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COASTAL RESERVOIRS

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International Association for Hydro-Environment Engineering and Research

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COASTAL RESERVOIRS: CHALLENGES AND OPPORTUNITIES

EDITORIAL BY ANGELOS N. FINDIKAKIS

This issue of Hydrolink focuses on the recently increased interest in coastal reservoirs and the opportunities and challenges they present. The term coastal reservoirs is used to describe water storage facilities at or near the mouth of rivers that are formed by constructing barrages across the river or containment dykes along one of each banks. Some of the early such reservoirs in the Netherlands were created by barriers constructed to provide flood protection while others were the result of land reclamation efforts. Coastal reservoirs have also been created by barriers as part of tidal energy power projects, such as the Rance power station in France constructed in the 1960s. Because of the continuous reversal of tidal flow direction, the salinity of the water in tidal power project reservoirs is high. The current interest in coastal reservoirs is concentrated on fresh water reservoirs that could serve the water supply needs of coastal cities.

Angelos N. Findikakis
Hydrolink Editor

The idea of using coastal reservoirs to capture fresh water in estuaries started getting traction in the second half of the twentieth century in coastal areas faced with increasing water demand that could not be satisfied by other water resources. This approach was pioneered in China, with the construction of one such reservoir in Hong Kong in the 1960's followed by several other similar projects along the East China Sea coast, the most recent of which being those serving Shanghai. The article by Lin et al in this issue gives an overview of the history of coastal reservoirs in China, and the article by Yuan and Wu discusses in more detail the reservoirs in the delta of the Yangtze River designed to augment the water supply of Shanghai. Another example of an early coastal reservoir is that formed by the Thaneermukkom salt water barrier across the Vembanad Lake, which drains in the nearby Arabian Sea, in the south of India. The barrier prevents salt water intrusion by tidal action, keeping fresh the water from the rivers flowing in the lake, so it can be used for irrigation as described in the article by Sitharam and Sreevalsa.

The construction and operation of coastal reservoirs in estuaries presents several challenges. One of them is the potential accumulation of pollutants such as excess fertilizers, herbicides and insecticides carried by runoff from surrounding agricultural lands, or discharges from industrial facilities within the drainage basin of the reservoir. An example of an initial failure to recognize this problem is the case of Lake Sihwa in South Korea, which was created by constructing a seawall across a bay in order to reclaim land for urban development and provide freshwater for irrigation. The effect of eliminating tidal seawater recirculation in combination with low natural freshwater inflows in the newly created lake and increased wastewater releases from nearby industrial complexes led to rapid deterioration of water quality making the water of the lake unsuitable for irrigation. This led the South Korean government to reconfigure the project and reestablish the circulation of seawater in the lake by opening periodically eight sluice gates along the seawall and installing 10 tidal power generation units creating a 254 MW power station.

Coastal reservoirs receiving urban runoff may face water quality problems because of oil, grease and different toxic chemicals. For this reason, the construction of such reservoirs especially as a source of drinking water supply, must be accompanied by strict controls on the use and release of toxic substances and other pollutants, thorough water quality monitoring programs and adequate treatment as needed. An example where such controls and monitoring are in place is the Marina Reservoir in Singapore, that receives stormwater from about a sixth of the island, a good part of which is urbanized.

Changes in local flow patterns and salinity distribution caused by the abstraction of water may affect the sensitive ecological balance of estuarine systems, threaten native species and introduce invasive aquatic plants and fish. This is especially so, in cases where large quantities of water are abstracted from delta areas. Such an example is the Delta of the Sacramento and San Joaquim Rivers in California, which is the source of water for two large water transfer projects designed to deliver irrigation and municipal water to the Central Valley of California and to several cities, mostly in Southern California. Water from the Delta is diverted to a small reservoir from where it is pumped to two canals that take it south. This affects the salinity distribution in the Delta waters and threatens some endangered species of fish. In response the operation of the system is often disrupted or modified by reducing water deliveries to different parties. Efforts to find a solution that addresses satisfactorily both the environmental concerns about the Delta and the water supply needs of farmers and cities has been sought over nearly fifty years without any success so far.

Today, coastal reservoirs are being discussed as an attractive solution to the water supply needs of several coastal cities, mostly in Asia. Examples are given in two articles in the present issue. Sitharam describes a proposal for a coastal reservoir at the mouth of the of the Netravati River to augment the water supply of the city of Mangaluru, and Tan et al discuss the potential for the construction of several coastal reservoirs in Malaysia.

The increased interest in the subject of coastal reservoirs and the need to share experiences and lessons learned led to the creation of an organization focused on the subject, the International Association for Coastal Reservoir Research (IACRR), which was formally established in 2017 during the IAHR World Congress in Kuala Lumpur. Earlier this year IACRR hosted an International Workshop on Coastal Reservoirs held at the University of Wollongong in Australia, which attracted university researchers, government water planners, and industry practitioners. IACRR is working now to organize the First International Congress on Coastal Reservoirs at Hohai University in Nanjing, China in October 2020, which will be cosponsored by IAHR.

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Cover picture: View of the Thanneermukkom bund

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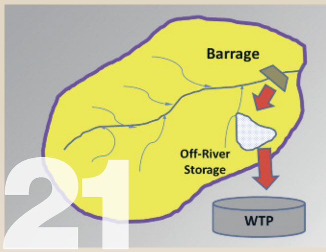


A MESSAGE FROM DR. B.R. SHETTY, PATRON OF IACRR

A paradigm shift from "storing flood waters in inland dams and reservoirs and natural discharging of river flood waters into the ocean" to "storing river flood waters in coastal reservoirs in, or close to the sea using downstream reservoirs"

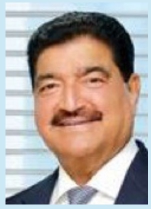
Despite water covering about 70% of the Earth's surface, fresh water for consumption is not as plentiful. Less than 3% of all water on the earth is fresh; most of which is in the ice caps and glaciers, with only about 1% of all fresh water being accessible surface water! More than 1 billion people lack access to clean water and about 3 billion people lack the same for about three months in a year. Many large cities in the world are facing a situation of 'water stress'. According to the United Nations, global demand for fresh water will exceed supply by 40% by 2030. The main reasons for this increasing water stress are climate change, human behavioral change and population growth. Most civilizations in the history of the human race have flourished in areas where abundant water was available. Now, it seems that there is enough rainfall on our planet to support all humanity, but it is unevenly distributed and a good part of it comes during heavy storms and is lost to the sea. Due to climate change rainfall events have become more intense and sporadic and as all this happens quickly, the majority of these flood waters flow through streams and rivers into the ocean and mix with salt water, thus getting lost as a water resource. A water crisis in many parts of the world can be prevented by starting to regard the large volumes of water flowing to the oceans during floods as a valuable water resource. Coastal reservoirs represent a paradigm shift in the history of water resources management, from storing flood waters in inland dams to storing freshwater in "downstream reservoirs", located in estuaries close to the sea. I have the fortune of being in the position of patron of a new society focused on this subject, namely the International Association for Coastal Reservoir Research (IACRR), and it is my ambition to contribute what I can to support the delivery of fresh water for all and reducing water stress globally.

I am happy to note that Hydrolink - the magazine of the International Association for Hydro-Environment Engineering and Research (IAHR) - is taking an interest in coastal reservoirs and bringing out a special issue on this new topic, highlighting the need for such activities to help solve the world's growing water crisis. On behalf of IACRR, I would like to thank IAHR for their support and I would encourage the IAHR community to work with IACRR to deliver the science and engineering needed to address the challenges and opportunities of delivering water security to many cities world-wide through coastal reservoirs.

I understand from Professor T G Sitharam, President of IACRR, that the Centre for Coastal Reservoir Research at the University of Wollongong held a very successful first International workshop on coastal reservoirs in collaboration with IACRR in January, 2018. I am pleased to note that this workshop had representation from water resources planners, politicians and water ministers from Australia, Malaysia, China and India, as well as researchers, engineers and scientists who spent time reviewing and assessing the feasibility of coastal reservoirs in securing universal access to safe and affordable drinking water. I am happy to note that the concept of storing water in downstream reservoirs (coastal reservoirs) is rapidly catching on and I understand that a number of major cities around the world are now actively pursuing coastal reservoirs as a sustainable solution to their water supply problems. I am also happy to hear that Hohai University will host the 1st IACRR World Congress on Coastal Reservoirs in Nanjing, China, in October 19-22nd, 2018. I am also pleased to hear that we are working to host this conference in association with world renowned learned societies such as IAHR.

I congratulate and thank IAHR's Hydrolink editor and its editorial board for taking this collaborative initiative to support and promote Coastal Reservoirs to its scientific and engineering community and I look forward to seeing closer links between IAHR and IACRR in the future.

Thank you. ■



Dr. B. R. Shetty is an Indian-born businessman and founder of many companies based in the UAE, and Chairman of BRS Ventures. He completed his pharmaceutical education in India and moved to the UAE in 1973. In 1975 he founded New Medical Centre Health to fill the need for personalized healthcare for all. He has invested considerably in medical institutions in India and also in recycling of water at the Jog Falls (the second highest water falls in India and a major tourist attraction) using a reverse pumping mechanism, which would make Jog Falls perennial and generate hydropower during the monsoon season. Dr Shetty has received many awards for his work, including the highest distinction in the UAE, the Abu Dhabi Award. He is now Patron of the IACRR and passionate about water security in India, the UAE and world-wide.

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COASTAL RESERVOIRS IN CHINA

BY PENGZHI LIN, ZHIGUO HE, ZELIN GONG & JINQUAN WU

Modern river basin management treats flooding not only as a threat, but also as a precious water resource. In inland areas, dams are built to impound water in reservoirs. In coastal regions, however, building reservoirs does not seem to be an obvious choice, at least at first glance. How to develop more freshwater for coastal cities becomes a challenging issue. For coastal regions with abundant precipitation and/or river outflow, the key to solving water shortage problem is to find a suitable place to store freshwater, especially during the flood season.

River mouth reservoir – the early form of coastal reservoir

In China, the first downstream reservoir appeared at the time of the Tang Dynasty, and was made possible by the Tuoshan Weir, one of the four famous hydraulic projects in ancient China. The Tuoshan Weir was constructed in 833 B.C. downstream on the Yin River near Ningbo (Figure 1 and Figure 2). The weir was about 134 m long and 3 m high, and was originally built to prevent seawater intrusion. Naturally it impounded freshwater upstream and created a reservoir in the river channel that helped to irrigate over 6,000 hectares of cropland.

In the past decades, many sluice gates were built on river mouths along the coastline of China, protecting inland areas from saltwater intrusion and storing freshwater for irrigation purpose. Examples include the Haihe Tide Gate in Tianjin and the Sheyang Tide Gate in Jiangsu Province, both of which were constructed in the 1950s. In the 1970s, more such river mouth reservoirs were constructed. Examples are the Datang Harbor Reservoir and Huchen Harbor Reservoir in Sanmen Bay, Zhejiang Province (Figure 3). The Datang Harbor Reservoir was built in 1973 with an area of 4.79 km^2 and a capacity of 46.75 million m^3 (Figure 4). The Huchen Harbor Reservoir was built in 1973 as well, with a total capacity of 81.73 million m^3 (Figure 5). Sluice gates in river mouths continue to be used effectively and new ones are added such as the Cao'e River sluice gates constructed between 2005 to 2007 in Hangzhou Bay.

Sluice gates in river mouths are easy to construct and can effectively prevent seawater intrusion. The gates, on the other hand, block sediment transport and result in river channel siltation. In addition, considering that the river channel is normally narrow, the freshwater stored in the reservoir can be limited.

To increase reservoir capacity, we need to extend our view to bay and coastal areas.

Bay reservoir - the modern form of coastal reservoir

In the 1960s, Hong Kong's economy development soared with the fast increase of population thirsty for more drinking water. Mr. T.O. Morgan, the former director of Hong Kong's Water Supplies Department, suggested converting the bay of Plover Cove into a

Figure 1. The Tuoshan Weir in Yin River


Figure 2. The Tuoshan Weir today

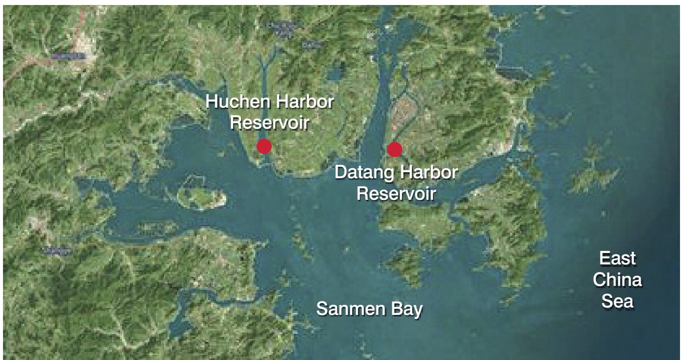

Figure 3. The Datang Harbor Reservoir and Huchen Harbor Reservoir in Sanmen Bay

Figure 4. The Datang Harbor Reservoir

Figure 5. The Huchen Harbor Reservoir


Figure 6. Aerial view of Plover Cove Reservoir

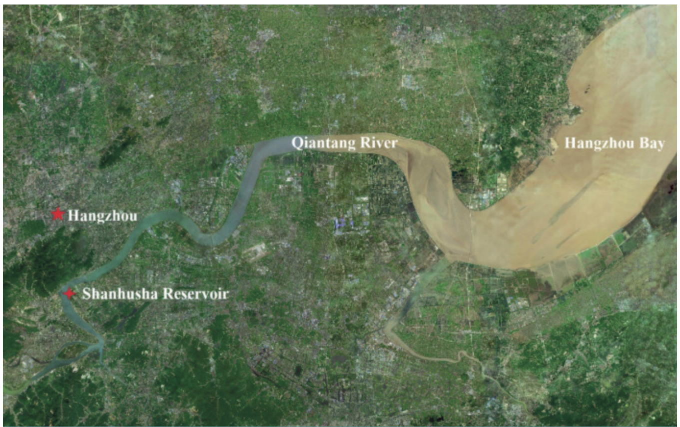

Figure 7. Location of Hangzhou city and Shanhusha Reservoir in Qiantang River

Figure 8. Shanhusha Reservoir in Qiantang River

reservoir, making use of existing islands and connecting them with dams. Construction work on this project started in 1960 and was completed in 1968, providing a capacity of 170 million m^3 (Figure 6). The dams were later raised from 1970 to 1973, increasing the reservoir capacity to 230 million m^3. Although the reservoir was later abandoned due to Hong Kong's successful contract with mainland China for trading freshwater, Hong Kong was the very first city in the world to construct a bay reservoir. As a pioneer in coastal reservoirs, the Hong Kong government showed great vision for the future of water supply.

