E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-0688

HISTORICAL REVIEW OF EXISTING COASTAL RESERVOIRS AND ITS APPLICATIONS

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ABSTRACT

In the world there exist two types of reservoirs, whose dams are situated in freshwater and seawater environment, respectively, i.e., inland dams and coastal reservoirs. This paper reviewed dam development and particular attention was paid to coastal reservoirs. It is found that for water supply, the inland dams are gradually petered out, but the numbers of coastal reservoirs are increased steadily. The analysis shows that most of the inland dams may be outdated in year 2150. In this paper, 67 coastal reservoirs were listed and reviewed from developed counties like Australia, the Netherlands, UK, Singapore, Japan and South Korea to developing countries like China and India. The earliest coastal reservoir still in operation today was constructed in China about 1185 years ago, the earliest modern coastal reservoirs were constructed in 1930s, namely the Zuiderzee in the Netherland and Alexandrina-lake in Australia. This review reveals that similar to inland dams which are constructed for different purposes, coastal reservoirs are constructed for prevention of seawater intrusion, land reclamation, flood control and water supply. After 1960s, majority of coastal reservoirs were constructed for water supply. Hong Kong is the first city whose water supply comes from the coastal reservoir, and Shanghai is the largest city whose water scarcity is solved by coastal reservoirs. Almost all existing coastal reservoirs are the 1st generation, which fully closes a river mouth and causes problems in water quality and ecosystem. The 2nd generation coastal reservoir is proposed without closing a river mouth fully and permanently. The preliminary analysis shows that coastal reservoirs may be useful for world coastal cities if there exists sufficient runoff, its application to the driest and the second driest continents as well as the Middle East is also discussed.

Keywords: Coastal Reservoir, non-point source pollution, soft dam, water crisis, inland dams.

1 INTRODUCTION (Use “Arial” font, uppercase, Bold, size 10pt)

Water is the most important substance for human’s survival. People are always chasing water for their better life, this is why all old civilizations originated from large river plains like the Nile River and Tigris-Euphrates rivers, Indus/Grange River, and Yellow River. This is also why always so many large to mega cities appear in deltas of large rivers. Groundwater development plays an important role for human survival in history. Hand-dug wells are present in every corner in the world. But this way gradually became ineffective after the industrial revolution that cuts off the umbilical cord between arable lands and people’s living places, and people start to live in cities, or the urbanization era has begun. River valleys and deltas are very important for civilization due to its fertile lands for food production, water supply and navigation.

The ancient earth and rock dams have been constructed in many places around the world, like Egypt (Biswas and Tortajada, 2001), Sri Lanka (McCully, 2001), India (Gupta, 2013), China (Cao et al. 2015). Till the 19th century, engineers in Europe started to design and construct dams using modern technology. In the 20th century, large dams were regarded as symbols of human capability to “control nature”. Fig. 1 shows the dam construction in the 20th century. By year 2000, the world had built 45,000 large dams in total, which had rapidly risen from the 1960s to the 1990s and petered out in the 2000s due to many social/environmental impacts. The growing mobilization of people against large dams results in governments’ cancellation to their planned dams, which can be inferred from Fig. 1. Table 1 shows number of dams by country, in which China has about 50% of the larger dams on this planet, followed by USA and India.

Currently about two-thirds of the global population (4.0 billion people) live under conditions of severe water scarcity at least 1 month of the year, and half a billion people in the world face severe water scarcity all year round (Mekonnen and Hoekstra, 2016; UN Water, 2013 and Gleick, 2001). Fig. 1 clearly shows that inland dams cannot supply sufficient water to the world in future. Besides, a concrete dam’s design life span is about 100-200 years, and its actual life span also depends on the sedimentation rate which reduces the storage capacity of the world’s reservoirs by 1~1.5% per year (White, 2001). Consider the average life span of a dam is about 150 years, the total number of dams and reservoir storage capacity can be predicted and the results are shown in Fig. 2, which clearly indicates that by 2150, all reservoirs may disappear and the water infrastructures will lose their function. Currently the world largest dam builders like USA, China and India are shifting their focus to decommission their outdated dams (Agoramoorthy, 2015). By 2017, USA had removed 1492 outdated dams in total and 2017 alone 86 outdated dams were removed.

Table 1. Large dam distribution among counties with highest dam number by year 2000, Source: Global Reservoir and Dam (GRanD) Database.

Country	China	United States of America	India	Japan	Brazil	S. Korea	Canada	South Africa	Spain
No. of dams	23 841	9 265	5 100	3 118	1 364	1 338	1 169	1 112	1 063
Country	Albania	Turkey	France	United Kingdom	Mexico	Australia	Italy	Iran	Germany
No. of dams	1 008	974	709	593	570	567	541	520	371

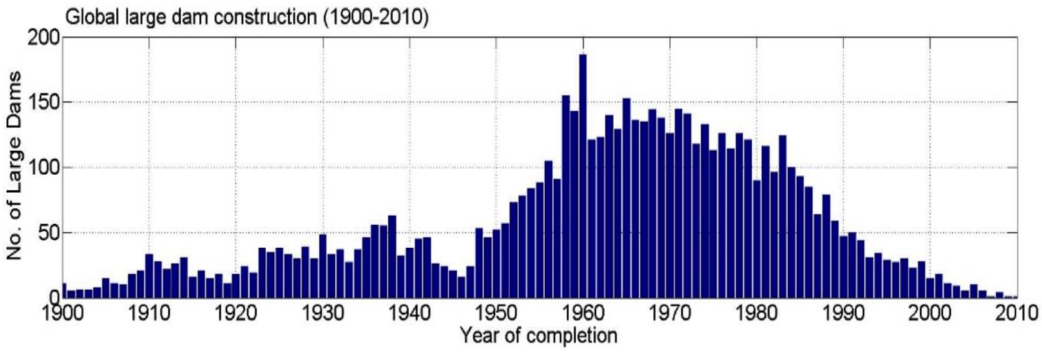


Fig. 1: Global dam construction over the past 100 years, Source: Global Reservoir and Dam (GRanD) Database.

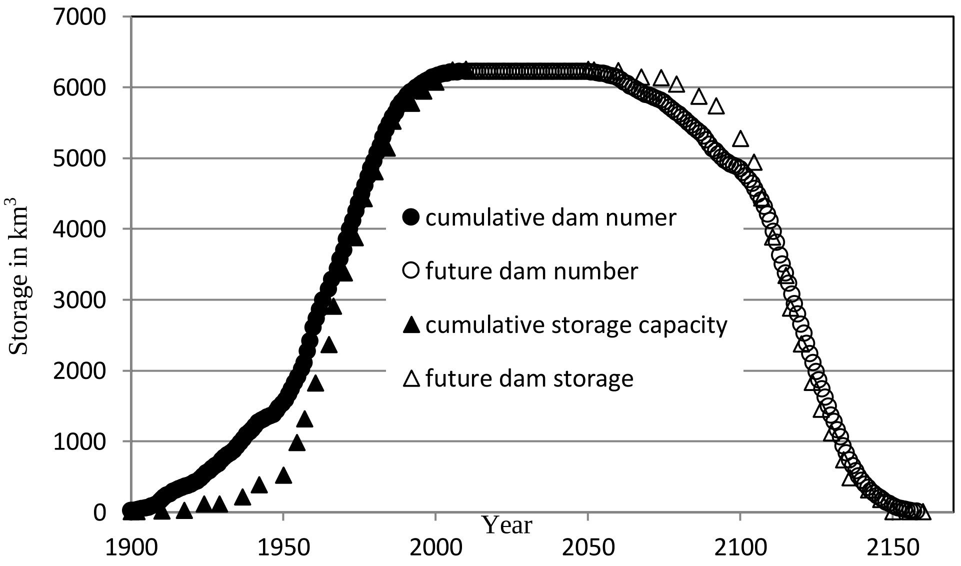


Fig. 2, The cumulative dam number and storage capacity in the world for the period of 1900-2160 based on the assumption of 150 years dam life span.

