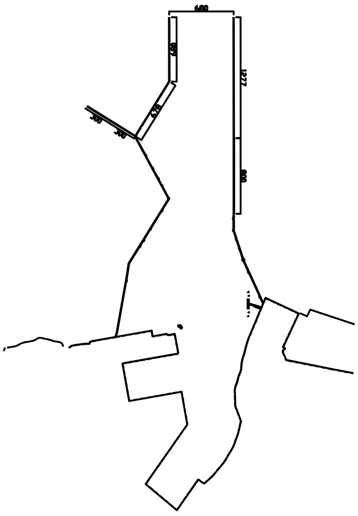


Figure 5. Option 1-1

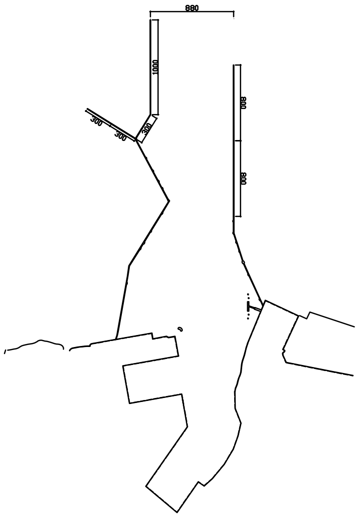


Figure 6. Option 1-2

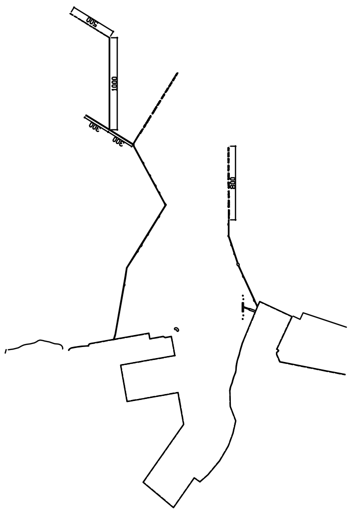
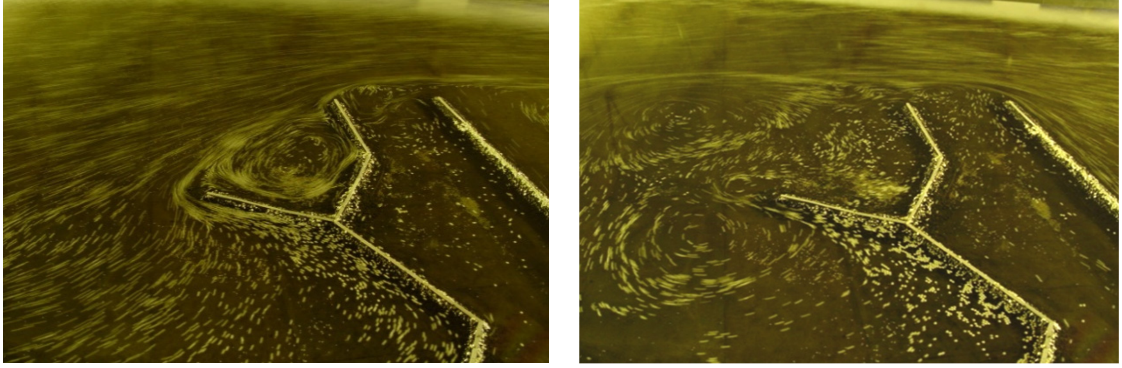


Figure 7. Option 1-3



（a） Flood peak （b） ebb peak

Figure 8. Option 1-1 flow regime of spring tide (no waves)

4 ALONG-SHORE OFF-SHORE SAND IMMOBILIZATION BREAKWATER

4.1 Selection of parameters for design of offshore breakwater

To better abate the siltation in the channel of Jingtang Harbour by intercepting the sediment transportation into the channel, an option of construction of sand immobilization breakwater was proposed as a supplementary to the sand retaining breakwater according to the properties of sediment movement in the sea area of Jingtang Harbour. Offshore sand immobilization breakwater is normally used for protection of beaches against erosion. However in this project it is used for its function in interception and immobilization of sediment.