Interestingly, almost at the same time, a similar idea of using the bay space for coastal reservoirs was also proposed and implemented in mainland China, although at a much smaller scale compared to that of the Plover Cove Reservoir. The Shanhusha Reservoir located by Qiantang River of Hangzhou Bay was built in August 1979 (Figure 7). Different from the river mouth reservoirs, the Shanhusha Reservoir was constructed inside the tide-dominated estuary (Figure 8) and has a very small capacity of nearly 1.9 million m^3. However, it is one of the most important water supply sources for Hangzhou in case of emergency. It could store freshwater from Qiantang River during the ebb tide by two inlets with a capacity of 500 thousand m^3/d and 1 million m^3/d, respectively, and provide water supply to the city with two outlets with a capacity of 450 thousand m^3/d and 880 thousand m^3/d, respectively.

Shanghai - the showcase of modern coastal reservoirs

Shanghai is located by the Yangtze River Estuary. It is the largest city in China with a total population of 24 million. According to the Revision of the Shanghai Urban Master Plan in 2005, the freshwater shortage in the city will reach 6 million m^3/d by 2020. To meet the increasing demand of freshwater, Shanghai took a bold step to construct a series of coastal reservoirs (Figure 9). Nowadays, three main coastal reservoirs, i.e., Chenhang Reservoir, Qingcaosha Reservoir, and Dongfengxisha Reservoir, meet over 70% of the water needs of Shanghai.

The history of coastal reservoirs in Shanghai can be traced back to the 1980s. To meet the water demand for iron and steel manufacturing, the Baogang Reservoir was built in the early 1980s. With an area of 1.64 million m^2, the reservoir has a total storage capacity of 12 million m^3. The Chenhang Reservoir, next to the Baogang Reservoir, started construction in the late 1980s and was completed in 1992 (Figure 10). The area of the reservoir is nearly 1.35 million m^2 with a capacity of 9.56 million m^3 after potential-tapping engineering works in 2008. Its average daily water supply capacity is 1.6 million m^3. Both the Baogang Reservoir and the Chenhang Reservoir are typical coastline reservoirs as they are constructed along the coastline, from which they further extend to sea.

The construction of the Qingcaosha Reservoir, the largest coastal reservoir in China, was started in June 2007 on the Changxin Island in the Yangtze River Estuary (Figure 11 and Figure 12). The area of the reservoir is nearly 70 km^2 with the total length of the surrounding dike being 48.41 km. The design capacity of the reservoir is 527 million m^3, while its effective capacity is 438 million m^3 when the water level is at 7 m. Its water supply capacity is 7.19 million m^3/d. At present, 50% of the drinking water in Shanghai is provided by the Qingcaosha reservoir, changing its history of depending on the Huangpu River as its major water source.

The construction of the Dongfengxisha Reservoir (Figure 13) started in November 2011 on the Chongming Island, the third largest island of China, and was completed in January 2014. Its total storage capacity is 9.76 million m^3 Its short-term water supply capacity is 215 thousand m^3/d, and its long-term water supply capacity is 400 thousand m^3/d. It mainly provides water supply for the residents of the Chongming Island.

The completion of these reservoirs has changed the water supply patterns for this large city, guaranteeing a safe and reliable freshwater supply in good and stable quality in all seasons. While the Baogang Reservoir and the Chenhang Reservoir were built along the coastline, Qingcaosha and Dongfengxisha Reservoirs were extensions of the islands, further into sea of the estuarine region. Shanghai created coastline reservoirs and island reservoirs, introducing new types of coastal reservoirs. This makes Shanghai a very proud showcase of modern coastal reservoirs to the world.

Vision of the future

Unlike inland reservoirs, coastal reservoirs face different technical challenges due to their special environmental surroundings. Problems such as saltwater intrusion, pollution, algal blooms, sediment accumulation, structural instability and ecosystem imbalance are important considerations for the design, construction and operation of coastal reservoirs. Finding solutions to all these problems requires the collaboration of researchers and engineers in different fields of hydraulic engineering, coastal engineering, environmental science and technology, structural engineering, geotechnical engineering, coastal oceanography, etc. The success of coastal reservoirs also requires the collaboration of different stakeholders.
In many circumstances, the construction of a coastal reservoir is similar to the construction of a harbor, except that the reservoir needs to be closed by gates for freshwater intake and storage. Thus, many technologies developed for harbor construction can be readily extended for coastal reservoir construction. First Harbor Consultants (FHC) has successfully designed and implemented a large number of marine engineering projects in various complex meteorological, hydrodynamic, and geological conditions. Their engineering practices cover design and construction of ports, waterways, ship locks, artificial islands, etc.

Nevertheless, there are many new challenges, and thus opportunities, open to engineers and researchers for coastal reservoir development. For example, new materials such as flexible curtains could be used to separate freshwater from salt water, considering the small pressure difference across the curtain. More careful treatments may be needed to minimize salt water intrusion into coastal reservoirs from both the bottom through seepage and the top by wave overtopping. Meanwhile, the degradation of water quality, harmful algal blooms, and reservoir siltation can become difficult problems for long-term reservoir operation.
There is no doubt that coastal reservoirs provide a new option to coastal societies for developing

Figure 9. The distribution of coastal reservoirs in Shanghai


Figure 11. Aerial view of Qingcaosha Reservoir


Figure 12. The water intake station of Qingcaosha Reservoir

Figure 10. Aerial view of Baogang Reservoir and Chenhang Reservoir


Figure 13. Aerial view of Dongfengxisha Reservoir

freshwater resources. On a longer time scale, it will inevitably change the pattern of water resources distribution in inland areas, forcing us to re-assess previous water distribution plans. With the spread of coastal reservoirs to many coastal regions, there is a chance that they will be multi-connected and further extended into the deeper ocean. New technologies would be developed along the way. We expect that coastal reservoirs will stimulate a new wave of ocean resources development.

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The authors would like to thank Prof. Roger Falconer from Cardiff University, UK for his encouragement during the preparation of this article. ■

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Mr. Zelin Gong is the M. Eng. student of State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University. He is the secretary of the IAHR Student Chapter at Sichuan University. His researches include coastal engineering and low impact development.

Mr. Jinquan Wu is the Vice General Manager of the CCCC First Harbor Consultants Co., Ltd., China. He has over 35 years of experience in design of harbors and has served as project manager/chief engineer for many major projects. He was awarded the title of Survey and Design Master of China Waterway Engineering for his distinguished contribution and commitment in his field of expertise. He has also severed as a member of Expert Committee of Ministry of Transport, China and a member of Consultant advisors of Tianjin Society of Waterway Engineering.

SHANGHAI COASTAL RESERVOIRS: THEIR DEVELOPMENT AND EXPERIENCE FROM THEIR DESIGN

BY JIAN ZHONG YUAN & CAI E WU

Shanghai has three coastal reservoirs used for drinking water sources in the Yangtze estuary. They are the Qingcaosha reservoir, the Dongfengxisha reservoir and the Chenhang reservoir. This article discusses why Shanghai needed to build coastal reservoirs and their evolution. The characteristics of the Shanghai drinking water sources are introduced. The key factors and the experience gained from the research and design of the Shanghai coastal reservoirs have been summarized and explained.

The evolution process of Shanghai drinking water sources

The search for drinking water sources in Shanghai goes back more than 100 years and can be divided into three stages. The first stage is the period before the 1980s when the city mainly took water directly from the lower reach of the Huangpu River and the Suzhou River. The second stage began in 1987, when the city started taking water from the upper reach of the Huangpu River. The third stage introduced the use of the Qingcaosha reservoir, the largest coastal reservoir for drinking water supply in the world. Today, more than 70% of Shanghai's drinking water comes from coastal reservoirs in the Yangtze estuary.

Why does Shanghai need to build coastal reservoirs in the Yangtze estuary?

The Huangpu River is located in the downstream part of the Taihu Basin, where water intakes are often threatened by many factors like low flow, water pollution caused by domestic and industrial wastewater, and where the fresh water sources are not protected in reservoirs, in case of an emergency such as when chemicals are accidentally discharged into the river from somewhere in the basin. The water quality of the Huangpu River is relative poor and unstable. At present, the total diverted water from the intakes in the upper reaches of the Huangpu River for the Shanghai water supply exceeds 30% of its average annual flow rate, which is close to the upper limit of the Falkenmark water stress index. If the rate of water withdrawals from the upper reach of the Huangpu River is expanded further, the river ecosystem will deteriorate, especially in the middle and lower reaches of the Huangpu River, and seawater intrusion may affect water quality at the lower intakes. Therefore, any further development or excess water withdrawals from the upper reach of the Huangpu River may cause high salinity at the intakes due to seawater intrusion.

Other rivers near Shanghai are scattered and their overall water quality is poor. Water quality in these rivers generally cannot reach the national surface fresh water standard for drinking purposes. Therefore, these rivers cannot be used as the main drinking water source for Shanghai. At the same time, the groundwater yield in the area is low. In order to effectively control land subsidence, further control and reduction in the rate of groundwater exploitation is needed in Shanghai.

With the development of Shanghai's economy and the growth of the urban population, the demand for water is rising. The population of Shanghai was 24.2 million in 2016. The water supply capacity of the city reached 11.52 Mm^3/d and the annual water supply was 3.2 Gm^3. In addition, there is a shift in the emphasis placed on the demand for water from quantity to quality. The lack of good water quality can have an impact on the sustainable development of Shanghai. Therefore, finding new water sources of adequate quality for urban water supply has become a pressing problem.

The Yangtze estuary has abundant fresh water resources of good and stable water quality that account for 98.8% of the total water resources in Shanghai. Its water quality meets the Chinese standard of fresh water for drinking purposes, and has a relatively high self-purification ability. It is better than surface water in other areas of Shanghai. The fresh water resources of the Yangtze estuary have great potential for development and utilization. Therefore, the development of the Yangtze estuary can satisfy not only the incremental fresh water needs, but also can improve the quality of the Shanghai water supply. The intermittent nature of freshwater/seawater in the Yangtze estuary may provide a feasible solution to the problem of drinking water in Shanghai.

Figure 1. Location of Shanghai Coastal Reservoirs

Shanghai authorities started in the 1980s to carry out long-term hydrological and water quality monitoring, research and analytical studies to support planning for the use of the water resources in the Yangtze estuary in order to solve the water supply problem. However, direct development in the Yangtze estuary was threatened by saltwater intrusion at the intakes. To address this problem, it was decided that a coastal reservoir with large storage capacity should be constructed to store fresh water during periods of low salinity and high quality.

Profile of Shanghai coastal reservoirs

The Shanghai municipal drinking water comes from surface water sources, which now include three coastal reservoirs in the Yangtze estuary (Figure 1): the Qingcaosha reservoir, the Dongfengxisha reservoir, and the Chenhang reservoir. These reservoirs are easily affected by saltwater intrusion because of the interaction of runoff, tide and wind, etc.

Figure 2. Map of Chenhang Reservoir

•Chenhang reservoir

The Chenhang reservoir was the first coastal reservoir used as a drinking water source in Shanghai. Its development was a milestone in the utilization of fresh water for Shanghai from the Yangtze estuary. Construction of the Chenhang reservoir started in November 1990 and was completed in June 1992. The Chenhang reservoir is located on the south bank of the South Branch of the Yangtze estuary, just downstream of the Baosteel reservoir (Figure 2). Total reservoir area is 1.336 Mm^2. Maximum high water level of the reservoir is 7.25 m (Wusong Datum). The dead storage water level is 0.5 m. The design effective capacity was 8.3 Mm^3, which has been increased to 9.5 Mm^3 after reinforcement and heightening of the reservoir dyke. The rate of water supply from the reservoir has been increased to 1.3 Mm^3/d and the maximum high water level of the reservoir is now 8.10 m. The reservoir can provide fresh water for about 7 days at the designed rate for water supply without interruption during extreme saltwater intrusion events.

•Qingcaosha reservoir

The Qingcaosha reservoir is China's largest coastal reservoir built in the Yangtze estuary. The construction of the Qingcaosha reservoir began on June 5, 2007 after nearly twenty years of research, and the reservoir started operating on June 8, 2011.

The Qingcaosha reservoir is located on the northwest side of Changxi Island between the South Channel and the North Channel of the Yangtze estuary. Figure 3 shows the general layout of the Qingcaosha reservoir. Figure 4 shows the upper water intake system and the north dyke, including the upper sluice and pump. The total length of the dyke is 48.4 km and the newly constructed dyke (IJKLMNOPQRS in Figure 3) is 22 km. The total reservoir area is 66.15 km^2. The maximum high water level of the reservoir is 7.0 m. The dead storage water level is -1.5 m. The total reservoir capacity is 0.527 Gm^3 and the design effective capacity is 0.438 Gm^3. The design daily water supply is 7.19 Mm^3/d. The capacity of the upper pumping station is 200 m^3/s. The upper gate net width is 70 m and its bottom elevation is -1.50 m. The lower gate net width is 20 m and its bottom elevation is -1.50 m too. Fresh water is conveyed by gravity out of the reservoir. The net width of each hydraulic gate is 24 m and its bottom elevation is -4 m. The design capacity of the additional pumping station was set to be initially 0.11 Mm^3/d, to enhance the intake's safety, and the pumping house's capacity now is 0.23 Mm^3/d. The reservoir's storage is large enough to ensure 68 days of water supply to Shanghai without interruption. Without this reservoir Shanghai's water supply could be at risk when the salinity at the water intake exceeds the standard during periods of continuous and severe seawater intrusion. The current water supply from the Qingcaosha reservoir benefits a population of more than 13 million in Shanghai.