2 Coastal Reservoirs used to control seawater intrusion and floods

Different from inland dams that are built in freshwater environment, the world also has long history for coastal reservoirs whose dams are situated in seawater environment for the purpose of water supply, prevention of seawater intrusion, tidal mills, seawater fish farming and flood control etc.. Coastal reservoirs can be defined as a small water body inside a large water body separated by a barrier or barriers for some specific purposes, such that the substance inside the reservoir is different from the outside seawater in terms of chemical, physical and biological properties like density, salinity, turbidity etc. For the purpose of freshwater supply, the coastal reservoir could be simply defined as a freshwater reservoir inside seawater, and the main difference is salinity. Water inside a coastal reservoir could be used for drinking, industrial, or agricultural purposes. The said coastal reservoirs could be classified into various categories, in terms of location: inside, beside or outside a river mouth;

in terms of barrage: impermeable solid dam, soft (rubber) dam, or its combination; in terms of water quality: freshwater, ballast water from ships to prevent non-native, aquatic and invasive species, and polluted water for treatment to protect coastal environment (Yang et al. 2001).

The primary renewable source of freshwater on earth is continental precipitation, which generates a global supply of 40,000–45,000 km^3 per year. Currently the world only uses 5~6% of the runoff (Yang and French, 2018). Hence, the technology of coastal reservoir has great potential for future water supply (Yang, 2015). However, the importance of coastal reservoirs seems to be underestimated, only a handful papers in the literature discuss coastal reservoirs, it is necessary to review the existing coastal reservoirs, their shortcomings/improvements should be discussed for possible future applications. To do so, this paper will not review the coastal reservoirs that are used for tidal mills that were built in Europe and North America widely, same for those used for fishing in Africa and Australia.

In the world, there are many coastal reservoirs that are used today as listed in Tables 2 and 3. People has a long history to battle with disasters caused by seawater intrusion and seawater floods during extreme weathers like droughts, high tides, storm surges and hurricane etc. Probably, the existing Tuoshan weir (see Table 2), China is the earliest coastal reservoir in the world that is still operational, but was constructed in year 833 near Ningbo, Zhejiang province (Lin et al. 2018). The 134m long and 3 m high weir was constructed by huge rocks in Tang dynasty. After 1185 years' operation, this weir today still can achieve its original design purpose, i.e., to prevent seawater intrusion into Yin River and supply river water for irrigation. The other ancient coastal reservoir was constructed in year 1064, the Song Dynasty in Putian, Fujian province, China. The 954 years old project is 110m long, 7.25m high with hydraulic structures like sluice gates, sediment flushing structures. Till today, these two coastal reservoirs still provide irrigation to a huge arable lands and function very well.

To increase food production and to prevent seawater floods, many coastal countries have conducted land reclamation projects to increase their arable lands, such as Japan, South Korea, India and Netherland as shown in Table 3. One of the most famous projects is Zuiderzee project in Netherlands. In the second half of the 19th century a development plan was drafted to protect its low land areas from the wave surges of the open sea and creating new agricultural land. In 1918 the government approved the Zuiderzee Act following the worst surge in 1916. The initial plan included a water body of 3,500 km^2 created by a 32km dike to protect the central Netherlands from the floods and to increase agricultural land. In 1932, the 32km long dam was constructed, the reclaimed land for farming and housing forms the new province of Flevoland. The 1962km^2 artificial lake became freshwater 5 years later after the dam was enclosed.

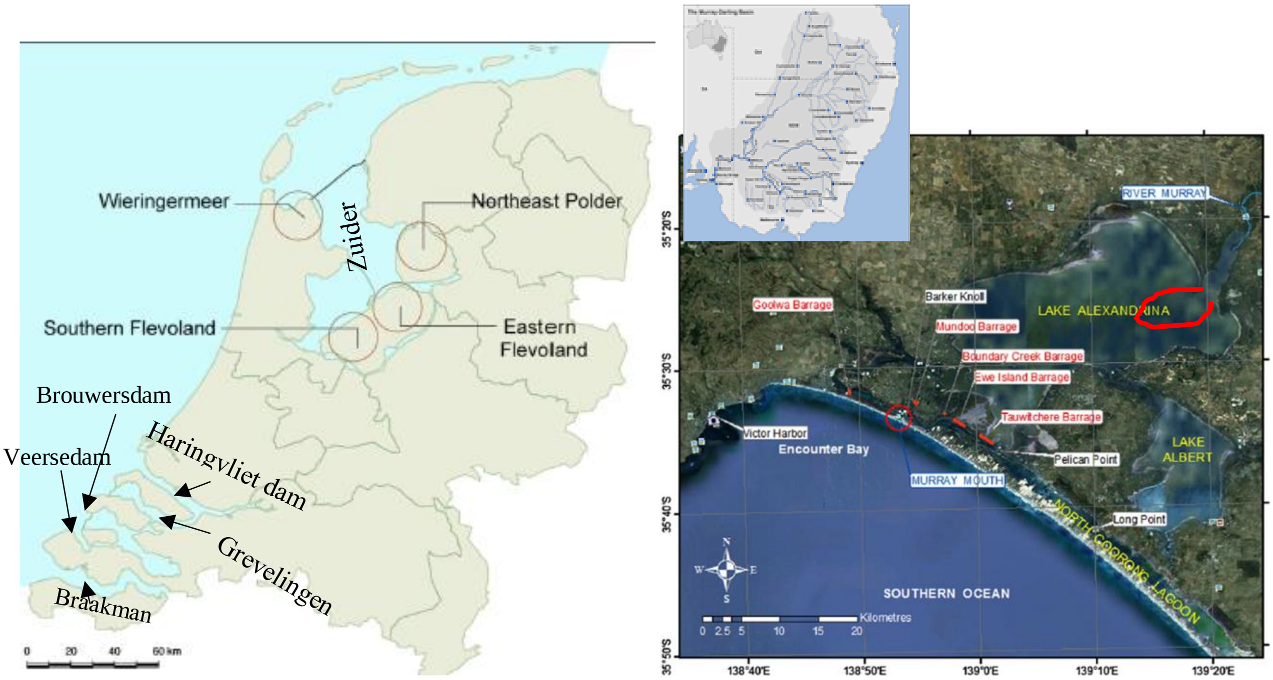
Now four major branches of the Rhine-Meuse estuary were also closed as shown in Table 3 and Fig. 3a after the 1953 major flood. These coastal reservoirs are effectively protecting the Southwest of the Netherland against floods and seawater intrusion. It is interesting to note that the purpose of coastal reservoir development in Netherlands keeps changing from initial flood defense and land reclamation to nowadays' freshwater development and biodiversity. For example, the Grevelingenmeer has been changed from a completely closed dam to a partially closed dam, and the freshwater body is replaced by blackish water today.

Almost at the same time when the Netherlands constructed the Zuider Zee coastal reservoir, Australia made its first attempt to change the Alexandrina Lake at the mouth of Australian largest river, Murray-Darling River into a freshwater lake in 1930s, as shown in Fig. 3b. In total 5 barrages were constructed at the lake's outlets. The primary reason for their construction was to keep the water fresh in the lake. Before the barrages were built, seawater intrusion occurred during periods of low flow, up to 250 km upstream along the river course from its mouth, which killed all vegetables from irrigation by farmers. In 1931, it was decided to construct 5 barrages which was commenced in 1935 and was completed in 1940. During the Australia Millennium Drought in 2000-2009, the measured salinity in the lake was found being very high. This failed coastal reservoir implies that its original design is not achieved. More innovative design is needed.

Russia has built a 25km long dike in the Gulf of Finland to protect Saint Petersburg after its 1955 flood and this dam is also used for a six-lane highway on the top. Its construction was begun in 1979, but it was suspended during 1995-2005 due to the fall of the Soviet Union. Construction was completed in 2011, President Putin said that the completion of the project was a "historic event" meaning that Saint Petersburg "is not just protected from floods, the ecological situation also improved."