The off-shore breakwater will be constructed along the quay line of proposed No. 4 Basin. The main function of the breakwater is to prevent the sediment deposited in the shallow water area from being disturbed during storm surge and supplying sediment to silt up the channel. Meanwhile sediment will be deposited behind the breakwater where land area will be reclaimed in future as the back-up land for No. 4 Basin. The off-shore breakwater is naturally making land at the same time of intercepting sediment carried by current from upper reach area. The deposition of sediment in the confined area will reduce the quantity of land filling during the development of No. 4 Basin. With little modification, the off-shore breakwater can also serve as a temporary cofferdam during the construction of diaphragm walling. Therefore the off-shore breakwater has multiple engineering benefits.

Major design parameters for design of the off-shore breakwater include the distance between breakwater and shore, expressed as X, the B, and the G, as shown in Figure 9.

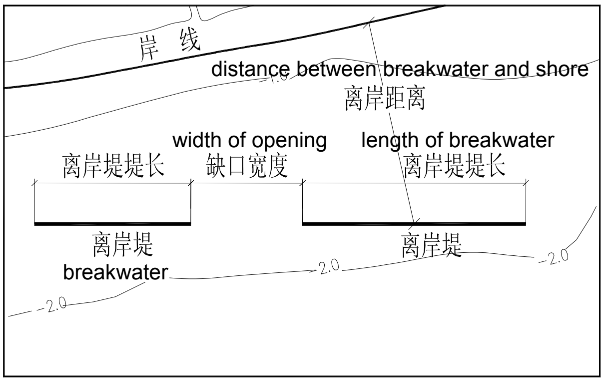


Figure 9. Parameters of the off-shore breakwater

(1) Distance between breakwater and shore

Normally off-shore breakwaters are located in shallow water areas. In view of the constructability of the breakwaters at the proposed site, the breakwaters in this project are planned to be located along the north quay line of No.4 basin, where the water depth is in the range of -1m～-2m. The distance between the breakwaters and the shoreline ranges from 200m to 400m.

(2) Breakwater length and width of opening

According to the literature of studies on off-shore breakwaters in the world, for a group of sectional off-shore breakwaters, the expected amount of sediment in the protected sea water area behind one section of breakwater and one opening, is related with the length of breakwater, the distance to shore and the width of the opening; and can be estimated through the relation graphic shown in the following Figure. During the design of the breakwaters, the relation graphic has been used in determination of the lengths of breakwaters which are different with the distance to shore. The length of each section of breakwater is taken to be 1.0 times the distance between breakwater and shore. The width of the opening between two neighboring breakwater sections is 0.5 times the length of breakwater.

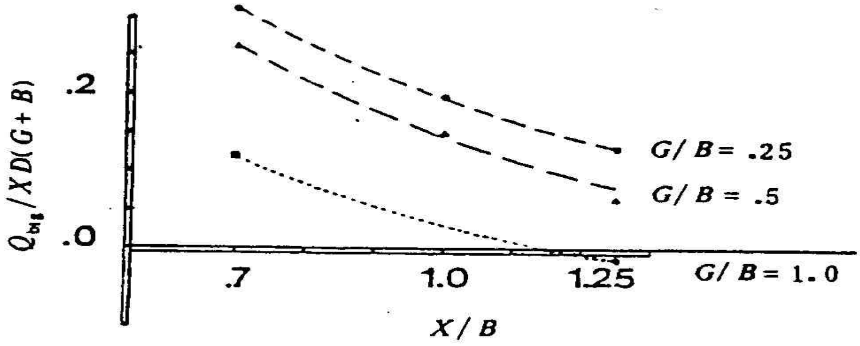


Figure 10. effect of quantity of sediment by the width of the opening(Reference 3)

In Figure 10, Q_{B+C} is the Quantity of sediment that enters the water area behind one section of breakwater and one opening; X is the distance between breakwater and shore; D is the depth of water at the location of the breakwater; G is the width of the opening between two neighboring breakwaters; B is the length of the offshore breakwater.

(3) Elevation of breakwater top

According to relevant study literature, the elevation of breakwater top shall be higher than the design high water level, and it is taken to be 2.5m (as compared with 2.03m of design high water level for Jingtang Harbour).