Jian Zhong Yuan has served in the Shanghai Investigation Design & Research Institute Co., Ltd (SIDRI) as an engineer since 1988 and professional senior engineer since 2007. He received his Bachelor of Engineering from the Wuhan Institute of Hydraulic and Electrical Engineering in 1985, and his Master of Engineering degree from Tsinghua University in 1988. His focus has been estuarine and coastal engineering and related research, especially the development and utilization of fresh water resources in Yangtze estuary. His areas of expertise are mainly in hydrodynamic analysis, engineering impact analysis, analysis of fluvial evolution, mathematical modeling, and engineering planning.

Cai E Wu has served in the Shanghai Investigation Design & Research Institute Co., Ltd (SIDRI) as an engineer since 1984 and professional senior engineer since 2009. She received a Bachelor of Engineering from Hohai University in 1984. She mainly participated in and is responsible for the design work of the four large drinking water reservoirs in Shanghai, three of which are coastal reservoirs. Her areas of expertise are mainly in hydro-structure (dyke & sluice), pumping stations and water supply system.

Figure 3. The general layout of Qingcaosha Reservoir

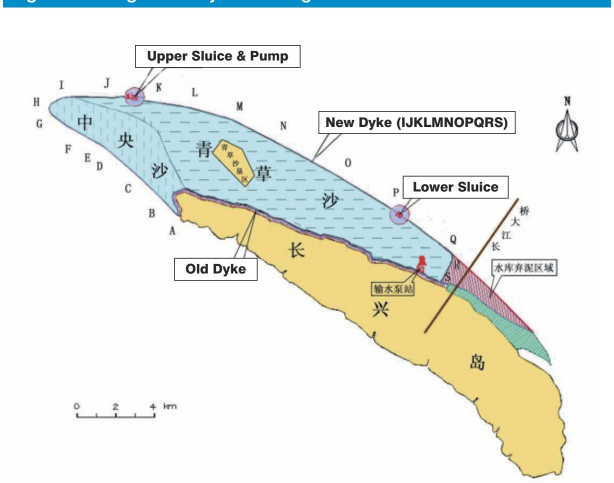

Figure 4. Aerial view of the Qingcaosha Reservoir (photo: Xinhua News UAV)

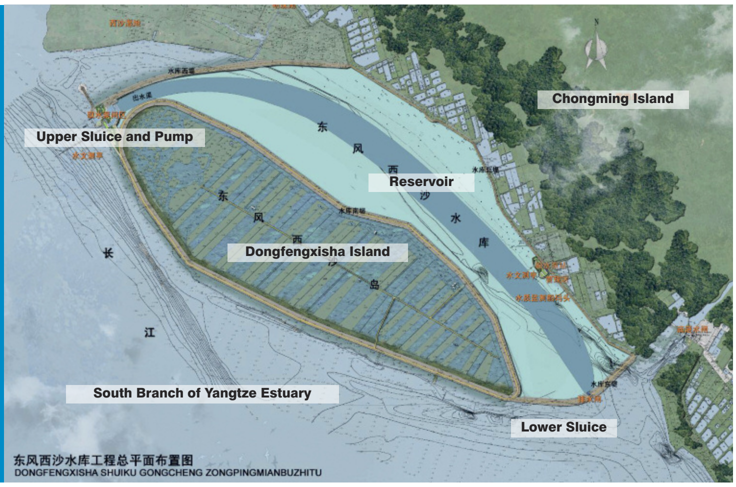

Figure 5. The Schematic Layout of Dongfengxisha Reservoir

•Dongfengxisha reservoir

The Dongfengxisha reservoir is located on the north bank of the South Branch of the Yangtze estuary, namely southwest of Chongming Island. Its construction began on November 29, 2011 and the reservoir started operating on January 17, 2014. The total length of the dyke is 12 km. In addition to this dyke there is a newly constructed dyke, which is 3572 m long. The total reservoir area is 3.74 km^2. The maximum high water level of the reservoir is 5.65 m. The dead storage water level is 1.0 m. The total reservoir capacity is 9.762 Mm^3, and its effective capacity is 8.902 Mm^3. The present design daily water supply is 0.215 Mm^3/d and it is expected to be 0.40 Mm^3/d in the future. There are upper and lower sluices and a pumping station at the entrance as shown in Figure 5. The upper pumping station capacity is 40 m^3/s. The upper sluice gate is 14 m wide and its bottom elevation is 0.0 m. The lower gate is 8.0 m wide and bottom elevation is -1.0 m. The current water supply benefits some 700,000 Chongming Island residents.

Lessons from the study and design of the coastal reservoirs of Shanghai

The main function of the Shanghai coastal reservoirs is to store fresh water during periods of low salinity and high water quality at the intakes, which means that their gates or pumps need to open and close daily based on the tidal/salinity level. In extreme cases like at very high tide, during typhoons, or oil/chemical spill accidents, the intakes close for as long as needed to avoid seawater/contaminant pollution. In any case, the hydraulic structures, intake and water supply facilities of the reservoirs must be safe and stable. The most important criteria for opening the gates/pumps is that the water quality in the reservoirs meets the requirements of the design standards at all times. Therefore, the following issues are important for any coastal reservoir design: site selection, intake operation method, arrangement of sluice and pumping house, scheduling scheme, deepwater dyke, gap closure, water quality protection and reservoir eutrophication prevention control technology, hydraulic fill dam in soft soil foundation, closure gap setting, protection and closure, permeable foundation pit maintenance and foundation treatment. In an effort to supply sufficient good quality water to Shanghai, all these aspects of the design have been proven to be correct and to have functioned properly. The experience gained from the Shanghai coastal reservoirs can serve as a useful case study for similar coastal reservoir studies, design and construction in other parts of the world. Totally different from inland reservoir designs, the coastal reservoir design needs to take account of the following issues:

Runoff and tide characteristics, fluvial processes. They play a key role in the water intake and site selection. When and how to take freshwater depends on the results of the analysis of runoff and tides. The location of the reservoir and the intake system should be selected in areas where scouring and silting is relatively small.

Saltwater intrusion and reservoir scale. Saltwater intrusion has a direct impact on coastal reservoirs. It also plays a key role in site selection, the layout of the hydraulic structures and the operation of the reservoir. A prerequisite for any coastal reservoir in an estuary is the study of seawater flow patterns and salinity profiles in the estuary. The longest continuous unfavorable time in terms of intake water quality is a decisive factor for the size of a coastal reservoir, similar to the Qingcaosha reservoir.

Site selection and arrangement of the dyke alignment. It is necessary to consider the impacts of the project implementation on the estuarine fluvial evolution, but also to take into account that regime changes may have environmental impacts on the project itself, which means that countermeasures should be proposed to minimize such impacts. The site of the reservoir and dyke alignment should be selected in areas where the riverbed/seabed is relatively stable and no serious scouring/silting occurs. There should be no obvious adverse effects on flood control and drainage, navigation channels, fluvial processes, existing engineering and other facilities.

Intake design 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 reliability of the reservoir water intake. The selection of the location of water intake and its design have a direct impact on water supply safety, the scale of water intake, reservoir operation costs, and getting high-quality fresh water. For reservoirs with a large water supply capacity, it is necessary to study the tidal characteristics and saltwater intrusion in the area of the intake and pay special attention to the arrangement of the pump and gate structures. In addition, appropriate scheduling operation studies are needed in order to reduce operating costs and save energy.

Flow to a reservoir by gravity via its sluice gates is possible when the outside water level is higher than the reservoir water level, and its salinity and water quality are acceptable. The reservoirs are prone to eutrophication if water in the reservoir remains stagnant over a long time at high temperatures. Therefore, in the Yangtze reservoirs described above, there is a sluice in the lower part of the reservoir which is used to drain water from the reservoir. This arrangement can make full use of the tides by taking water into the reservoir at higher tidal level, reducing the operating energy consumption. At the same time, the operating scheme in which water taken from upstream is drained from downstream at low tide level can control the water retention time in the reservoir.

Water quality protection and reservoir eutrophication prevention and control. Coastal reservoirs are generally shallow. Flow patterns in these reservoirs also influence water

quality. After their completion, they are at great risk of eutrophication. Full consideration must be given to the reservoir shape, the layout of the pumping station and gate, scheduling operation, etc., to make the water flow smoother through the reservoir and keep water residence time as short as possible to prevent stagnation, which may facilitate eutrophication.
The way to prevent eutrophication is to optimize the shape and morphology of the reservoir; select the appropriate layout; optimize reservoir operation to increase the flow of water, supporting the establishment of a sound ecological system; and take other measures to maintain and improve water quality in the reservoir.

Through the linkage of the operation of the upstream and downstream facilities, the mobility of water in the reservoir is increased and the residence time of water in the reservoir is reduced. The ability of the reservoir to resist eutrophication is also enhanced. Dredging to make the water flow more smoothly can also reduce the risk of local algal outbreaks.

Hydraulic fill dam in soft soil foundation. The dykes around coastal reservoirs are generally constructed in a seawater environment where the water depth is generally around 10 m. Therefore, conditions like deep water, fast flows and high waves are unfavorable for construction. Furthermore, the foundation soil is often unfavorable to stabilize the dyke due to its soft and weak nature and severe settlement potential. Because the long dykes for many such reservoirs may be built on water there is no land for activities supporting the construction of the dykes. In such cases specific, plastic drainage plates can be used for foundation treatment, and large and high strength geotextile bags with hydraulic filling can be placed to form a sloping dyke.
For seepage proofing of the hydraulic fill dyke, an impermeable wall of triaxial cement mixed piles has been successfully applied to the hydraulic fill dyke. For the closure section of the dykes for the coastal reservoirs of Shanghai, a new type of impermeable wall was built by assembling one row of high pressure jet grouted piles between two rows of triaxial mixed piles.

Closure gap setting, protection and closure. The coastal reservoirs in Shanghai were formed by building an encircled dyke. Therefore, the greatest concern and risk point during the construction period was on the arrangement and protection of the closure gap, as well as the closure design. Because of the effect of the reversing tide at the closure gap, the periodic tidal variation limited the continuous and available working time. Due to the shortage of stone material and land riprap, the soft and weak soil foundation can be easily washed away and it is difficult to protect. Any scouring is extremely difficult to control.
To accommodate the construction of underwater structures equipment operated from a ship whose size meets the local hydrological and water depth requirements was used. The armor face of the closure gap had a multi-layer composite protection structure. The layers of this structure were from the bottom up, large-sized high-strength geotechnical cloth bags filled with sand (sand quilt), 1,300 g/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. For damming the closure gap, a plain plug with steel-caged riprap was used.

Permeable foundation, pit maintenance and foundation treatment. The average tidal range in the Qingcaosha reach is 2.43 m. The foundation base elevation of the main pumping house is -12.0 m. Therefore, it was necessary to build a cofferdam in the middle of the river. Within the part surrounded by the cofferdam a deep foundation pit needed to be excavated. The soft soil layer underlying the structure was deep and thick and the load of the upper structure of the pumping station and sluice was relatively high. Because of the difference in loads, the foundation was required to be treated in consideration of the deformation that might occur between the pumping station and the sluice and both sides of the connecting embankment.

Taking the protection requirements of the cofferdam and foundation pit into consideration, a composite protection system formed by combining the cofferdam, sloped excavation and underground continuous cutoff wall was used. Consequently, the function and requirements of water retention, seepage and the construction conditions on dry land were satisfied.

The foundation reinforcement was conducted by using high pressure jet grouting piles to coordinate the deformation at the connection of dyke and gate; thus the hidden danger of leakage caused by potential uneven settlement at the connection of the structures and the dyke was avoided.

Prospects

So far the Shanghai coastal reservoirs have performed well and the water quality in the reservoirs meets the requirements of the design standards. However, some areas are still worthy of further study.

- Because the Qingcaosha reservoir forms the upstream division area between the South Channel and North Channel of the Yangtze estuary, the evolution of the channel system by sedimentation and scouring is extremely complex. The hydrodynamic processes in the reach of the Qingcaosha reservoir, especially in the waters near the west, and the upstream section at the north side of the Qingcaosha reservoir, should continue to be monitored. Beach protection measures must be carried out if necessary.
- The residence time of water in Qingcaosha reservoir was considered to be 15 ~ 20 days. The eutrophication risk in this reservoir is relatively high because nitrogen, phosphorus and other nutrient levels are high in the Yangtze estuary. A study on how to increase the reservoir water mobility to shorten the residence time to 7 ~ 10 days and further reduce the risk of a algal blooms is necessary.
- It is recommended to continue dredging and to optimize the reservoir underwater topography to enable flow conditions to meet the requirements for ecological restoration both inside and outside the reservoir embankment.
- The capacity of the Chenhang reservoir is small. It cannot meet the water demand because of the growth of the population. Research is needed on how to expand capacity and improve the water supply guarantee rate of the Chenhang reservoir.
- Water quality at the intake of the Chenhang reservoirs is easily affected by irregular drainage from the Liuhe River of Jiangsu province. Optimizing the reservoir operation scheme is still needed because the Chenhang reservoir is located downstream from the Liuhe River.
- Other potential water sources in the Yangtze estuary are still worth studying in order to meet the water demand of Shanghai in 2040, when the population is predicted to reach 25 million people. ■

THANEERMUKKOM SALT WATER BARRIER TO PREVENT SALT WATER INTRUSION: AN OVERVIEW OF KUTTANAD LOW LAND DEVELOPMENT

BY THALLAK. G. SITHARAM & KOLATHAYAR SREEVALSA

The Thaneermukkom salt water barrier bund was constructed in 1974 to prevent tidal action and intrusion of salt water into the Kuttanad low land across the Vembanad Lake in Kerala, India. This bund divides the Vembanad lake into two, Thaneermukkom in the south with fresh water fed by the rivers draining into the lake and Vechur in the north with brackish water fed by the Arabian Sea. This bund creates a fresh water storage reservoir by storing river flood water, which has helped the farmers in Kuttanad, where farming occurs below sea level. The gates of the bund are opened during the monsoon period and are closed after approximately six months. This article reviews the present status of the Thaneermukkom reservoir and provides suggestions for tackling its environmental and ecological problems such as the pollution of the backwaters and the entire land nearby and the rampant hyacinth growth in the freshwater reservoir.