Likewise, after 2012 Hurricane Sandy whose 3.3-meter sea surge drowned parts of New York City, USA planned to construct an 8km long dike in the New York Harbor to protect the city against future storms. The 8km long dike would connect Sandy Hook in New Jersey to the Rockaways in New York, separating all of New York City from the sea. The barrier would have three huge gates that would normally be open to allow ships to pass, and 11 other smaller "sluice" gates within the wall that would also remain open to allow the mixing of seawater and freshwater necessary to keep the bay alive. All the gates would close as a surge approached.

It can be seen that seawater intrusion and floods are the main driving force for the construction of coastal reservoirs. It can be predicted that both factors will continue to be the main concerns in future, because more and more people move to coastal cities where the sea level keeps rising and extreme weather is expected to occur more frequent and more severe due to climate change. It is interesting to note that fully closed barrage is gradually abandoned after its significant environmental impacts have been realized, this change becomes obvious for coastal reservoirs at the Rhine-Meuse estuary. This change can be also observed from other countries like Japan, South Korea and China. It can be predicted that, like inland dams, any barrage that fully cuts off a river flow at a river mouth may be very difficult to construct due to the public opposition.



(a) (b)

Fig. 3 coastal reservoirs for flood defense in Netherland (a), for seawater intrusion in Australia (b) where the enclosed redline is the proposed coastal reservoir for Adelaide's water supply.

Table 2. Existing coastal reservoirs in China

Name	Catchment (km^2)	Dam length (m)	Capacity (million m^3)	Surface area (km^2)	Year completed	Province/River
Tuoshan Weir (b)	350	134			833	Zhejiang/Yin
Mulanpi (b)	219	110			1064	Fujian/Mulanxi
Sheyang tide gate (b)	4036	1900			1956	Jiansu/Sheyanghe
Xinyanggang tide gate (b)	2478	240			1957	Jiangsu/Mangsehe
Haihe Tide Gate (b)	32700	2100			1967	Hebei/Ziyahe
Duliujian tide gate (b)	46000	220			1967	Hebei/Hiaihe
Plover Cove (c)	45.9	2000	230	12	1968	Hong Kong
Datang Harbor (b,c)	Ningbo	70	46.7	4.79	1973	Zhejiang
Huchen Harbor (b, c)	Ningbo	102	81.7	9.4	1973	Zhejiang/Zhongbu
High Island (c)	200	750+431	281	6	1978	Hong Kong
Shanhusha (c)	55600	2000	1.9	0.4	1979	Zhejiang/Qiangtang
Baogang/Shanghai (c)	1.8milliom	3700	12	1.8	1985	China/Yangtze
Chen Hang/Shanghai (c)	1.8milliom	4700	8.3	1.35	1992	China/Yangtze
Yuhuan (a, c)	166	1080	64.1	36.5	1998	China/ Zhejiang
Reservatorio (c)		2000	4	0.33	2002	Macao

Bahe (c)	256	2622	10.5	11	2004	Shandong/Wangli an
Caoe (b, c, d)	5099	700	146	43.1	2007	Zhejiang/Caoejia ng
Qing Chaosha/Shangha i (c)	1.8milliom	43,000	553	66	2011	China/Yangtze
Dongfengxisha (c)	1.8milliom	12000	9.8	3.74	2016	China/Yangtze
Yuguang island (c)	489	7000	6.7	13.6	Under study	Shangdong/Heng he/Baima/Jili
Dayawan (c)	62.7	1000	2	0.5	Planned	Shengzhen

a=land reclamation; b = seawater intrusion; c = water supply; d = flood defence.

Table 3. Existing coastal reservoirs in the world

Name	Catchment (km^2)	Dam length (m)	Capacity (million m^3)	Surface area (km^2)	Year completed	Country/river
Lake Alexandrina(b)	1061000	5 barrage	1610	850	1930s	Australia/Murray
Cardiff Barrage (e)	510	1100	7.5	2	2001	United Kingdom/Taff
Razim (a)		1790		41.5	1970	Romania/Danube
Zuider Zee (a, b, d)	170,000	33000	5600	1962	1932	Netherlands/Zuiderzee
Haringvliet dam (d)	Rhine-Meuse delta	3500	550	81.1	1970	Netherlands
Braakman (d)	Rhine-Meuse delta	600	10	1.6	1952	Netherlands/Braakman Kreek
Veersedam (d)	Rhine-Meuse delta	1500	107	22.3	1961	Netherlands/Veerse Meer
Brielse Gat (d)	Rhine-Meuse delta	1000	47	3.1	1967	Netherlands/Oostvoornse Meer
Lauwerszee (d)	Rhine-Meuse delta	4100	50	21.4	1969	Netherlands/Lauwersmeer
Brouwersdam (d)	Rhine-Meuse delta	6200	570	125.3	1972	Netherlands/Brouwershave nsche Gat
Ooster Scheldekering (d)	Rhine-Meuse delta	1400	2780	327.9	1986	Netherlands/Oosterschelde
Grevelingenmeer	Rhine-Meuse delta	23000	(not closed)	110	1971	Netherlands
Sub-total	11 projects		11,330	3438		European
Thaneermukkom/ Kuttanad (b)	145	1460	400	132	1974	India/Pamba/Meenachil
Kalpasar (a,c)	159500	64000	12248	2070	planned	Indian/Sabarmati/Mahi/Nar mada/Dhadhar
Nethravati (c)	3657	45000	2250	225	Study	Indian/Netravati/Gurupura
Sub-total	3 projects		15,000	2427		India
Muhuri (b)		240	60	20	1985	Bangladesh/Feni
Isahaya Bay (a,d)	249	7000	79	26	1997	Japan/Honmyo
Kojima Bay (a,c)		1560	26	10.9	1963	Japan/Okayama
Hachirogata (a, c)	688	52	110	48.2	1975	Japan/Akita
Kahokugata (a)		1700	6.3	8.17	1985	Japan/Ishikawa
Kasaoka Bay (a)		4670			1990	Japan/Okayama
Sub-total	6 projects		221.3	93		Japan
Taegye Do (a, c)		13300	25	15	1995	North Korea/
West Sea Barrage (c)	20344	7800	2700	372	1986	North Korea/Taedong
Asan (a, c)		2.56	99	24.3	1973	S. Korea/Gyeonggi
Saemanguem (a, c)	332	33000	530	118	2011	S. Korea/Gyeonggi
Sihwa (a, c)	476.5	12400	323	42.3	1994	S. Korea/Gyeonggi

			(not closed)			
Geum Barrage (a, c)	9912	1760	138	33.0	1990	S. Korea/Cungnam
Namyang (a, c)		2060	31.5	7.7	1973	S. Korea/Gyeonggi
Sapgyo (a, c)		3360	84.1	20.2	1979	S. Korea/Gyeonggi
Yeongsangang (a, c)		860	253.2	34.6	1981	S. Korea/Jeonnam
Seosan/Ganwol (a, c)		124	6460	27.3	1995	S. Korea/Chungnam
Seosan/Bunam (a, c)		1230	84.4	15.6	1995	S. Korea/Chungnam
Daeho (a, c)		7800	122.9	21.8	1985	S. Korea/Chungnam
Seokmun (a, c)		10600	14.6	76.3	1995	S. Korea/Gyeonggi
Yeongam (a, c)		2220	244.6	42.9	1993	S. Korea/Jeonnam
Geumho (a, b)		2120	133.1	23.3	1996	S. Korea/
Hwaeung (a, c)		13810	54.4	17.3	2008	S. Korea
Sub-total	16 projects		11300	877		Korea peninsular
Marina Barrage (c, d)	113	350	50	24	2008	Singapore/S’pre/Kallang
Kranji (c)			15.8	4.5	1975	Singapore
Lower Seletar (c)		751	3.6	9.4	1969	Singapore
Murai (c)		232	4	2	1984	Singapore
Pandan (c)		2030	5	1.7	1974	Singapore
Punggol (c)		130	2	1.0	2011	Singapore
Serangoon (c)		226	2	1.1	2011	Singapore
Tengeh/Poyang (c)		4510	11	5.2	1981	Singapore
Sarimbun (c)		270	1.4	0.7	1981	Singapore
Sub-total	9 projects		95	50		Singapore
Saint Petersburg Dam (d)		25000	(not closured)	378	2011	Russia/Saint Petersburg
New York Harbor Storm-Surge Barrier (d)	36,260	8000	(not closed)		Studied	USA/New York

a=land reclamation; b = seawater intrusion; c = water supply; d = flood defence, e = urban regeneration.