(4) Estimated effect of works of sediment interception and immobilization

According to the studies with prototypes and simulation models conducted in other countries in the world, the quantity of sediment that enters the protected area as determined by B, X, and D, expressed as Q_B, can be calculated with the following empirical equation (reference paper 3):

$$\frac{Q_B}{B \cdot X \cdot D} = \exp(0.31481 - 1.92187\frac{X}{B}) \qquad [1]$$

Where,

B is the length of off-shore breakwater;

X is the distance between breakwater and shore;

D is the depth of water in front of breakwater on the sea side.

Estimated by using the empirical equation [1], the expected quantity of sediment in the area confined by the breakwater in four sections will amount to about 520,000 m^3. Calculated with opening length of 0.5 times the length of breakwater, the quantity of sediment derived from using graphic in Figure 11 amounts to 860,000 m3. Therefore, the quantity of sediment in the area confined by the offshore breakwater with four sections and the gaps are estimated to be in the range of 500,000 m^3 and 800,000 m^3.

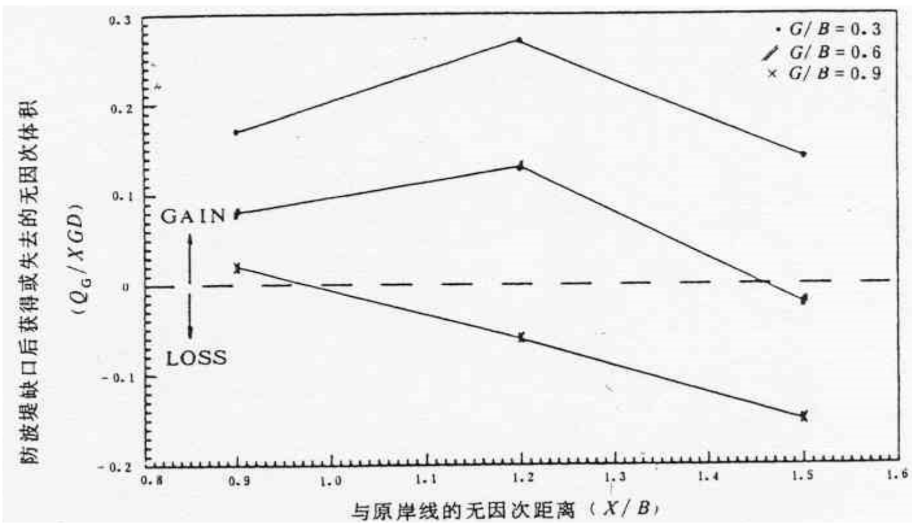


Figure 11. Expected quantity of sediment in the area confined by the breakwater (Reference 3)

According to results of studies conducted by scholars in other countries of the world, the non-dimensional length of sand spit formed in the area confined by offshore sectional breakwater, expressed as $S^* = S / X$, the non-dimensional length of offshore breakwater, expressed as $B^* = B / X$, and the non-dimensional width of gap between sections of breakwater expressed as $G^* = G / X$ (B is the length of offshore breakwater; X is the distance between breakwater and shore; S is the length of sand spit; G is the width of gap between sections of breakwater) have the following empirical relation(Reference 3 and 7):

$$S^* = 14.8\left(\frac{G^*}{(B^*)^2}\right)\exp\left[-2.83\left(\frac{G^*}{(B^*)^2}\right)^{1/2}\right] \quad [2]$$

Calculation with design parameters derives $S^* \approx 1.00027$, showing that the sand spit is long enough to form tombolo.

4.2 Result of modeling test on offshore breakwater

The modeling test on offshore breakwater was conducted with four gap widths respectively of 0.5L, 0.75L, 1.0L and 1.5L and the layout of breakwater as determined for Phase 3 project. The test has derived the results as listed in Table 1.