The Theneermukkom bund was constructed in 1974 as part of the Kuttanad low land development scheme and the creation of a fresh water reservoir in the coastal area of Kerala. The Thaneermukkom salt water barrier / bund is considered the largest mud regulator in the country and has been in operation since 1976. It divides the Vembanad Lake into a fresh water lake fed by the rivers draining into the lake, and a brackish water lake fed by ocean currents into the low lands of Kuttanad. The four major rivers of Kerala, the Pamba, Meenachil, Achankovil and Manimala flow into the region before they reach the Arabian Sea. The lake is fed by ten rivers of which the above four major rivers are the largest. The region receives a good amount of annual rainfall, which is above 3000 mm. These four rivers carry a large quantity of water. By constructing the salt water barrier, a coastal reservoir having fresh water has been created for increasing agricultural activities in the area in addition to facilitating land development. However, there are reports of environmental and ecological damage such as rampant propagation of water hyacinth in fresh water and decline in brackish water fishing in the area. However, these are attributed to a faulty operation of the reservoir system and the lack of a scientific plan for the Thaneermukkum bund to function based on water level and salinity. The problems faced by fishermen and the water hyacinth problems need to be addressed with innovative alternative schemes of operation. In fact, efficient operation of this fresh water reservoir is essential for regular supply of drinking water to nearby areas and also supply fresh water for irrigation in the low lands of Kuttandu, which would help the local farmers.

Figure 1. View of the Thanneermukkom bund

Conditions before the construction of the bund

The Kuttanad region includes the lowest lying lands of Kerala. The region has the lowest altitude in India. It is one of the few places in the world where farming is carried out at 1.2 to 3.0 metres below sea level. The ecology of the Kuttanad region is greatly influenced by the mixing of flood water and sea water entering the Vembanad Lake. Before the construction of the Thanneermukkom barrier, the low-lying lands in the Kuttanad region were periodically inundated with salt water and only a single crop was raised annually from the paddy fields. Kuttanad is the major rice producer in the state and popularly known as the rice bowl of Kerala. In earlier days, the farmers usually constructed temporary bunds, known as "muttu", across the canals and rivers to prevent the ingression of salt water, which were pulled down soon after harvesting.

The process of bund construction and operational issues

The Thanneermukkom bund has a length of 1400 m which includes a 470 m long stretch of reclaimed land at the centre of the bund. Construction began in 1955 but completion of the project took many years. The western and eastern portions of the bund have 31 shutters (gates) on each side. The construction of these parts was completed in 1967. Only two-thirds of the construction was complete by the year 1973. The remaining one-third was temporarily bunded with sand and clay by mobilising local labour. Though incomplete, the regulator was commissioned by the end of 1974. In 1977, the government started building the middle section. The second phase at the Vechoor end was completed in 1974 with 31 shutters (gates) and one lock. A coffer dam was erected in 1975 when work of the third phase was delayed.

Land had to be reclaimed from the backwaters to complete the construction. The shutters were connected on either side to control the entry of salt water. As per existing practice, the shutters remain open only during the annual monsoon. A detailed study of the economic and ecological problems of the Alappuzha district as well as the Kuttanad wetland ecosystem was carried out by the M.S. Swaminathan Research Foundation (MSSRF) in the year 2007. They recommended completing the work on phase 3 of the Thanneermukkom barrage following a modern design compatible with the renovated phase 1 and phase 2 portions and with all shutters operational. They suggested to provide a middle lock in the Phase 3 section with a width of about 40-50 m, with the modification of the bridge in a manner to open up the bridge upward for navigation. They also recommended to renovate and modernize the Phase 1 and 2 with corrosion-free shutters, with a smooth closing and opening system so that all the shutters could be totally opened and closed in

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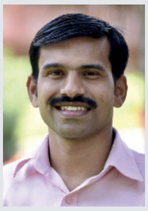

Dr. Kolathayar is a member of the faculty of Civil Engineering at Amrita Vishwa Vidyapeetham Coimbatore and Secretary of the Indian Chapter of IACRR. In 2017, Dr. Sreevalsa was featured in the New Indian Express and honoured with the Edex award: 40 under 40 - South India's Most Inspiring Young Teachers.

15-30 minutes like the shutters to be installed in the Phase 3 section. It was suggested to explore the possibility of computerized operation of the shutters and its lock systems based on standardised inputs on post and pre-monsoon water level, salinity level, etc.

Conditions and challenges after the construction of the bund

In addition to supplying water for agriculture, the bund facilitates road transportation and connects two districts of Kerala (Alappuzha and Kottayam). One of the major adverse effects of the barrier is the growth of water weeds, especially Salvinia and Eichornia. The southern side of the Vembanad Lake has become a static pool because of the operational defects of the Thanneermukkom barrage, as the shutters were operated without considering the post and pre-monsoon water level and salinity. The drained waters from the paddy fields with large quantities of fertilizers, pesticides, and industrial effluents, human and agricultural wastes become stagnant in the rivers, lakes and canals. An acute drinking water shortage is felt even in the lower areas because of saline water intrusion.

During times of limited rainfall and when the water flow from the Manimala and Pampa rivers into the lake is reduced, the salinity level increases, which affects paddy cultivation. Consequently, this causes a drop in the production of rice. Paddy farming is being carried out over around 20,000 hectares of paddy fields in Alappuzha and 8,200 hectares in Kottayam.

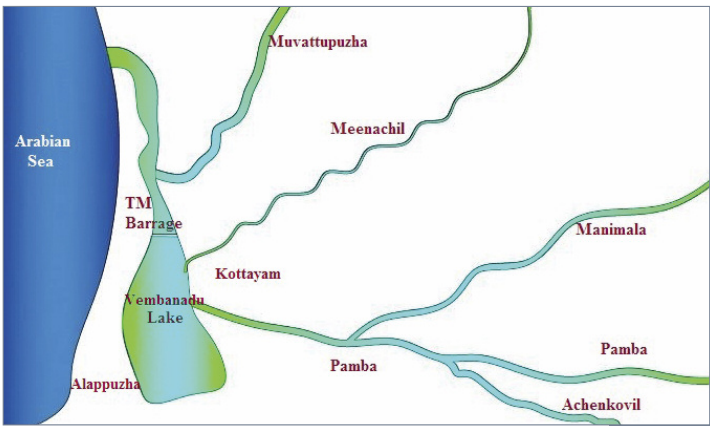

Figure 2. Location of barrage across Vembanadu Lake

Current status and way forward

The construction of the third stage, at the middle portion of the bund is in progress. The third phase consists of 28 shutters, of which 14 have been completed. These shutters are now mechanised and can be operated very easily. Earlier it was very difficult to operate them, and only one shutter could be operated at a time. The operation of the reservoir is now a boon to farmers of Kuttanad, since they can use salt-free water for farming throughout the year. The shutters can be kept open during the monsoon and during the fish breeding periods. During the summer, the shutters need to be closed to bring down the salt content in the water. Wireless sensors can be employed to monitor the salinity of the water and a network of sensors can efficiently aid in gate operation to control the entry of salt water into the freshwater lake. The passage of houseboats will not be affected much since there are gateways on both sides of the bund. The pollution by human activities has to be controlled and the gate operation must be adjusted to prevent the stagnation of water, which will be effective in preventing hyacinth growth along with pollution control.

Though there are many controversies regarding the Thanneermukkam Bund, it remains a fact that it is helping the farmers in the rice bowl of Kerala. If the people learn to cherish the water and take ownership of it, their inclination to pollute or vandalize will be diminished. With efficient operation and maintenance, the bund will help the local population by providing salt-free water as well as by contributing to the growth of the tourist sector by attracting people from other places. ■

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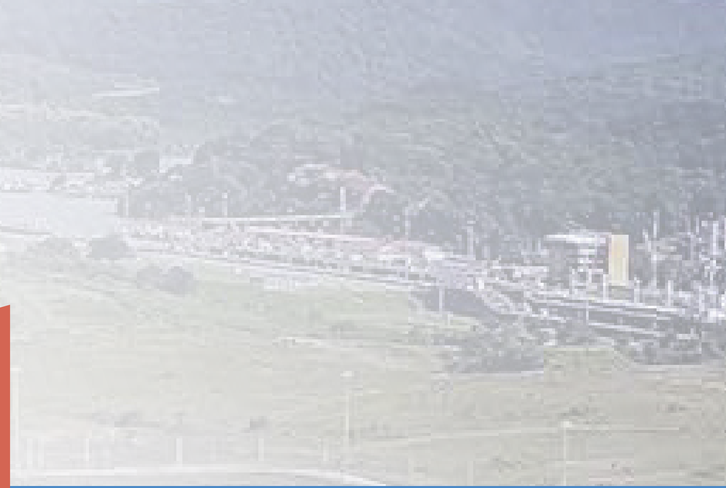

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ENVISAGING A FRESH WATER RESERVOIR IN THE ARABIAN SEA TO IMPOUND THE FLOOD WATERS OF NETRAVATI RIVER

BY THALLAK. G. SITHARAM

A solution to the water problem in parts of India along the coast is to conserve the abundant monsoon water bounty, store it in coastal reservoirs, and use this water in areas which have occasional inadequate rainfall, or are known to be drought-prone, or in those times of the year when water supplies become scarce. Coastal reservoirs are an innovative concept, which offers the potential to store the flood waters of a river near the point where it flows into the sea and meet the water requirements of water starved cities [1]. Mangaluru city, in Karnataka state, India is blessed with the river Netravati, which carries a great quantity of water during the monsoon and ends up in the sea. The annual runoff at the mouth of the Netravati River is estimated to be 388 thousand cubic meters (TMC). Just 3% of this would be sufficient to meet the present water shortfall of Mangaluru city and Bangalore the capital city of Karnataka. This article describes a feasibility study executed for the Bangalore Water Supply and Sewerage Board (BWSSB), Bangalore.

The use of coastal fresh water reservoirs is a new emerging concept of storing flood water close to the shoreline [2]. Coastal reservoirs can be constructed in shallow waters at appropriate locations close to the river mouth along with a barrage at one or two ends. Sea walls or breakwaters with some modifications along with new and sustainable construction technologies are used to construct such coastal reservoirs. Many countries like China, Singapore, Hong Kong, The Netherlands, India, South Korea, Japan, and the United Kingdom have already constructed such reservoirs to augment water supply and serve other purposes [2].

Mangaluru, a coastal city, situated between the Arabian Sea and the mountain ranges of the Western Ghats, is the chief port city of Karnataka. It is the largest city in the Dakshina Kannada district of Karnataka and is one of the most cosmopolitan non-metro cities of India. Mangaluru is a moderately earthquake-prone urban center and is categorised under the Seismic III Zone in the seismic zonation map of India. Mangaluru city had a population of 0.485 million in the 2011 census of India. The city is located at the confluence of the Netravati and Gurupura rivers, and has an average elevation of 22 m above mean sea level. The rivers form an estuary at the south-western region of the city and then discharge into the Arabian Sea.

A fresh water reservoir near the coast would bring a positive transformation in coastal Mangaluru in terms of cleanliness, living standards of the people, human resource development and livelihoods. The envisaged coastal reservoir project scheme in Mangaluru comprises mainly two steps; first, the

Figure 1. Artist's view of Mangaluru Coast near the Netravati estuary, after the construction of the coastal reservoir

construction of a dyke in the Arabian Sea, and, second, the process of natural replacement of salty water in the reservoir by rainwater and surface runoff. Considering the tidal variations and wave heights, the dyke must be designed to separate fresh water from the salty waters of the Arabian Sea.

Course of the Netravati River

Figure 2 shows the Netravati River basin in the state of Karnataka. The Netravati River originates in the Western Ghats in the Bangrabalike forest Valley in the Yellaner Ghats of the Kudremukha range in Karnataka. The Netravati is joined by the Kumaradhara River near the Uppinangadi village. The Kumaradhara River also originates in the Western Ghats in the Subramanya range. After it flows through Uppinangadi, it arrives in the city of Mangaluru. After merging with the Kumaradhara River, the Netravati then ends in the Arabian Sea. As shown in Figure 3, this river drains a large quantity of water into the Arabian Sea every year close to Mangalore city.

Average Annual Rainfall and Runoff in the Netravati Basin

The average annual runoff in the Netravati Basin during 1989-2013 was 388.5 TMC with a standard deviation of 78 TMC, and a maximum of 528.34 TMC in 2007-2008 The average annual rainfall in the Netravati Basin over the decade 2003-2013 was 3922.5 mm with a standard deviation of 383 mm and a maximum of 4427.8 mm in 2009-2010. No major variation in the rainfall has been experienced in the last decade. The sediment load is negligible and hence silting in the proposed coastal reservoir should not be a major problem.

Geotechnical considerations

Geotechnical investigations carried out at the coast off the Ullal beach near Mangaluru suggested that no extreme geotechnical challenges exist and that construction of the proposed coastal reservoir can be undertaken. Two exploratory boreholes at each of two sites off Ullal beach at a water depth not more than 6.5 m were drilled. The soils at these sites consist of clayey medium dense sand in the top 1.5 m followed by clay up to 3 m. Below 3 m, dense to very dense clayey sand was encountered up to 9m deep followed by poorly graded dense sand with pockets of clay. Beyond 20 m depth, a thick clay layer along with dense sand is present. The settlement (immediate and long term) of the proposed coastal reservoir dyke is expected be about 300 mm to a meter.

A detailed integrated site survey comprising of a geophysical investigation (bathymetry, sidescan sonar and sub-bottom profile) and a geotechnical investigation (borings, in-situ testing and laboratory testing) shall be undertaken in order to develop an appropriate geological model for the site of the proposed coastal reservoir.