3 Coastal Reservoirs used for agricultural/industrial and cities’ water supply

Different from the Netherlands where 26% of its territory and 21% of its population are located below sea level, so the flood defense is more important. For densely populated countries like Japan and South/North Korea, the agricultural land and water are more important. To provide sufficient freshwater to Pyongyang, the capital of North Korea, constructed a coastal reservoir at the mouth of Taedong River from 1981-1986. The works include an 8km long dam, 3 lock chambers, 36 sluices, 3 fish ladders and barrage monument. There are railway, motorway and pavement on the dam and lock chamber capable of passing 50000-ton ships through. The reservoir provides water for irrigation, industrial uses and drinking and tourism.

South Korea in 2011 constructed the Saemangeum project by enclosing Mangyeong and Dongjin River estuaries in order to reclaim 283km^2 new land and to create 118km^2 reservoir. The ambitious reclamation project has incurred public opposition and the project’s initial purpose was changed and seawater is allowed to enter the created reservoir now (Park, 2011). Among 14 coastal reservoir projects in South Korea, the Shiwa Lake project was initially designed for freshwater supply, but the poor quality forced the government to change it as a tidal power plant today (Sung-Hyun and Hee, 2005).

In Japan, the Hachirogata project is the second largest freshwater body, next to the Lake Biwa. With the Netherlands’ engineers help, the project started in 1957 and created 175km^2 land and 48.2km^2 freshwater reservoir which collects water from its 688km^2 catchment. Similar to the Shiwa lake in South Korea, this coastal reservoir also has the poor water quality problem (Akita Prefecture, 2006). The Isahaya Bay project has the same fate like S. Korean Saemangeum project, in 2008 the local court issued an order to the local government that the dike’s gates must keep open to allow seawater back to the bay.

In India, the Thaneermukkom barrier was constructed in 1974 to prevent seawater intrusion into the Kuttanad low land where water from the Meenachil, Pampa, Manimala and Achancoil rivers. Its dike construction started in 1961 and its crest level is 2m +MSL, crest width of 3~4m and total length is 10.4km, but the project was suspended halfway due to funds. Now the 1.46km long dike divides the Vembanad lake into two, freshwater

Thaneermukkom in the south fed by the rivers and brackish water Vechur in the north fed by the Arabian Sea. Kalpasar Project is located the Gulf of Khambhat, Gujarat, one of the driest states in India. The project aims to create the world's largest freshwater coastal reservoir by a 30 km long dam to store more than 10,000 GL of surface water from Sabarmathi, Dhadar, Mahisagar and Narmada rivers for irrigation, industrial and drinking purpose. Currently the project is waiting for the government's final decision.

Before 1960s, almost all coastal reservoirs in Tables 2 and 3 were constructed for agricultural purpose, because at that time there were very little problems for drinking water supply, but food shortage was the first priority for about 3 billion people on the planet. At that time, water was an abundant resource. The world's population is rapidly increasing after 1960s. Subsequently the water crisis started to appear in the end of 1960s. Hong Kong was the first mega city in the world had the water shortage problem and made the attempt to build coastal reservoirs for city's water supply. From 1963 and 1967, serious droughts coupled with high population growth led to its water crisis in Hong Kong. The government implemented a water restriction policy, i.e., every 4 days water was supplied within 4 hours. This forced Mr. T.O. Morgan, the former director of Hong Kong's Water Supplies Department, to discover new water sources for Hong Kong. Finally, Mr. Morgan ingeniously decided to construct the coastal reservoir of Plover Cove after he realized that Hong Kong's water shortage was caused by storage shortage as its annual rainfall is about 2.5m/year. The 50 years old Plover Cove is historically meaningful for coastal reservoirs' development because:

1) It is the first coastal reservoir in the world used for city's water supply, no longer for agricultural water supply.
2) It provides an opportunity to examine coastal reservoirs' feasibility and its environmental/social impacts.

The Plover Cove's construction work was completed in 1968. Its storage capacity was about 170 GL. In 1970, its 2km long dam was arisen to 28m high, and its capacity was increased to 230 GL. The success of Plover Cove inspired Hong Kong's second largest reservoir, the High Island coastal reservoir that was constructed in 1978 and costed 1.35 billion Hong Kong dollar. It should be mentioned that different from other coastal reservoirs, the Plover Cover and the High Island's initial seawater was pumped out after construction of its enclosing dam, not by gravity, this is because there are no great rivers in the island.

Most reservoirs in Singapore are coastal reservoirs like Pandan reservoir, Kranji reservoir, and Marina Bay reservoir. Its Marina Bay is the first coastal reservoir in the world catching water from its central business districts, it is natural that the reservoir water cannot be used for drinking after conventional treatment. Singapore offers the world with its innovative solution—to feed its desalination plant with the reservoir water, instead of seawater, thus the energy cost is reduced significantly. This method may be useful to other coastal cities like Perth in Australia and the Cape Town in South Africa.

Indian Silicon Valley city, Bangalore, is one of the worst cities with water crisis, its government expressed interest in the coastal reservoir at Netravati river mouth, about 300km away and 900m below. If 3% of its runoff is harvest, the city should have sufficient water, now the feasibility study report has been endorsed by the Bangalore Water Supply and Sewerage Board (BWSSB).

Shanghai is another mega city that successfully solves its water stress problem. Shanghai, China's largest city, is situated on the Yangtze delta and the Yangtze River is the third longest river in the world. Shanghai is notorious for water crisis caused by pollution as its mother river-Huangpu has been heavily polluted. Shanghai's water crisis has long been foreseen by international communities. For example, in 1996 a conference organised by the UN Center for Human Settlements (UN -Habitat) predicted that Shanghai would be one of the dozen cities with the most severe water crisis worldwide (N'Dow 1996) in the 21st century. The Shanghai Urban Master Plan in 2005 also predicted that the freshwater shortage in the city will reach 6 million m^3/d by 2020 (Lin et al., 2018). Surprisingly, the journey to solve this megacity's water problem comes from an idea in a near failed industrial project.

In 1980s, China started its reform and opening-up policy to speed up its economic development. The central government decided to build one of the world-class new factories in Shanghai to make iron and steel. At the beginning, the builders did not carefully check the design documents about the quality of cooling water. At the final stage of construction, the builders found that the specified salinity of cooling water must be lower than 50ppm, much lower than the potable water that is 250ppm in China. Yangtze estuary's average salinity is much higher than this criterion, this problem could lead to the huge steel company useless. Finally, one of the steel engineers got similar idea like Mr. Morgan in Hong Kong--- to build a coastal reservoir in the Yangtze estuary. Its intake gates will be open to take the river water during lowest salinity period, but be closed when salinity is higher than 50ppm. In 1985, the Baogang Reservoir was built, which has ensured the high quality of iron/steel products from this factory. Inspired by the industrial water supply mode, Shanghai Water Authority in 1992 built the Chenhang Reservoir, just next to the Baogang Reservoir as shown in Fig. 4.

Shanghai constructed the Qingcaosha Reservoir in 2011, the largest coastal reservoir in China. Its enclosing dike is about 48km and water surface area is nearly 66 km^2. The total storage capacity of the reservoir is 527 GL, while its effective capacity is 438 GL. Its water supply capacity is 2624 GL/yr at the reliability of 97%, and its total construction cost was 6.45 billion Yuan (≈ 0.97 billion US$). Two 7.21km long underground pipelines with 5.84m diameter connect the reservoir with Shanghai. 24 large pumps are used to deliver the water. Together with Dongfenxisha reservoir, the coastal reservoirs in Shanghai supply 75% of the drinking water used by 24 million people in Shanghai, the remaining 20-30% of water still comes from Huangpu River.