Table 1. Result of modeling test on offshore breakwater

Gap width	Quantity of sediment deposited behind breakwater in three years under normal wave action	Quantity of sediment deposited behind breakwater in three years under storm surge action	Impact on upper reach coast during storm surge
0.50L	500000 m^3	Added by 30000 m^3	No obvious impact
0.75L	190000 m^3	A part of sediment lost	Considerable corrosion
1.0L	350000 m^3	A part of sediment lost	Beach partially scoured at location 4000m away from channel axis
1.5L	170000 m^3	Major part of sediment lost	Upper reach beach and seabed at breakwater gap seriously scoured

From the test result it can be seen that the sediment confinement achieves best result when the gap is 0.5L. The scheme includes the construction of offshore breakwater in length of 1120m, at estimated cost of about 11.42 million Yuan. If land is reclaimed by deposit of sediment in quantity of only 500,000 m3, the economic benefit yielded would amount to 8 million Yuan (based on rate of 16 Yuan per cubic meter of filling material). The test has also been conducted taking into account an offshore breakwater constructed along the south quay line of No. 4 basin. The test result has shown that the total quantity of sediment deposit in the channel can be reduced by 21%. It can be anticipated that it is feasible to construct the offshore breakwater together with the development of No. 4 Basin. The test models for Scheme 3-1 of offshore breakwater are shown in shown in Figure 12 and Figure 13.

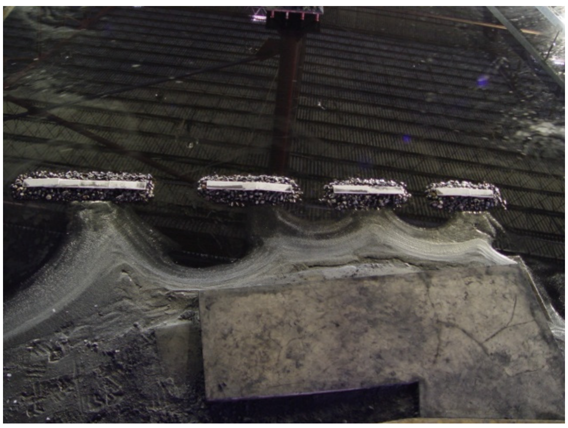


Figure 12. Option 3-1 the form of sediment deposited behind breakwater in three years under normal wave action

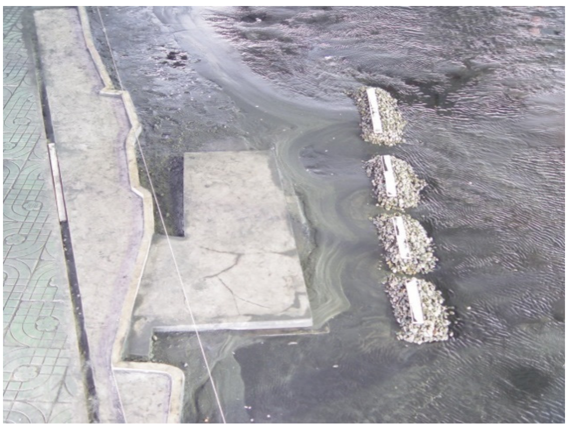


Figure 13. Option 3-1 the form of sediment deposited behind breakwater in three years under storm surge action

5 CONCLUSIONS

The study, through analyses and model tests, on the mechanisms of coast development, sediment movement and siltation in navigation channel in the water areas of Jingtang harbor, has led to proposal of engineering measures for abatement of siltation by baring sediment or confining sediment. The scheme of sediment barrier has been used in the improvement of Phase 2 breakwater, in the design and construction of Phase 3 breakwater. The scheme for confinement of sediment has been proven, by physical model tests, to be effective in abatement of siltation to meet the design objective, and thus having a significance in the development of port facilities in the future. With the rapid development of Jingtang Habour, the relevant study works will be conducted into more details. Jingtan Harbour is doubtlessly an exemplary case for successive construction of dredged-in port on silt-sandy beach.

ACKNOWLEDGEMENTS

The study on engineering measures for abatement of siltation in the navigation channel of Jingtang Harbor has, up to the time of conclusion of this paper, received careful direction and ardent assistance from a number of experts, e.g. Xie Shileng, Gu Minquan, Weng Zhuzhang, Wang Chenghuai, Liu Jiaju et al. The completion of the study is the result of the common effort of my colleagues who have been diligently working over years for the construction of Jingtang Harbor. The draft of this paper has been proof read by Professor Wang Yongxue. Their contributions to the study work and the completion of this paper are acknowledged with cordial gratitude and respect.

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