Inferences and Feasibility Implications

It is imperative that a small percentage of waters of the Netravati is more than sufficient to cater for the water requirements of Mangaluru. The data for the last few decades suggest that there is no scarcity of water in the Netravati River, but the city faces water shortages. This necessitates revisiting the current water storage strategies and exploring new ways to tap at least a small amount of the river flow to meet the water demand. The concept of a coastal reservoir seems to be the best solution to meet future water demand in Mangaluru. The feasibility implications are summarized below.

The average annual runoff in the Netravati basin is 388.5 TMC. According to the Bangalore Water Supply and Sewerage Board (BWSSB), the shortfall in demand in Bangalore for 2051 will be 26.16 TMC which is 7% of the average annual runoff in the basin. In 2021, the shortfall in demand is estimated to be only, 8 TMC which is just 2.1 % of the total basin runoff.

Silting in the proposed coastal reservoir is unlikely as the average annual sediment load in the Netravati River is 0.04 TMC.

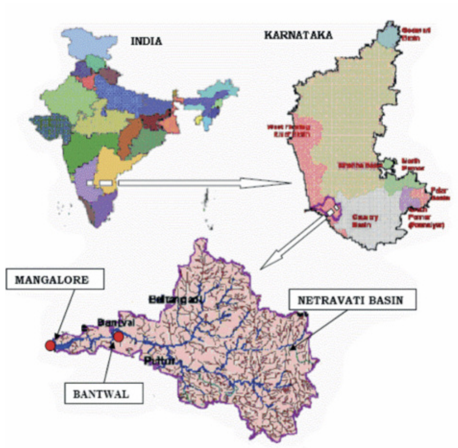


Figure 2. Netravati River basin

The water quality parameters in the Netravati River are within safe drinking water levels, which means that the water can be used directly without any major treatment.

The creation of the coastal reservoir may affect marine fishing in the area, but it will open up the possibility of freshwater fishing. A fishing wharf can be established along the dike of the coastal reservoir which will provide deep water fishing options for the fishermen and pave the way for Mangaluru to become a large exporter of both marine and fresh water fishes.

The seismic hazard in the area is very marginal and hence the site is safe in terms of seismicity. The coastal reservoir can act as a safety structure to protect the coastal region from tsunami hazards.

Figure 3. Average Annual Runoff at Netravati basin [3]

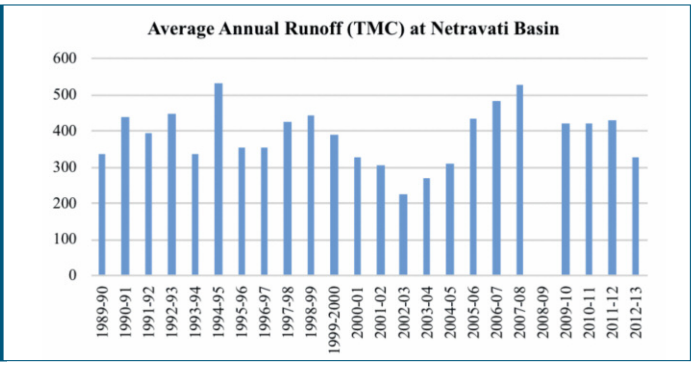
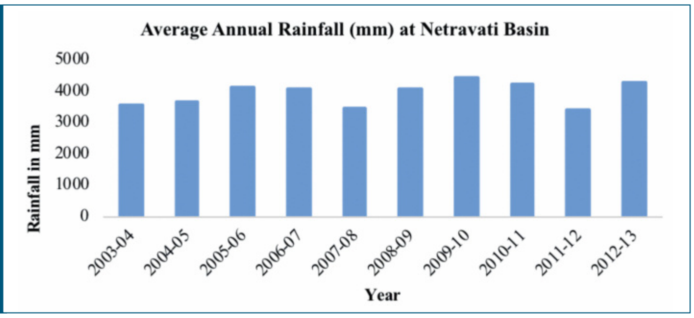
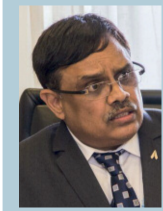


Figure 4. Average Annual Rainfall in Netravati basin [3]



Renewable energy can be used for pumping, lighting and other energy requirements. Consultation with and input from renewable energy developers would support the planning phase of the project to achieve cost effective renewable energy generation.

We recommend two phases for the construction of the coastal reservoir. Figure 1 shows the proposed reservoirs (phase 1 and Phase 2) along with Coastal Regulation zone (CRZ) of 500 m. Good quality water from the Netravati and Gurupura rivers can be diverted into these proposed coastal reservoirs during the monsoon months. Smaller water quantities during non-monsoon months could also be diverted after ascertaining that the quality of the water is good. In Phase 2 the proposed coastal reservoir will save the Ullal beach, which is endangered due to erosion. The length of this coastal reservoir is about 8.3 km starting from the river mouth to the South of Mangaluru Port with a width of 6 km. The coastal reservoir will not affect the built-up area. The assessment of land use in this area indicates that the built-up area is limited, while the vegetation cover is more extensive. Also, because the construction of the fresh water reservoir will cause a reduction in the salinity of the water, its effect on the vegetation must be pre-assessed and analyzed. The construction phase and later the maintenance of the coastal reservoir will create employment opportunities for the local people. As part of the sustainable city development plan, rehabilitation of the areas around both the Gurupura and the Netravati River are recommended as part of the project component in order to change the existing landscape making Mangaluru an attractive, clean and beautiful water front City (see Figure 1).



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Acknowledgment

The work and the ideas described in this article are the product of contributions of many people including Dr. Sreevalsa K, Professor Subba Rao, Professor Amai Mahesha, Dr. H. Ramesh, Dr. Basavarju Manu, Dr. Raviraj H. Mulangi, Dr. T. Nasar, Professor Shu-Qing Yang, Mr. Lim Sin Poh, Dr. Manoj Samuel, and Dr. Partha Sarathy, as presented in the report to Bangalore Water Supply and Sewerage Board (BWSSB) [4].

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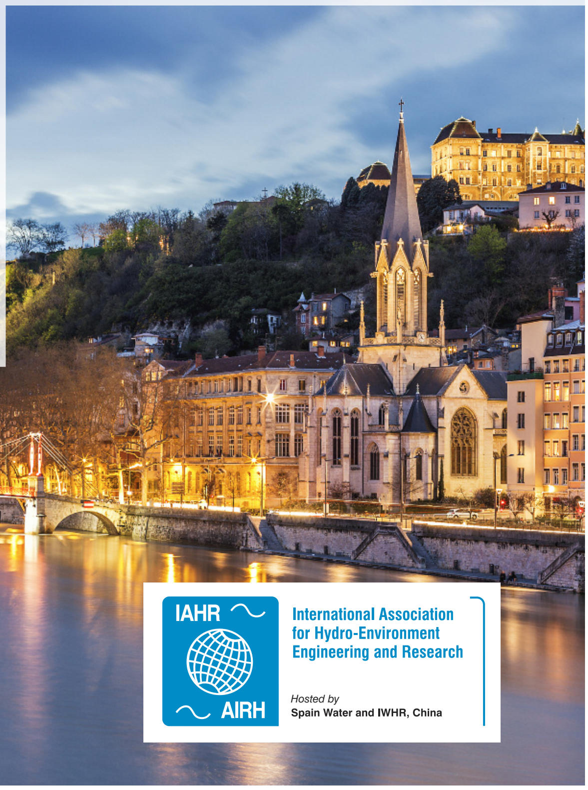


IAHR GENERAL MEMBERS ASSEMBLY (GMA)

Venue: **Lyon Convention Center "Espace Tête d'Or" France**
Date: **Saturday 8th September 2018**
Time: **14:00**

AGENDA

1. **Opening**
2. **Approval of the Minutes of the 2017 GMA**
3. **2017 Financial Report**
4. **Secretariat Activities Report**
5. **IAHR Governance Structure Discussion**
6. **Closure**

A PARADIGM SHIFT FROM UPSTREAM RESERVOIR TO DOWNSTREAM/COASTAL RESERVOIRS MANAGEMENT IN MALAYSIA TO MEET SDG6

BY TAN YEW CHONG, MD NASIR BIN MOHD NOH, LIM SIN POH & MICHEAL TEH JIN CHOONG

Water is the core of sustainable development. Water scarcity affects more than 40% of the global population and this percentage is projected to rise. Malaysia, despite having abundant annual rainfall, experiences water stress in major cities. In order to achieve Sustainable Development Goal 6 (SDG6), the Malaysian government recognizes the need to harvest water using alternative methods. As a result, Malaysia has recently seen a paradigm shift in water resources development works from traditional upstream reservoirs to downstream reservoirs.

In the recent 2018 budget, the Malaysian government listed several water resource development projects emphasizing off-river storage (ORS), a downstream reservoir concept. This concept is gaining popularity after several successful ORS implemented projects, solving both quantity and quality problems that persist in the traditional approaches of Run-Off River Schemes or Regulated Dam systems. It has also been proven to be more economically, socially and environmentally friendly.

Introduction

Malaysian water demands are anticipated to escalate over the next twenty years as the country continues to develop. The population is estimated to increase to 41.5 Million by year 2040, compared to the present population of about 30 Million, (2010 Population Census). This translates to an increase of an 11.5 million population increase over the next 20 years. Figure 1 shows the projected demand used for planning purposes and the water supply system development from 2010 until 2050, (National Water Resources Study 2010). This indicates a need for water supply system development with capacity of about 10,000 million liters per day (MLd) from 2010 to 2030. Considering the present stress on water resources quantity and quality in major cities, this has become one of the key issues for development in Malaysia. Figure 2 shows a map of Malaysia with the location of the major cities. A sustainable solution to water resources development is critical in order to support the increasing water demand.

Figure 1. Long term water demand and supply development requirements for Malaysia

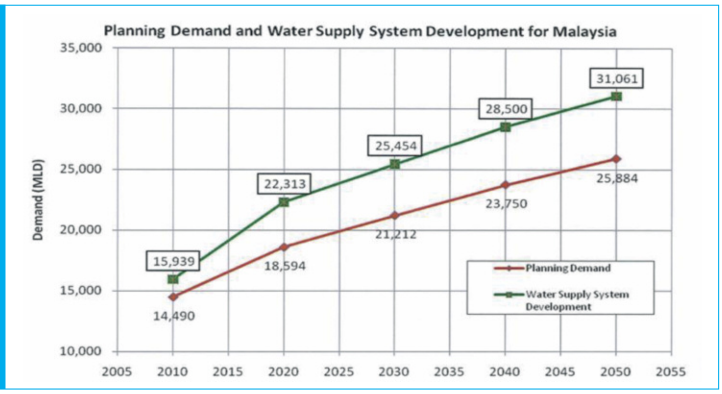
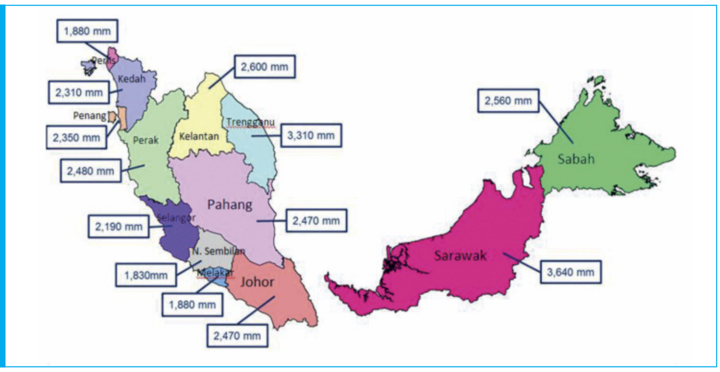


Figure 2. Map of Malaysia with the location of the major cities, which are mostly located near the coast

Figure 3. Malaysian annual rainfall distribution in each state



Evolution of water resources development in Malaysia

Currently, there are three main approaches to raw water abstraction in Malaysia. Surface water is the most extensively developed resource due to the abundance of rainfall in Malaysia, which can be as high as 3310 mm annually at Terengganu (East Coast) and 3640 mm annually at Sarawak (East Malaysia). Figure 3 shows the average annual rainfall at each state in Malaysia. About 81% of raw water resources is directly abstracted from rivers for water treatment plants (WTPs). Flow regulation or direct supply from dams comprises 17%, while the remainder is supported by ground water.

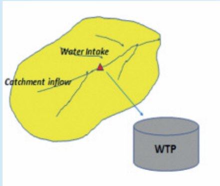
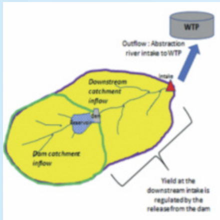
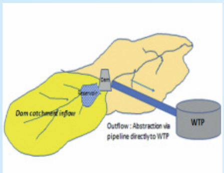
Runoff river schemes are facing both water quantity and quality problems. As more and more intakes are built along rivers to supply developments in the same catchment, drought effects on flow and water levels become more pronounced. Intake yields are thus affected based on land use and development scenarios, and WTPs cease operations when river water quality does not meet required standards. High ammonia content is a frequently reported cause of disruption. WTPs at Cheras Batu 11, Bukit Tampoi, Skudai, Linggi, Sembrong in particular have been struggling with river water pollution problems during the dry season.

Water resources development by means of dam construction has become less favorable since its portrayal as a non-environmentally friendly solution, facing strong objections from the public and NGOs. Dam construction is counterproductive to government efforts and commitments to reduce the carbon footprint of the country. State governments also express concerns about losing huge land areas, which are submerged underwater in the reservoirs formed by dams, as well as about the constraints in developing the dam catchment post-construction.

The uneven distribution of rainfall, particularly in the West 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 44.6 km in length, to the recently completed Langat 2 water treatment plant at Selangor. Other interstate transfer schemes currently at the planning stage include the Johor-Melaka, Melaka-Negeri Sembilan, and Perak-Selangor water transfer scheme. These transfer schemes need to be reviewed as the energy cost for their operation is high.

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 abandoned tin mining pits located within the water catchment as storage to store sufficient water for river flow regulation during the dry season. While HORAS managed to increase the water resources yield, there were water quality concerns due to the residuals of heavy metals in the beds of the abandoned tin mining pits.