Not only solving coastal cities' problems like water scarcity, flood disaster, seawater intrusion, sea level rise, can also coastal reservoirs make coastal cities more attractive, two of the examples for urban regeneration are the Cardiff Bay Barrage project, UK (Falconer and Sutherland, 2018), Singapore's Marina Bay, both now have become the tourism attractions. It can be predicted that future coastal reservoirs may become coastal cities' landmarks. It is also worthwhile to note the soft coastal reservoirs emerged in the world. Larson and Malm (1992) proposed a floating coastal reservoir made by bottomless tank based on the principle that freshwater is lighter than seawater, thus it can be contained by the tank without severe mixing on the interface (Chua and Shuy, 2006). It is important that these researchers have realized that floodwater lost to the sea is a resource and attempts have been made to develop it.

The above discussion clearly shows that coastal reservoirs have been applied in the world for at least a thousand years for different purposes that are changing with time, namely: flood disaster mitigation, land reclamation, water supply, prevention of seawater intrusion and urban regeneration. Table 4 shows the distribution of the existing coastal reservoirs for these purposes. From ancient time, seawater intrusion has been a big problem, especially in dry period over a flat plain. A coastal reservoir has proven to be effective for seawater intrusion prevention. From 1930s, about 1/3 of the existing coastal reservoirs have been used to reclaim land areas, but the examples from S. Korea and Japan show that large reclamation of intertidal area becomes more difficult due to public opposition. It is expected that future coastal reservoir development should place land reclamation at a reasonable and acceptable level. About 17% of coastal reservoirs are constructed after major floods. With the ever-growing population in the coastal areas subject to sea-level-rise, it is expected that in future all coastal reservoirs should be constructed to mitigate the flood disasters and also to convert the floodwater into water resources. About 62% of coastal reservoirs are constructed for freshwater supply from 1968, which is understandable due to urbanization. It is interesting to note the new role of coastal reservoir, i.e., urban regeneration. The examples in Singapore and Cardiff, UK, show that a well-designed coastal reservoir and its water front can greatly improve a city's outlook and attract tourists and other opportunities. It is recommended that future coastal reservoir development should have mild land reclamation, but be able to meet other 4 purposes in Table 4 simultaneously. Before discussing the optimal design, it is important to review the problems in the existing coastal reservoirs.

Fig. 4, Shanghai's coastal reservoirs and its waterways.

Table 4, purposes of coastal reservoir development in the world

	Seawater intrusion prevention	Land reclamation	Flood defence	Water supply	Urban regeneration
Percentage	20.3%	33.3%	17%	62%	2.8%
Year started	833	1932	1932	1968	2001

4. Problems in the existing coastal reservoirs and improvements

It must be admitted that not all existing coastal reservoirs function well as planned. The failures could be caused by many reasons like high salinity in reservoir water, land-based pollution, social and environmental impacts, etc. It is natural that a coastal reservoir is vulnerable to seawater pollution as it is situated in seawater environment. As stressed by the Netherlands experts' (Savenije et al. 2018), "In the past, many mistakes had been made in particular regarding the salt balance, whereby expensive projects turned out to become failures.", one of the examples is 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 reservoir water body. Another example is Lake Alexandrina in Australia where the 330 EC units salty water comes from its feeding river—the Murray River, high evaporation over 850km^2 surface area in the dry period led to very high salinity of 7232 EC measured in 2011 in the lake, compared to the upper limit of 800 EC for human consumption.

As saline water is heavier than freshwater, it is suggested that all coastal reservoirs should install pipes near seabed so that the water near the bottom can be discharged out of reservoirf needed. To reduce evaporation loss, shallow water should be excluded in the reservoir as shown in Fig. 4b where the red line encloses a deep water body. In other words, coastal reservoir size must match its water demand, not too big, not too small.

Probably the worst enemy for coastal reservoir development is not seawater pollution or structural strength against wave surges, but land-based non-point source pollution. Almost all coastal reservoirs in Tables 2 and 3 are formed by barrages that close a river mouth, those reservoirs have the potential to collect all rainwater runoff from the catchments, but also collect the pollutants from the catchment, such as domestic waste overflows, industrial and agricultural chemicals, pesticides and fertilizers. As a result, there is an accelerated growth of algae and other life-forms that thrive on the nutrients in the coastal reservoir, and eventually some coastal reservoirs have become a wastewater reservoir that needs membrane technology to treat its water (like Singapore Marina Barrage). The Sihwa Lake in Korea could serve as an unsuccessful example, this coastal reservoir was initially designed as a freshwater supply source, and in 1994, a 12.4km seawall was built to separate Sihwa Lake from the sea, severe water contamination occurred with high concentrations of Perfluorooctanesulfonic acid (PFOS), resulting from an excessive inflow of polluted waste waters, mainly from a nearby industrial complex. The polluted water was not even fit for agricultural use. In order to improve the water quality, the decision was made to abandon the original freshwater reservoir scheme and allow seawater exchange. In 2005 seawater entered into the lake and the reservoir was converted and became the world's largest tidal power generation plant. It can be predicted that as the wastewater amount keeps the same growth pace as population, in future the raw water quality from all coastal reservoirs cannot meet the requirement if no new technology solves this problem caused by the point and non-point source pollution. Algal blooms caused by eutrophication have been found in many coastal reservoirs like Kranji reservoir (Singapore), Qingcaosha (Shanghai, Chen and Zhu 2018), Zaider Zee in the Netherlands (Lammens et al. 2008), Isahaya reservoir in Japan (Ittisukananth et al. 2008) etc.

As the incoming river flow is unstable in quantity and quality, it is suggested that a coastal reservoir should have the capacity to store high-quality water and discharge unwanted/poor quality water into the sea. For this purpose, a water quality measuring system should be established and the reservoir's intake gates should be operated according to the incoming water quality and quantity. A bypass channel can be constructed for the water quality management. In the world, the coastal reservoirs for Shanghai's water supply have installed the system and highest quality water is selected for storage. If it is needed, wetland pre-treatment is also recommended to purify the water in a reservoir, the wetlands have been proven to be the most environmentally sustainable and inexpensive water treatment method, and if properly designed it can become the most effective and efficient water treatment method (e.g. Boudreau and Jorgensen, 2005; Biggs et al, 2005; Kadlec 2000; Statzner, 2008). To keep the reservoir water clean, it is also important for a coastal reservoir to have a minimum stagnant water body or its detention time should be as short as possible.

Except coastal reservoirs in Shanghai, China, the alignment of all existing reservoir barrages in Tables 2 and 3 is perpendicular to the flow direction. This alignment of barrage changes the river flow significantly and causes many environmental and ecological problems, for example the passage of fish upstream has been cut off, navigation is disrupted and severe flood disasters could be worsened. Just as people are abandoning the large inland dams, it is predictable that in future such coastal reservoirs that cut off the river flow completely would be difficult to be approved by some government. All these coastal reservoirs that simply enclose its river mouth by a dam as shown in Fig. 4b can be classified as the first generation coastal reservoir, which just extend the design method of inland dams to coastal reservoirs.

To minimize coastal reservoirs' impacts, it is suggested that river mouths are not closed as shown in Fig. 3, this type of coastal reservoir can be called as the 2nd generation coastal reservoir which is totally different from the inland dam, which can be simply defined as: a freshwater reservoir inside seawater without pollution by unwanted water, it is able to mitigate flood disasters (Yang et al. 2001) by regulating its intake gates (orange block in the river of Fig. 5a), high-quality/wanted water is diverted to the coastal reservoir for storage via channels (grey lines in Fig. 5a), but the poor quality water is discharged into the sea through a by-pass channel. The main difference between the first and second generation coastal reservoirs is that the river mouths are not always closed, so sediment, nutrients and migratory fish can connect to the sea without significant interruption. Table 5 shows the differences of inland dams, 1st and 2nd generations of coastal reservoirs.

Because the water depth of estuaries is generally less than 10m, and the water level inside a reservoir is almost the same as the sea level, thus the pressure difference on the dam is significantly smaller than that of inland dams. The construction cost of an inland reservoir is generally very high incurred from very high and strong dam walls, but the pressure force on both sides of the dam of a coastal reservoir is generally small (around 10m), but the storm and tidal wave surge is the main concern for its design. The primary barrier in Fig. 5 provides a relatively calm environment against tidal flows, storm and wave surges, and it also separates freshwater and seawater, it should be height sufficient to withstand normal tidal surges and wave action of the unwanted water. A concrete dam, caisson, earth/rock dike or huge geotubes could be used for its construction, similar to ports' breakwater. This is achievable as the water levels on both sides of the coastal reservoir are almost the same and the net pressure force is very small. Small sandbag is an old technique used to prevent floods, recently large scale sandbags have successfully been used for embankment construction as shown in Fig. 5b (Yang, 2004, Chu et al. 2012). Giant geotubes filled with sands/clay (Fig. 5) has been used to construct the Qingcaosha coastal reservoir in Shanghai. Its dam cost was only 0.1 billion RMB yuan/km (=US$15 million/km). Obviously, the construction cost of second generation coastal reservoirs is much smaller than those dams in Hong Kong, Singapore, and the Netherlands as shown in Tables 2 and 3.

The seawater seepage from the dike can be prevented using an impermeable layer inside the dike like a traditional earth dam. The same purpose can be achieved by introducing a soft dam inside a coastal reservoir and that is parallel to the primary barrier as shown in Fig. 5. The soft dam can even prevent mixing of freshwater and seawater from overtopping caused by extreme surges. It can separate fresh water and seawater and create a blackish water buffer zone between the solid and soft barriers. During low tide, the water in this zone will be discharged in to the sea first without mixing with the central freshwater body that is stored within the inflatable barrier.

A multitude of coastal reservoirs can be inter-connected to each other by artificial channels or pipes as shown in Fig. 5. Hence, the inter-basin water diversion route should be along the coastline. Comparing with the inland water diversion like China's South-North water diversion project (Yang, 2004) and Indian river-linking proposal (Kolathayar et al. 2018), the water diversion along coastline provides one more choices for decision-makers. Most importantly, the 2nd generation coastal reservoir can minimize environmental/social impacts, and a win-win solution can be achieved for water supply and ecosystem protection, because in term of water quantity, an inland reservoir can only collect water from part of a catchment, generally only 10-50% of total catchment, but a coastal reservoir has the potential to collect all runoff from 100% of the catchment. An inland dam can flood a large area of land and cause million people to be relocated like the Three-gorge dam, China, but this social impact becomes zero because coastal reservoirs have no submergence of land or forest or displacement of people. An significantly reduce downstream river flows and cause many negative environmental impacts, but a coastal reservoir has no such impacts, because the same amount water used by the coastal cities will be treated and discharge back to the sea. As the sea is the biggest reservoir in the world, the coastal reservoir can be constructed in any place in the sea, even offshore if it is required, so its site is renewable, and meets the requirements of sustainable development, i.e., to be able to meet the needs of the present without compromising the ability of future generations to meet their own needs (Yang, 2004).

The need of the 2nd generation coastal reservoirs may be justified by the facts: if river runoff is not developed, many coastal cities in the world will have water shortage crisis. If river runoff is developed by barrages (1st generation coastal reservoirs), the water stress problem may be alleviated, but environmental impacts could be discernible, such as the migration path of fish to their breeding places is cut off, which may result in the income decrease of fishing industry. The natural sedimentation is also interrupted by dams, causing the coastline unstable or erosion. However, the second generation coastal reservoirs balance the water demand and environment as it partially closes a river mouth and develop its highest quality of water. Besides, it may provide a solution to flood disasters caused by heavy rain/wave surges and even sea-level-rise caused by climate change. It is possible that the coastal reservoirs in Fig. 5 protect the coastal cities like New York in USA, or Brisbane in Australia against wave surges or storms, both are inundated by Hurricane Sandy in 2012 and heavy rainwater in 2011, respectively. For some heavily polluted rivers, its best quality water can be collected and stored in a coastal reservoir for drinking purpose, its worst quality water can be also collected and stored in another coastal reservoir for treatment before discharging into the sea, thus the coastal environmental can be improved.

Table 5. Difference between Inland Reservoirs and Coastal Reservoirs.

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

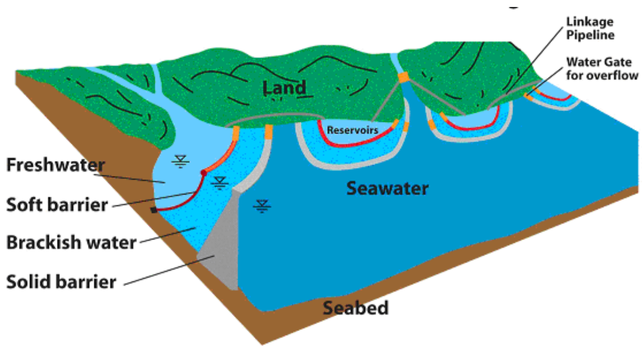


Fig. 5. The second generation coastal reservoirs (with a bypass channel for polluted water) on the left and the dam by giant bags on the right.

5. Future outlook of coastal reservoirs

Many researchers have realized that one day human needs to develop its floodwater in a feasible way, and most of them also worry about its environmental impacts. For example, Kassas (1980) foresaw that “in the near future, practically all the world’s major rivers will be brought under control”. He also worried “Some rivers will even be sealed off by estuary barrages (e.g. barrages across Morecombe Bay and the Solway Firth in the UK). But rivers represent an important agency in the hydrologic cycle: collecting surface drainage and discharging it into seas and oceans. Estimates of world total run-off of water from land to sea (mostly river flow) are in the order of 91,000 X 10^9 Litres per day (1.05 billion m^3/s). This is equivalent to about 7 percent of the total evaporation from land and sea. Rivers discharge into the Northeastern and Pacific Oceans between California and the Aleutian Islands about 21,000 m^3 /s. Freshwater discharges into the Bering Sea by Alaskan and Siberian rivers average 10,000 m^3/s. The Columbia Rivers discharges about 3,200 m^3/s, and its surface water of the ocean is perceptible several hundreds of km out to sea. The water masses emerging from the Bering Straits northward to the Chikchi Sea bring fresh waters and sediments together with warm water. What would be the effects of sealing off these rivers on climate, biota and the hydrological cycle?”. As discussed, the second generation coastal reservoirs provide a solution for water resources development without sealing off an estuary. It is useful to discuss the potential application of coastal reservoirs in the world.

Australia is the driest inhabited continent in the world with 24 million people in 2016 spread over 7.7 million km^2, where desert makes up about 18% of the mainland area of Australia. The long-term average rainfall across the whole country is 457 mm/year (i.e., 3.52×10^6 GL/year); and only 11% of it becomes the mean annual run-off from Australian catchments, i.e., 390 ×10^3 GL/year. In 2013-14, Australia used 23.5×10^3 GL/year of water by agriculture, industry and households (Bureau of Meteorology, 2015). Compared with the annual runoff to the sea, the used water is only 6% of total runoff, similar to the rest areas in the world. The largest river-the Murray-Darling river had the average annual flow about 5000GL/year during the Millennium Drought (2000-2009) in Australia. Adelaide, the driest capital city of South Australia, depends on the river for its water supply. Obviously, from the coastal reservoir point of view, Adelaide is blessed by the plentiful water resources. Adelaide is similar to Las Vergas, another desert city nearby a great river—Colorado River in USA. Both should have no water shortage problem if the "Hoover dam" in Fig. 3b is constructed. The second water-rich city in Australia is Melbourne which receives 1193GL/yr of water from its Yarra river, and Australian water tower—the Snowy mountain pours 1034GL/yr of water to Michell River, 1200GL/yr to Thompson River and about 1000GL to Latrobe River, in total, about 4427GL/yr of water is available for Melbourne/Victoria to develop. Sydney's Hawkesbury estuary receives 3000GL/yr of water. Brisbane River discharges 2750GL/yr of water to the sea. Even the Swan river in Perth receives 590GL/yr of water from its catchment, and its neighbouring rivers like 720GL/yr from Murray River and 450GL/yr of Moore-Hill River, in total three rivers yield 1760GL/yr of water. Table 6 shows Australian capital cities' available water resources and used water in 2015-2016 (Bureau of Meteorology, 2017), it clearly shows that the available water is much higher than the used water for each capital city. On the other hand, these capital cities have no new dams in 30-40 years and the dam water was very low in the Millennium drought (2000-2010). It seems that coastal reservoirs may quench Australian thirst completely if the water resources are developed using properly designed coastal reservoirs.