Table 1. Issues and challenges of the current approaches to water resources development and management

Approach	Challenges
1. Direct river intake 	(i) Low river water levels during drought do not allow water to enter intakes, and result in limited operation or shutdown of WTPs. (ii) Sedimentation at river intakes requires dredging maintenance. (iii) Saline intrusion moves further upstream due to increase in upstream abstraction and the impacts of sea level rise. (iv) River pollution results in poor water quality, especially during dry seasons. Increasingly frequent exceedance of acceptable limits for WTPs, such as high ammonia content, has caused shutdowns. (v) High total suspended solids (TSS) content result in high treatment cost. (vi) Lower river yield due to increase in upstream abstraction and climate change.
2. Regulating Dam 	(i) Reservoir water levels drop during droughts due to the inland location of dams and reduced rainfall. (ii) Active land development and agricultural activities upstream of the dam catchment causes reservoir water quality deterioration. (iii) Illegal encroachment into dam reservoir areas or fringe developments. (iv) As the intake lies on a river, it will still face similar issues as per 1. (i) to (v).
3. Direct Supply Dam 	(i) Same challenges as 2.(i), 2(ii) and 2(iii). (ii) Extremely difficult to mitigate when reservoir water starts to deteriorate.
4. Groundwater 	(i) Development is discouraged due to abundance of available surface runoff. (ii) Geologically dependent, and more suitable for remote areas where water supply networks are not extensive. (iii) Involves high pumping and drilling costs. (iv) Inventory not available.
5. Interstate/Inter catchment Transfer	(i) Involved high capital expenditure (CAPEX) and operating expenses (OPEX). (ii) High pumping costs. (iii) Involves interstate contractual issues.

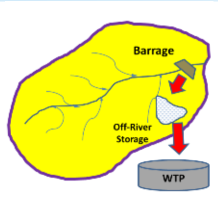
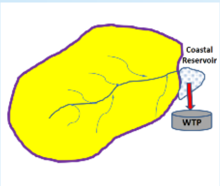
An alternative solution is needed to increase storage capacity without compromising water quality. The downstream/coastal reservoir (CR) concept could serve this purpose very well. The introduction of coastal reservoirs, as promoted by the International Association of Coastal Reservoir Research (IACRR), provides another innovative solution in addition to ORS. While ORS utilizes existing pond storage facilities, the CR concept can be a good alternative if suitable pond sites for ORS have been exhausted. Compared to ORS which utilizes land space, a CR creates additional space which can be potentially utilized not only for water resources, but for other purposes such as waterfront development, power generation, and tourist facilities. CR can be one of the sustainable solutions utilized to solve the water scarcity problems in many coastal cities globally and in Malaysia, thus meeting the SDG 6 set by the United Nations. Table 2 summarizes the issues and challenges of new water management approaches.

Coastal reservoir as an innovative and sustainable solution

Water Availability

Based on the rainfall depths and recipient land surface area in Malaysia, there is an annual rainfall volume of roughly 971 Bm^3. Assuming that 50% of rainfall becomes surface runoff, after evaporation losses and groundwater recharge, the surface runoff volume is approximately 496 billion m^3. The total water demand as of 2020 is about 18.2 Bm^3 for all sectors, only 4% of this volume, See Figure 4.

Table 2. Approach and challenges of policy shifts to downstream water management

Approach	Challenges/Remark
6. Off-River Storage  	(i) Utilizing an existing former mining pit, or a natural pond to store water to regulate flow. This is viable as it utilizes the water storage and does not involve changes in the water surface area. (ii) When former mining pits and natural ponds are exhausted, the construction of new ponds changes parts of the land to water areas. Disadvantages: - (i) May potentially create environmental problems by changing part of the land cover to a water body. (ii) Loss of land areas for land development. (iii) High land acquisition cost. (iv) High excavation and disposal costs (lower if the soil is of sand that can be excavated easily).
7. Downstream/Coastal Reservoir  	(ii) CR configuration is site specific. Requires detailed study and planning before implementation. Specialist input is required. (iii) Main issues in planning, study and design are saline intrusion, water quality and costing.

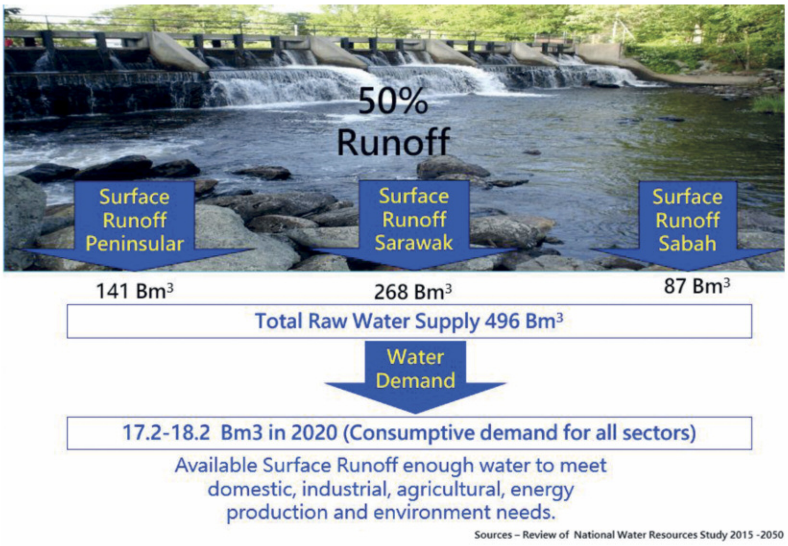


Figure 4. Water availability in Malaysia

As such, Malaysia is not running out of water but water is running out of Malaysia. Downstream/coastal reservoir technology can potentially be a long-term and sustainable solution for water resources in Malaysia. The present river runoff and dam system utilizes about only 3.7% of the available water, with most of the remaining water discharged into the sea. Water shortage is primarily an issue of storage rather than availability.

Why Coastal Reservoir

Instead of using abandoned mining pits, storage can be created downstream or nearshore by utilizing river reservoirs, oxbow lakes, or by constructing reservoirs nearshore (see Table 2). Considering the demand increase of an additional 10,000 ML/d over the next 20 years, with provision of 3 months of storage, this will require a total volume of about 900 Mm^3, which is less 1% of the total runoff available. This suggests that utilization of downstream/coastal reservoirs to store the required water would be sufficient to meet the long term water demand in Malaysia and resolve the water shortage problem during droughts by storing the excess water during wet seasons.

Traditionally, dams and reservoirs are sited in the upper catchment, river intakes are located at the middle catchment to avoid saline intrusion while most demand centers are located in coastal regions. Locating the water supply reservoirs closer to the demand centers downstream, makes it possible to harvest runoff from bigger catchments, with lower environmental flow requirements, and much shorter water distribution networks. In contrast to conventional downstream river intakes, downstream/coastal reservoirs are also protected from salinity intrusion by virtue of their containing structures. Real-time water quality monitoring systems can be used to allow only high quality water to enter these reservoirs. Depending on the demand at each specific locality, water from coastal reservoirs can be utilized for various purposes such as domestic, irrigation or industrial usage.

Downstream/coastal reservoir as sustainable solution to meet SDG 6

The SDGs of the 2030 Agenda for Sustainable Development adopted by the world leaders at the United Nations Sustainable Development Summit in September 2015 cover a broad range of social and economic development issues, including poverty, hunger, health, education, climate change, gender equality, water, sanitation, energy, environment and social justice. They build on the achievements and experiences of the Millennium Development Goals set in year 2000, and focus on 17 goals and 168 targets. The SDGs are a global call to end poverty, protect the planet and ensure that all people enjoy peace and prosperity. SDG 6 aims at ensuring the availability and sustainable management of water and access to sanitation for all. CRs can be one of the sustainable solutions to ensure the availability and sustainability of water supply in Malaysia.

Downstream/coastal reservoirs have limited local environmental impact compared to inland dams and reservoirs. They can be designed to minimize environmental impacts, as demonstrated in the case of Shanghai's QingCaoSha reservoir which took advantage of the existing river alignment and geographical condition (see Figure 5). Located at the river mouth, QingCaoSha reservoir is capable of providing extensive water storage capacity as it is not limited by land area restrictions.

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 5 and thus do not disturb environmental flows or require the rerouting of channels.

The retaining structures of a downstream/ coastal reservoir can be constructed with concrete, earth or other materials depending on the soil condition. 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 QingCaoSha reservoir was formed by a dike structure with a depth of about 25 m, which is a comparatively lower risk structure compared to higher conventional dams. The relative construction costs are reduced by utilizing local sand material as part of the dike body.

A freshwater reservoir such as QingCaoSha also creates a man-made wetland making it environmentally and aesthetically friendly. Figure 5 shows the constructed wetland at QingCaoSha Reservoir.

Ensuring Good Water Quality for Coastal Reservoir

Water quality is critical for downstream coastal reservoirs. However, the QingCaoSha Reservoir has successfully addressed this problem through the following measures:

- Installation of series of real time water quality monitoring stations upstream of the inlet structures.
  By doing so, the inlet gate opens only when the water quality at the inlet meets the required water quality standards. Therefore, a system was designed to allow only selective good water quality water to enter the reservoir.
- Construction of a wetland at the upper part of the reservoir intended to function as a natural filtration system to improve the water quality, see Figure 5. The same concept can be adopted for CRs in Malaysia.

In Malaysia, the Putrajaya constructed wetland is one of the success stories of using wetlands to improve the water quality in the Putrajaya Lake. Figure 6 shows the Putrajaya Wetland system, including its conceptual design and site conditions. By having the upstream wetland system, the water quality in the Putrajaya Lake managed to achieve Class IIA water quality, which represents water bodies of good quality.

Malaysian monsoon weather patterns, with seasonal rainfall and monthly distribution as such shown in Figure 7 make for the use of CRs attractive. The highest rainfall typically falls towards the end of the year, while dry seasons last typically about 2 to 3 months during which time water shortages occur. Storage of excess flood water during the wet season can ensure adequate water supply during the next dry spell. The amount of storage required at the downstream/coastal reservoir can be estimated by assuming zero inflow into the reservoir during drought to account for the worst case scenario. Actual storage requirements can be further refined during detailed design and detailed reservoir storage simulations.

Way forward

Malaysia is a water-rich country. Improving water resources management by adopting the new and innovative approach of downstream/coastal reservoirs can potentially increase the utilization of raw water resources. In order for Malaysia to meet its projected water demand in 2050, it is sufficient to increase the utilization of surface

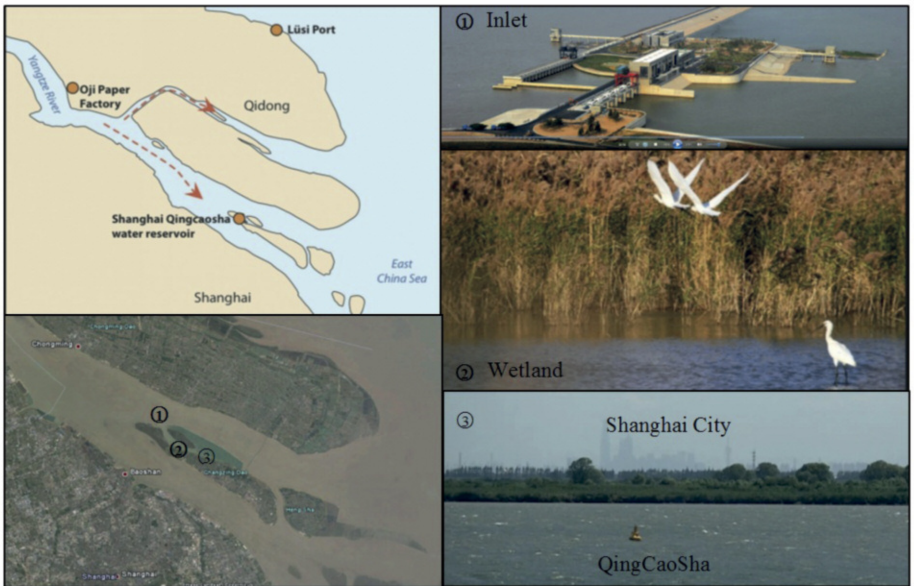


Figure 5. The QingCaoSha reservoir maintains freshwater storage without obstructing waterways

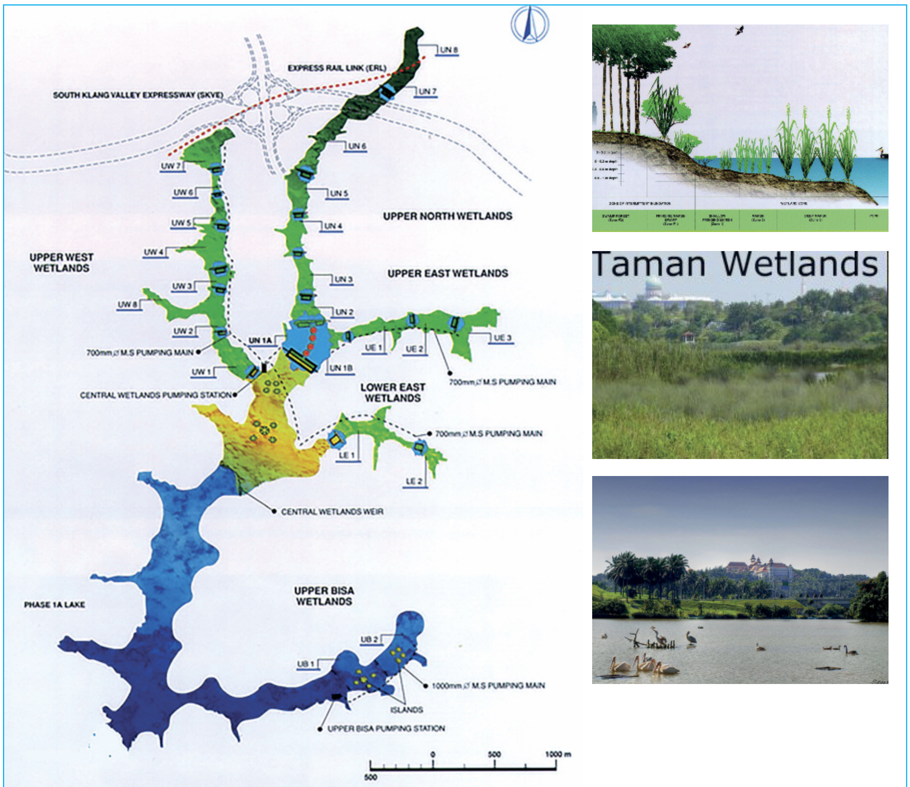


Figure 6. Putrajaya Wetland system with Class IIA water quality at the downstream Putrajaya Lake

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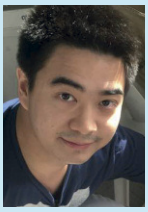

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runoff from the present 3.7% to 5%. This potentially would solve the water shortage problem during droughts by storing the excess water during wet seasons. There are many significant advantages to adopting downstream/coastal reservoirs when compared to inland dam reservoirs, or other alternative solutions such as desalination plants, which do not make sense for Malaysia with its abundant raw water resources. The use of CRs is, overall,

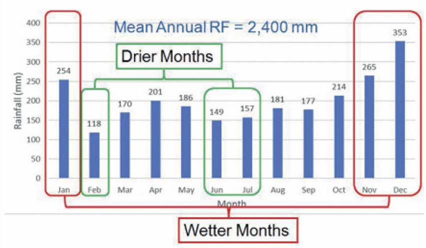

Figure 7. Typical monthly rainfall distribution of Malaysia

a cost-effective, environmentally friendly, green and sustainable solution for the development of water resources in Malaysia.

In order to expedite the implementation of the CR system, it is recommended that the State Government of Malaysia consider the construction of CRs for major coastal cities in the country such as Johor Bahru, Melaka, Penang, Kuantan, Bintulu. Setting CRs as one of the requirement for new onshore, nearshore or reclamation land development at these areas can be one way to incentivize the development of CRs.

CR planning and future operations require significant research in topics such as saline intrusion and water quality. The establishment of CR research centres at local universities is strongly recommended. Support from government agencies in terms of research and study is important to ensure the effective implementation of the CR system in Malaysia for the near future. The CR concept should be incorporated in the National Water Balance System (NAWABS), a newly established programme by Malaysia Government.

Acknowledgments

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PLWMOS, Putrajaya Lake and Wetland Management & Operational System.

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

Comparison	Dams	Downstream/Coastal Reservoirs
1. Land Acquisition	A large land area must be inundated riparian zones, buffers, waterways, shore	Minimal land acquisition required, using river 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	Create man-made wetlands and new ecosystems
	Loss of green area and thus carbon absorption	Minimum impact
3. Social impact	Creates social issues and face strong objection from locals and public	Less social issues as site selection can be very flexible
4. Heritage/ Historical site	May inundate heritage or historic sites	Can be avoided as site selection is flexible
5. Distance to demand point	- Very far, can be up to hundreds of km - High energy cost for pumping from sources to demand points - More losses due to longer conveyance works	- Site near demand points - Low energy cost - Fewer losses due to much shorter conveyance works
6. Catchment area	- Often sited upstream, thus having smaller catchment areas - During droughts, reservoirs receive no runoff	- Sited downstream, thus having much larger catchment areas - Receive water even during low flows
7. Expandability	Limited and difficult	Can be easily expanded
8. Risk	Pose dambreak risk to downstream population and properties	Low risk
9. Construction	Difficult and slower	Simpler and faster
10. Maintenance cot	Higher	Lower
11. Life span	Limited	Longer

CARDIFF BAY: A COASTAL RESERVOIR FOR URBAN REGENERATION

BY ROGER FALCONER & JAMES SUTHERLAND

The world faces considerable water management challenges now and increasingly in the future; primarily brought about by: the predicted impacts of climate change, the increasing need to provide more water, food and energy for a growing global population, and increasing globalisation - leading to a wider global wealth distribution and a corresponding increase in demand for water, associated with the need for more commodities (such as cars, clothes) etc. In addition, in most countries world-wide there is an increasing population shift away from rural communities to larger urban cities, where there are better employment prospects, and with these cities often being located near the coast.

However, coastal cities are frequently vulnerable to limited access to adequate water resources, poor water sanitation, coastal and estuarine flooding, sea level rise, increased energy demands etc. It is therefore timely that we look to the future to address some of these challenges in a sustainable manner and working with nature to develop coastal reservoirs to contribute to the solution of some of these challenges.

Coastal reservoirs have recently been primarily considered as a means of providing a cost effective solution for storing freshwater towards the end of a river basin, enabling the freshwater to be treated and distributed around the city at a lower cost than such alternatives as building high head reservoirs, upstream along the river basin, and then having to pump the treated water to the city for distribution. The water level can also be controlled in coastal reservoirs, thereby also offering opportunities to reduce flood risk from the sea locally and abstract more water during river floods, thereby lowering upstream water elevations, and hence reducing city flood risk. Furthermore, by taking water from the estuary at the end of the river basin, rather than from an impounded reservoir some distance upstream, then the river flow is not reduced disproportionately during drought conditions and the river ecosystem is less affected by water abstractions.

Coastal reservoirs can also be developed to provide other opportunities for urban regeneration and potentially renewable tidal energy. An excellent example of a coastal reservoir built for urban regeneration is that provided through the Cardiff Bay Barrage project, opened in 1999, to reconnect Wales' capital city of Cardiff with its waterfront. In the period mid-1800s to 1920 the Port of Cardiff grew considerably, with significant investment and expansion leading to the port reaching its full potential by about 1920 (see Figure 1), and with the port then being ranked as one of the largest in the world, shipping coal and iron-ore globally [1]. From the 1920s onwards the port went into decline; there was a major loss of trade to other ports world-wide, as the ships became larger and with the increasing challenges associated with the Bristol Channel and Severn Estuary having the second largest tidal range in the world.

In 1987 the UK government set up the Cardiff Bay Development Corporation with a brief to regenerate Cardiff Bay and reconnect the city of Cardiff to its waterfront. The Corporation prepared a strategy for regenerating the area with the aim of creating 30,000 new jobs, 840,000 m2 of industrial development and commercial premises and 6,000 new homes. The strategy was underpinned with a tourism potential of bringing 2 million visitors annually to Cardiff's waterfront [2]. However, the major problem with Cardiff's existing waterfront at that time was that Cardiff Bay was sited along the Bristol Channel, which experiences the second highest tidal range in the world, with spring tidal ranges being typically 14 m. At low tide Cardiff Bay was virtually dry and the Bay exposed mud-flats for typically 12 h per day. In overcoming the challenge of developing a water-front in such conditions, it was decided to construct a 1.4 km long tidal exclusion barrage across the mouth of the Bay, impounding the rivers Taff and Ely and creating a 200 ha fresh water lake, with a constant water level.

In 1987 initial legislation was commenced alongside feasibility studies, led by Wallace Evans and Partners. From 1987 to 1988 HR Wallingford undertook hydraulic feasibility studies covering flows, waves, flow routing, morphology and water quality [3].
HR Wallingford's 500 m grid numerical flow

Figure 1. Illustration of Cardiff Port taken in its heyday around 1900

Figure 2. Physical model at HR Wallingford with Gibb design

model of the Severn Estuary was used to provide boundary conditions for a new 90 m grid TIDEFLOW-2D depth-averaged flow model. TIDEFLOW-2D is part of the of the TIDEWAY modelling system developed at HR Wallingford. This extended 16 km alongshore and 7 km offshore [3] including the barrage and showed that the effects of the barrage were confined to an area close to the barrage. As expected, flows in front of the barrage (including the approach channel to Queen Alexandra Dock) were reduced, while flows were increased on the Penarth shoreline (to the south of the barrage). A physical model was constructed to scales of 1:250 (horizontal) and 1:100 (vertical) and had a pneumatic tidal generator driven by water levels from the 90 m grid TIDEFLOW-2D model. This was used to study the conditions prior to and after construction and sedimentation [4]. It was viewed by many interested parties.

Numerical models were used to look at wave disturbance in the approach channel to Queen Alexandra dock and raised concerns that were addressed in design studies. Water routeing studies looked at different combinations of river flows, tidal levels and sluice operations on water levels within the barrage, while the morphology study looked at how the bed of the rivers Taff and Ely, would change. Water quality in the barrage was examined using a 1-D model in the Ely, and a combination of a TIDEWAY-3D flow model, a water quality model and a primary production model within the impoundment. These studies also revealed some concerns.

Sir Alexander Gibb and Partners began detailed design in 1989 and in 1990 HR Wallingford was commissioned to undertake the hydraulic studies of a revised design that included a single set of sluices and a harbour of refuge outside the lock gates. This work included siltation, navigation studies, morphological change (including the effects of extreme flows through the single set of sluices) tests on the wave screens used at the harbour of refuge, flow routing, water quality and studies on providing an alternative feeding ground for birds [3].

The 1:250 scale physical model was recommissioned and modified to include the Gibb design (Figure 2) for use in siltation and navigation studies. A 1:50 scale model of the harbour of refuge was constructed to test wave disturbance, while a 1:16 model of the cross-section of the barrage was tested in a flume. Flume tests were also used to minimise the reflection coefficients from the wave screens, used to form the breakwater of the harbour of refuge. An innovative approach to joint probability was adopted for the assessment of flood risk [5]. Studies were substantially complete in 1992, by which time five physical models and thirty numerical models had been used. At the peak of activity 30 research staff were involved simultaneously on the design studies.

Figure 3. Cardiff Bay (taken 2008): a coastal reservoir and urban regeneration project

In 1993 the Cardiff Bay Barrage Act was passed through parliament and given Royal Assent. The act required that dissolved oxygen levels within the Bay were at least 5 mg/l at all times for the benefit of migratory fish. In addressing this requirement a system of aerators was installed across the Bay, with the aerators injecting air into the water body, rather than oxygen, and being designed to operate continuously during the period March until September each year. The barrage was designed and constructed to include: an 800 m long embankment wall with a 25 m crest, a fish pass allowing for the passage of migratory fish and with a design flow of 10 m^3/s, five sluice gates, each 9 m wide and 7.5 m high, with the total capacity of the sluices being 2300 m^3/s and three locks provided for small craft access between the Bay and the outer estuary. The Barrage was completed in 2001, with regeneration of the region now virtually complete (see Figure 3).

In addition to the barrage and lock gate structures etc, the impoundment of the two rivers and the change of the Bay from an estuary, with extensive flooding and drying, to a freshwater reservoir would have major impacts on the hydro-environmental characteristics and water management issues upstream of the barrage. In particular, and following impoundment, the main water quality issues needing to be addressed were as follows:

- the Bay now experienced long retention times, whereas previously the estuary was well flushed with substantial tidal variations, particularly during spring tides;
- several combined sewer overflows (CSOs) discharged directly into the watercourses under wet weather flow conditions, thereby leading to effluent discharges reaching the Bay;
- nutrient and pathogenic diffuse source inputs were expected from agricultural runoff etc, particularly via the River Ely, which primarily drained agricultural land; and
- low dissolved oxygen levels were expected in the lower layers of the water column of the Bay, particularly during summer months, leading to potential stratification and interaction with the contaminated sediments.

As a result of some of these concerns the Hydro-environmental Research Centre (HRC) at Cardiff University undertook a number of research studies to refine and apply an integrated modelling tool for water quality management of the Bay. The project strategy consisted of integrating a CSO model (namely

SWMM), with a 1-D river model (namely FASTER) and a 3-D hydro-environmental numerical model (namely TRIVAST). The latter two models were developed by the Hydro-environmental Research Center (HRC) at Cardiff (HRC), whereas the model SWMM is a stormwater rainfall-runoff model developed by the U.S. Environmental Protection Agency. An example of such a research study involved investigating the impact of a barrage and the creation of a freshwater coastal reservoir on the Faecal Indicator Organism (FIO) levels in the Bay, before and after construction of the barrage. The numerical modelling studies were complemented with an extensive field monitoring programme to establish more precise values for the kinetic decay rates in the Bay, for various meteorological conditions (such as different sunlight intensities), thereby providing improved predictions of FIO levels across the Bay. A scaled hydraulic laboratory model study was also constructed of Cardiff Bay Barrage for: numerical model validation, retention time predictions and estimating scaled dispersion values within the basin (see Figure 4).

The numerical model was set up (in 1998) for the Bay and riverine inputs, using a regular grid of 50 m grid cells, and with the downstream boundary being governed by the barrage and its operating conditions. The 3-D model had 10 vertical layers, each of height 1.25 m. Simulations were first undertaken to predict the movement of an arbitrary spillage of a conservative tracer with zero decay into the rivers Taff and Ely. The corresponding predictions were compared to the results obtained from the scaled physical model results, with good agreement being obtained between both sets of results [6]. The model was then set up to study the impact of episodic inputs into the rivers and for a range of wind and riverine flow conditions. Some of these predictions were compared with the field data, with the corresponding comparisons for different boundary conditions enabling a comprehensive set of conclusions to be drawn to indicate water management strategies for the coastal reservoir and the river basins.

As part of this research study, simulations were also undertaken to investigate the impact of using dynamically varying decay rates for predicting the FIO levels in the receiving coastal reservoir. In particular, comparisons were undertaken for a range of variables and the results showed that the FIO levels in the Bay were highly dependent upon the key variables of sunlight intensity and darkness and daylight conditions. The model was first run for hypothetical spillages into the rivers and for a constant decay rate (T90), both for day- and night-time conditions. The model was then re-run for dynamic day- and night-time decay rates, ranging from 10 h to 100 h respectively and based on field data and genetic algorithm based equations (see Figure 5). The difference in the predictions was significant and indicated that, for this freshwater reservoir, night-time spillages during the autumn and winter months led to reduced FIO levels in the Bay, in comparison with corresponding spillages occurring during the notional 12 h day-time period. Further field measurements and model predictions were undertaken, with the die-off being related to sunlight intensity, temperature and irradiance.