Table 6. Australian capital cities' water crisis for dam water and its available water resources.

	Adelaide	Melbourne	Sydney	Brisbane	Perth
Water sources	Murray-Darling River	Rivers of Yarra, Michell, Thompson, Latrobe	Hawkesbury River	Brisbane River	Rivers of Swan, Murray & Moore-Hill
Annual water yield (GL)	5000	4400	3000	2750	1760
Year of last dam constructed	1977 (Little Para)	1983 (Thomson)	1976 (Tallowa)	1985 (Wivenhoe)	1994 (Ten Mile Brook)
Annual water used in 2016 (GL)	160	460	570	320	300
Lowest % full dam in Millennium drought	0	26%	33.8%	18%	0

Africa is the world's second-populous and second largest continent, where 16% of the global population (1.6 billion in 2016) lives in 30.3 million km^2 land area. It is also the second-driest continent in the world after Australia, 60% of the African land surfaces are dry lands and deserts. The volume of renewable freshwater in Africa is 3931km^3 per year, which only is about 9% of world freshwater resources, its volume of freshwater for per capita only was 4008m^3/year in 2008, less than 50% of that in Europe (= 8941m^3/capita/yr in 2008). Mr Taal (2015), Executive Secretary of the African Ministers' Council on Water, analyzed Africa's population growth and stressed "More than half of global population growth between now and 2050 is expected to occur in Africa. Of the additional 2.4 billion people projected to be added to the global population between 2015 and 2050, 1.3 billion will be added in Africa and the difficulties African cities currently face in providing sustainable water services will be further exacerbated. Now about 340 million people in sub-Saharan Africa still do not have access to potable water. The water challenge in Africa calls for newer and innovative ways of ensuring water security for all Africans".

Table 7 shows main rivers and its runoff from the continent, in total there are 2990 km^3 of stream flow discharge to ocean per year. This is 76% of the total volume of renewable freshwater in Africa. In Africa, 1858 large dams have been constructed, 43% of which are located in South Africa (=656 dams). Most of these dams were constructed during 1960s-1980s. South Africa may provide a vivid example that the inland dams cannot well solve the water stress problems in Africa well. Cape Town city is the second largest city in South Africa, and the first mega city in the world whose taps almost run dry in 2018 and its residents have been living with stringent consumption restrictions and only 50 liters person per day are allowed to use. A close look of its annual runoff shown in Fig. 6 clearly reveals that the “Day Zero” phenomenon is not caused by water shortage, but storage shortage. It can be seen that the average runoff in 2013-2017 is 540GL/yr, higher than its water consumption around 300GL/yr. Obviously, if the runoff to the sea is developed, and part of this water is stored in the coastal reservoirs before the river water mixes with seawater, water crisis can be largely mitigated without desalination. The water demand in South Africa will be increased from 15km^3 in 2016 to 17.7km^3 in 2030, this is beyond the limit the country can safely supply, but the strategy of coastal reservoir can fully seal the gap.

Table 7, the main river systems in Africa where coastal reservoirs can be considered

	River	Length (km)	Catchment area $\times 10^3$(km^2)	Rainfall(mm/yr)	Annual runoff (GL/yr)	Discharge to
1	Nile	6500	3400	615	89000	Mediterranean sea
2	Moulouya	520	54.5	300	50	Mediterranean sea
3	Sebou	496	37		4300	Atlantic Ocean
4	Bou Regreg	240	10	400	700	Atlantic Ocean
5	Oum Er-Rbia	555	48		3300	Atlantic Ocean
6	Draa	1100	3.5	250-760	24	Atlantic Ocean
7	Senegal	1641	450		20500	Atlantic Ocean
8	Gambia	1130	23			Atlantic Ocean
9	Great Scarcies	129	2.75		3100	Atlantic Ocean
10	Rokel	290	10.6	3769	63-60076.08	Atlantic Ocean
11	Sierra Leone	40	2.95	3000-5000	-	Atlantic Ocean
12	Moa	425	17.9		-	Atlantic Ocean
13	Saint Paul	450	21.9		-	Atlantic Ocean
14	Oueme	510	6.99		53400	Atlantic Ocean
15	Volta	1609	400	1600	38159	Atlantic Ocean
16	Cross	489	6.8	2508	1200-8000	Atlantic Ocean
17	Cestos	387	11.5		-	Atlantic Ocean
18	Niger	4180	1173.9	770	176000	Atlantic Ocean
19	Cavalla	515	30.2	1700	4	Atlantic Ocean
20	Sanaga	600	7.6	1570	37500	Atlantic Ocean
21	Congo	4344	3789	1500	129000	Atlantic Ocean
22	Cuanza	258	147.7	500	15800	Atlantic Ocean
23	Swakop	460	30	100	40	Atlantic Ocean
24	Kuiseb	480	11.77		20	Atlantic Ocean
25	Orange	200	855	700-800	11500	Atlantic Ocean
26	Gamtoos	645	34.6	400	30	Indian Ocean
27	Tugela	502	29.1	300	3780	Indian Ocean
28	Maputo	85	30	500	2800	Indian Ocean
29	Limpopo	1800	412.9	425-530	5360	Indian Ocean
30	Onilahy	525	32	750	0	Mozambique Channel
31	Zambezi	3540	1300	559-762	107200	Indian Ocean
32	Mania	19	18		4600	Mozambique Channel
33	Rufiji	600	177.4		25300	Indian Ocean
34	Tana	800	100		4980	Indian Ocean
35	Jubba	1610	210	400	5870	Indian Ocean
total			12900		1998858	

The Middle East and India have been classified by the United Nations as water-scarce nations, it is worthwhile to investigate whether coastal reservoirs and its water diversion along coastline can significantly alleviate the water crisis in this region. For the Gulf states, Gulf Cooperation Council’s report (UN-Water, 2014) shows that only Oman’s available water is slightly above the severe water scarcity threshold of 500 m^3/capita/yr, Saudi Arabia has 89.5m^3/capita/year, Qatar with 35, Untied Arab Emirates (UAE) with 21.6, Kuwait with 7.2 and Bahrain with 3.4m^3/capital/yr only. The largest country in Arabian Peninsula, the Saudi Arabia has no permanent rivers or lakes. Except oil, this region is one of the poorest nations in terms of natural renewable water resources.

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Consequently, this region has become a global leader in both the development and use of desalination technologies. In Saudi Arabia, approximately 2045 GL of surface water comes from rainfall each year (DeNicola, et al., 2015). As the groundwater resources are being depleted and the accumulated brine from desalination plants may severely damage the coastal ecosystem, A UAE company plans to tow huge icebergs from the Antarctica over 12000km to this region. In fact, the West flowing rivers in India can serve as the water source to the Middle East where only 2600km away from the Kalpasar coastal reservoir to Kuwait.