In conclusion, the creation of a coastal reservoir in the form of Cardiff Bay has been a considerable success in terms of re-uniting the City of Cardiff with its waterfront. The bay region has met and surpassed most of its urban regeneration targets and has rejuvenated an area of Cardiff City that had gone into decline since the loss of the coal and port industries to deeper ports around the UK. An evaluation of the regeneration of the Bay published in 2004 concluded that the project had "reinforced the competitive position of Cardiff" and "contributed to a massive improvement in the quality of the built environment". Brief details are herein given of the project background and design, and an example is cited of part of a major research study to investigate the change in the faecal indicator levels, both before and after construction of the barrage. This study showed that coastal reservoirs can provide significant urban regeneration and recreational opportunities, as well as freshwater supplies for coastal cities. ■

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James Sutherland is a Technical Director in the Coasts and Oceans group at HR Wallingford. He is an internationally known specialist in coastal & marine processes with 25 years' post-doctoral experience of working and publishing on coastal management projects. His areas of expertise include sediment transport, scour around structures, coastal erosion, beach management and wave forces on maritime structures.

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Figure 4. Cardiff Bay physical model as sited in the tidal basin at Cardiff University

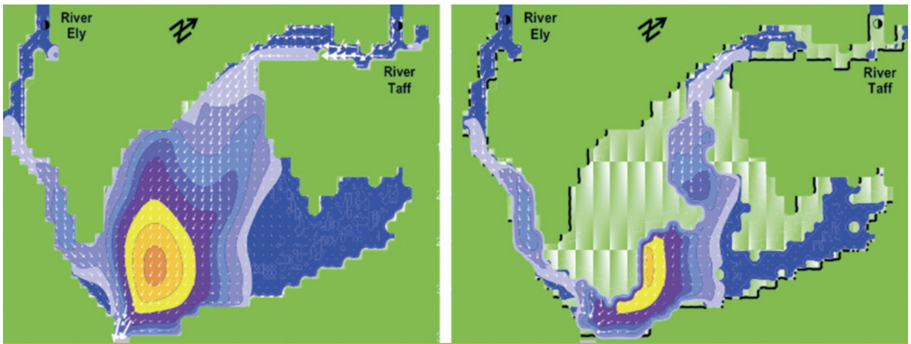

Figure 5. TRIVAST predictions of surface and third layer FIO concentration distributions for an arbitrary input into the rivers

The International Association for Hydro-Environment Engineering and Research (IAHR) seeks nominations and applications for a dynamic individual to lead the Association through its next period of expansion in professional activities and membership growth. IAHR is one of the oldest professional associations dedicated to the water challenges facing society and the global environment.

After two decades of leading IAHR, Dr. George will retire as Executive Director later this year. IAHR has made many advances and engaged engineers in many new countries during this period and a full description of Dr. George's career and his contributions to IAHR will be covered in 2019. IAHR is now initiating the search to identify a successor to Dr. George. The successful candidate will be fluent in English, have a minimum of 10 years professional experience in the water sector and be committed to building international collaborations that serve the needs of a diverse individual and institutional membership. Compensation will be commensurate with background and experience.

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COASTAL RESERVOIR (PAST AND FUTURE) IN THE NETHERLANDS

BY HUBERT SAVENIJE, JAAP KWADIJK & ARTHUR MYNETT

The Netherlands, situated in the delta of the Rhine-Meuse-Scheldt estuary, contains a large number of coastal reservoirs. For centuries the Netherlands have been constructing so-called ‘polders’ to reclaim land from the sea for agriculture and urbanisation. After the flood of 1916, a 32 km long closure barrier (de Afsluitdijk in the North of the Netherlands) was constructed in the 1930’s to protect the area along the former Zuider Sea against flooding.

Gradually, this water body, now called IJssel Lake, turned into a fresh water reservoir that is being used for excess floodwater storage as well as drinking water supply. Parts of the lake were developed into reclaimed land for agricultural use and urban expansion. More recently the emphasis has been on increasing the recreational capacity of the coastal reservoirs in the Netherlands, while plans are being developed to extend the airport capacity of part of the reclaimed land, notably for the tourist industry.

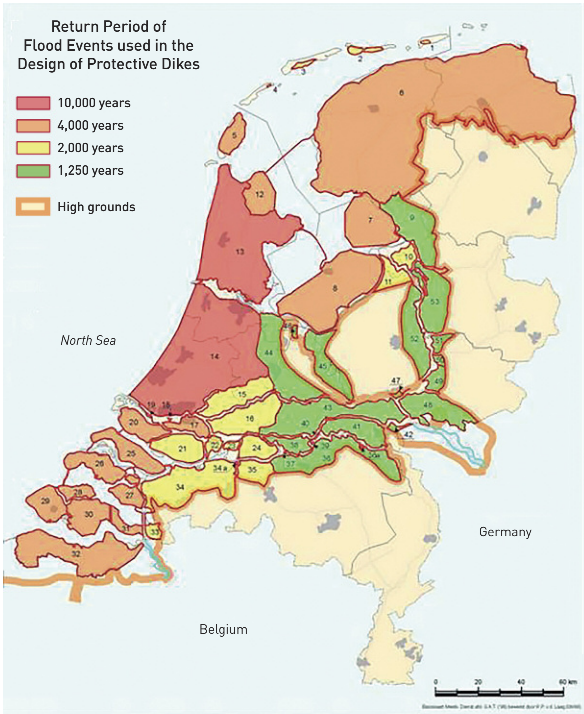

Figure 1. Coastal reservoir areas in Central and Southwest

In the 1970’s and 1980’s four major branches in the Rhine-Meuse estuary were closed following the major 1953 flood that severely damaged a large part of the Southwest of the Netherlands. The main purpose of these projects was to provide safety against flooding while additional objectives were to reduce salt-water intrusion and provide fresh water storage for agricultural use and drinking water supply. Already during construction of these "Delta Works" the importance of environmental considerations increased. The design of the Eastern Scheldt storm surge barrier was changed from a completely closed dam to a semi-open barrier that could be closed during extreme storm surge conditions if needed, but was to remain open during most of the time in order to sustain fishery demands and service environmental needs.

Similarly in the IJssel Lake, the purpose of land reclamation has changed considerably over time, in response to environmental considerations. In fact, the last polder planned in the lake was never completed and the water body now serves as a much-appreciated recreational are for water sports. At present, a part is being converted into an environmental reserve with the intention to restore biodiversity and attract migratory birds. A large part of one of the existing land reclamation areas has been converted into a national park with free roaming wildlife, where it was originally designed as an industrial complex. At the same time the IJssel Lake land and water areas are now host to numerous wind turbine parks for sustainable energy generation.

With several centuries of experience in the design and construction of coastal reservoirs, the Netherlands has long been engaged in providing expertise to other countries around the world. About one century ago, Johannes de Rijke was one of the pioneering engineers who worked in Japan to contribute to developing solutions for numerous water management problems at hand. In the 1960’s and 1970’s Professor Adriaan Volker provided the scientific foundation for including hydrological science and fundamental hydraulics into the design of coastal reservoirs and land reclamation works within such reservoirs. He brought the expertise developed for the IJssel Lake to various parts of the world, including Portugal and India. One of his important contributions was to consider not only the water balance but also the salt balance when assessing the feasibility of constructing coastal reservoirs. In the past, many mistakes had been made in particular regarding the salt balance, whereby expensive projects turned out to become failures. Properly accounting for the salt balance is a crucial element in assessing coastal reservoir feasibility, particularly in hot climates. But also in temperate climates, as was demonstrated by the failure of the Braakman coastal reservoir in the Netherlands where seepage from old marine deposits and saline groundwater caused significant salinity intrusion into the empoldered area.

Meanwhile experience in the design and construction of coastal reservoirs has grown considerably. At the same time, the motivation for the construction of coastal reservoirs has changed over time. In the past the main consideration was to create additional land for agriculture and urbanisation. At present, the dominant considerations for coastal reservoir construction or for modifying existing works are (i) to deal with effects of Sea Level Rise; (ii) to secure adequate fresh water supply in densely populated coastal regions; (iii) to reduce salinity

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Jaap Kwadijk received his PhD from Utrecht University in 1993. Since 1997 he has been at Deltares (WL|delfthydraulics). His expertise is climate change, flood and water management and worked on these issues in Europe, Iran, Hong Kong, Mongolia, Bangladesh and Egypt, where he lived for two years. He was one of the founders of the Deflt-FEWS forecasting system, one of the most widely used forecasting systems in the world. Currently he is Director of Science of Deltares. Since 2012 he is also part time professor Climate and water management at the Twente University.

Arthur Mynett (1950) is Emeritus Professor of Hydraulic Engineering and River Basin Development at UNESCO-IHE Institute for Water Education, and Emeritus Professor of Environmental Hydroinformatics at Delft University of Technology. He was director of strategic research at Delft Hydraulics and served as head of the water science & engineering department at UNESCO-IHE. He is past Vice-President of IAHR and was chair of the LOC of the 36th World Congress held in 2015 in Delft-The Hague, Netherlands. He is Honorary Professor at the Nanjing Hydraulic Research Institute (NHRI) working on ecohydraulics and flood risk management.

intrusion; and (iv) to enhance environmental quality. In recent times, reclaimed land is being used for harbour and port extension as well as for creating high value urban development and real estate, like the Marina Bay area in Singapore.

Nowadays over half of the world population is living in urban conglomerations that are often located in coastal areas where rivers meet the sea. As a consequence, the design and construction of coastal reservoirs is becoming increasingly important. However, in order to deal with uncertainties in the planning procedure due to (yet) unknown effects of climate change, population growth, economic development etc. it is extremely difficult to plan ahead for any prolonged period of time. This implies that flexibility is required in the planning process to deal with unknown and unforeseen circumstances.

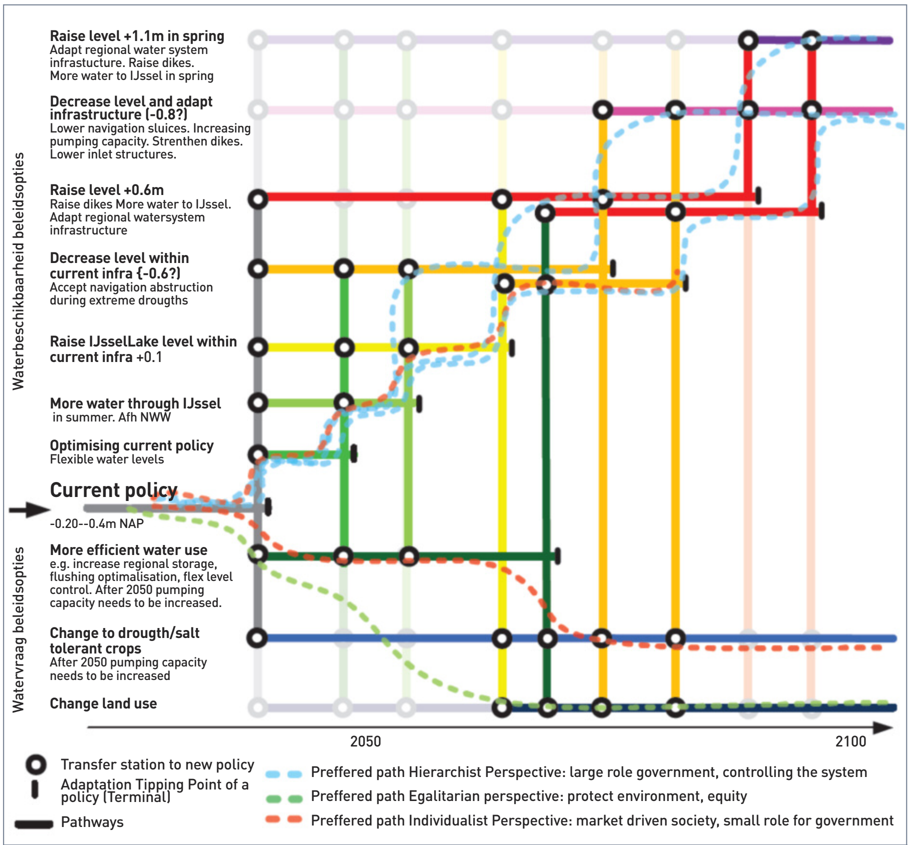

Figure 2. Adaptation pathway planning and tipping points

The Adaptive Pathway Planning approach identifies tipping points in decision tree analyses where proper decisions need to be made in order to secure adequate safety levels and other decision variables that government together with stakeholders have agreed to. Research efforts in this field include elements from Real Options Theory and Tipping Point Analysis, as well as innovations in climate change adaptation in combination with socio-economic considerations.

Figure 3. Multi-level Safety Mechanisms in the Netherlands

In the Netherlands considerable attention is being paid to securing sustainability of the various functions of coastal reservoirs. Rather than waiting for disasters to happen before responding by taking measures, the Dutch government has pro-actively initiated a second Delta Plan to anticipate effects of climate change and socio-economic development. Multiple defence mechanisms have been established against the risk of flooding: (i) primary safety from dikes, dunes, and storm surge barriers; (ii) adequate infrastructure for timely evacuation; (iii) early warning systems for proper planning and implementation.

In accordance with these measures, a Delta Fund has been secured by parliament to assure adequate funding for projects that are considered of national importance. A Delta Commissioner has been appointed at the ministerial level to assure proper planning and implementation of nationally agreed measures to be taken. All this and more to secure the sustainability of coastal reservoirs in the Netherlands. ■

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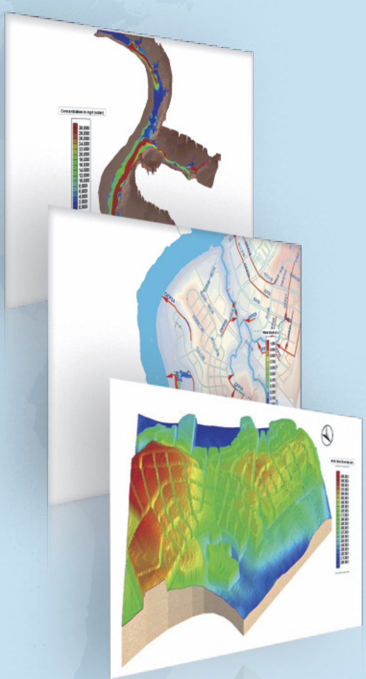
The numerical model of National Center for Computational Hydroscience and Engineering（NCCHE）



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