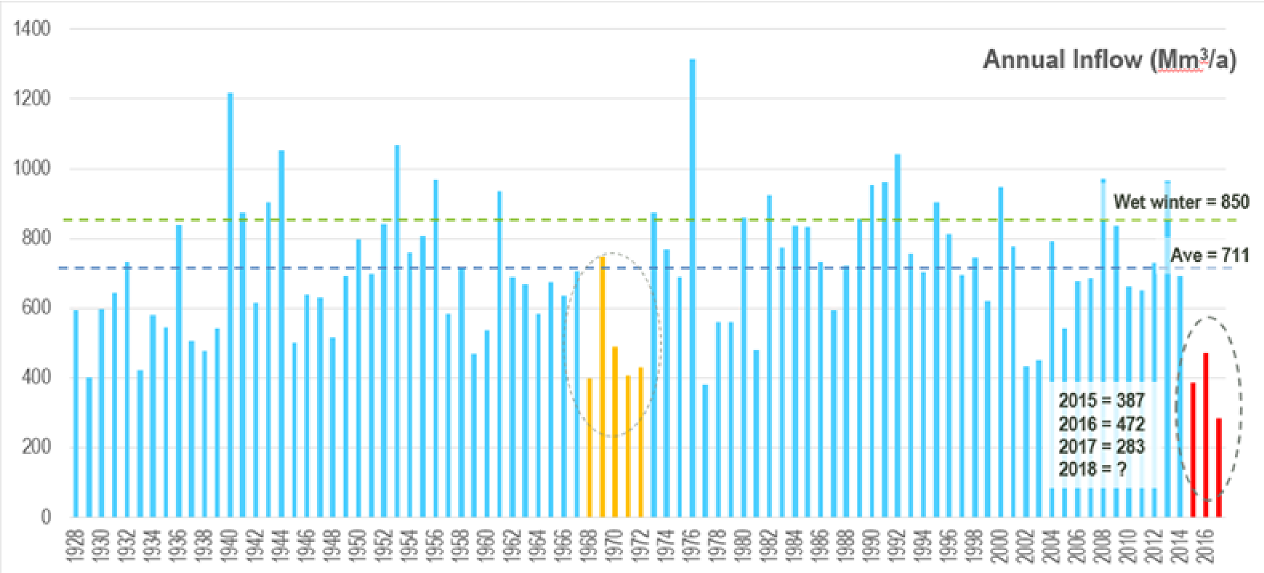

Fig. 6, Annual runoff to the sea from Rivers near the Cape Town City (Courtesy of Professor Neil Armitage, University of Cape Town).

India is the seventh-largest country in the world with 1.2 billion people in 2016 and 1.6 billion by year 2050, the most populous country. Its 3.3 million km^2 land receives 4000 km^3/yr rainfall and the total runoff is 1869km^3/yr or 46.7% of rain water as shown in Table 8. India's total water demand for irrigation, industrial and domestic sectors was 277km^3/year in 1960s, but it was increased to 680km^3/yr in 2000, which is almost the supply capacity from dams, rivers and lakes. In 2025 and 2050, the total water demand will be increased to 830km^3/yr and 900km^3/yr, far more than the water supply capacity. The existing 5000 dams are aging, among it, 100 large dams were constructed 100 years ago, and more than 500 dams were built 50 years ago (Agoramoorthy, 2015). 54% of Indian area faces high to extremely high water stress.

Table 8 shows Indian river flows. Its east flowing rivers like Krishna, Godavari, Kaveri, Mahanadi discharge 97.4 km^3/yr, and out of this 867 km^3/yr of water flows into Bangladesh and Myanmar. This means that in total 964km^3/yr of water is lost to the Bay of Bengal. The west flowing rivers like Netravati, Narmada, etc. add up to 212 km^3/yr of water every year is drained into the Arabian sea. It is clear that India is not running out of water but water is running out of India. As shown in Fig. 5, the connected coastal reservoirs by channels/pipes can supply sufficient water to Indian coastal cities. Additional 200km^3/yr of water supply from coastal reservoirs can greatly alleviate Indian water stress in 2050. More than that, coastal reservoirs at Indian west flowing estuaries could be the source of water supply to the Middle East where the total capacity of desalination plants was 13.6 km^3/year only. This could be a feasible alternative solution relative to towing icebergs over 12000km away.

Table 8, the main river systems in India where coastal reservoirs can be considered

	River	Catchment of the County	Annual runoff ($\times10^3$GL/yr)	Exploitable ($\times10^3$GL/yr)	Discharge to
1	Granges	26.5	525	*250*	*Bangladesh*
2	Brahmaputra	6	537	*24*	*Bangladesh*
3	Meghna/Barak	1.5	48		*Bangladesh*
4	Minor rivers of the northeast	1.1	31		Myanmar/Bangladesh
5	Subernarekha	0.9	12	6.8	Bengal Bay
6	Brahmani-Baitarani	1.6	28	18.3	Bengal Bay
7	Mahanadi	4.4	67	50	Bengal Bay
8	Godavari	9.7	110	76.3	Bengal Bay
9	Krishna	8.0	78	58	Bengal Bay
10	Pennar	1.7	6.3	6.9	Bengal Bay

11	Cauvery	2.5	21.4	19	Bengal Bay
12	East flowing rivers between Mahanadi and Pennar	2.7	22.5	13.1	Bengal Bay
13	East flowing rivers between Kanyakumari and Pennnr	3.1	16.5	16.7	Bengal Bay
14	West flowing rivers from Tadri to Kanyakumari	1.7	113.5	24.3	Arabian Sea
15	West flowing rivers from Tapi to Tadri	1.7	87.4	11.9	Arabian Sea
16	Tapi	2.0	14.9	14.5	Arabian Sea
17	Namada	3.1	45.6	34.5	Arabian Sea
18	Mahi	1.1	11	3.1	Arabian Sea
19	Sabamati	0.7	3.8	1.9	Arabian Sea
20	West flowing rivers of Kutsh and Saurashtra	10	15.1	15	Arabian Sea
21	Rajasthan Inland basin	0	n.a.		
22	Indus Eastern tributaries	10	11.1	46	Pakistan
23	Indus Western tributaries		61.2		
total		100	1869	690	

6 CONCLUSIONS

In the world, water scarcity affects more than 40% of people, and this percentage is projected to increase due to climate change, population growth and urbanization etc., on the other hand, the world damps 40000-45000km^3/yr of water into the sea, most of it is floodwater and only 5~6% of the runoff is used by human. Coastal reservoir is a freshwater reservoir in the sea, which can convert the disastrous floodwater into water resources, it may provide a water solution for coastal cities. Therefore it is necessary to review the existing coastal reservoirs and their associated shortcomings and advantages, then the improved design of coastal reservoirs can be suggested. Based on this review of 67 existing coastal reservoirs, the following conclusions can be drawn:

1), the world's water supply heavily depends on large dams. This research shows that large dams may be petered out completely in year 2150 if average life span of 150 years is assumed. This means that the world water scarcity may be worsened than previous estimation that assumes that our dams' life span is infinite.

2), the first coastal reservoir appeared in China more than 1000 years ago. The coastal reservoirs by modern technology started in 1930s in Netherlands and Australia. The purpose to construct coastal reservoirs keeps changing as the societal demands and priorities change. With the ever-growing population on coastal regions, and the intensified use of coastal water resources, integrated and sustainable management of coastal reservoirs is only going to become more important. It can be predicted that more coastal reservoirs will be constructed for water supply, seawater intrusion control, flood defense and urban regeneration, less coastal reservoirs will be constructed only for land reclamation.

3) the existing coastal reservoirs can be generally classified as the first and second generations of coastal reservoirs. The former fully closes a river estuary, but the latter keeps a river mouth open. Many huge projects of the first generation have failed due to problems like high salinity, deterioration of water quality and public opposition. It is likely that the second generation coastal reservoirs will be constructed widely, its successful example can be seen from Shanghai, China.

4) by examining the world's driest and second driest continents (i.e., Australia and Africa), one can find that coastal reservoirs may provide sufficient water to the coastal cities including the Cape Town, the first city with "Day Zero" in the world, whose taps are predicted to run dry. This paper also suggests that inter-basin water transfer could be implemented by connecting coastal reservoirs via pipes/channels, this may provide a water solution to populous country like India, and more importantly, it could supply water to the Middle East from coastal reservoirs in Indian west coast, this may be a more economical way compared with the proposal of 12000km iceberg towing.

5). Coastal reservoir can develop freshwater from the sea, also can mitigate the flood disasters by heavy storm and wave surge. It can prevent the seawater intrusion and regenerate a city. When considering that inland dams are petering out, larger and mega cities appear in coastlines, sea-level keeps rising and extreme weather patterns becomes a main threat to human, one may conclude that sooner or later, almost all coastal cities will construct coastal reservoirs for their own interests. However, it is extremely important to optimize the design through research and examining the experience in the design, development and management phases of such complex systems.

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