Coastal reservoir strategy to enhance India's freshwater storage by impounding river flood waters: a detailed overview

Sreevalsa Kolathayar, T. G. Sitharam and Shuqing Yang

ABSTRACT

This paper revisits the water resource scenario in India and presents the adequacy of the coastal reservoir concept to address water scarcity by impounding excess river flood waters. Though there has been no significant change in India's rainfall pattern in the last 100 years, there is a spatial non-uniformity in the rainfall events that occur which makes it difficult to pre-plan large-scale water storage at different locations. This study highlights the fact that there is enough water available but the deficiency is in storage. A large portion of freshwater from river systems, groundwater and wetlands drains into the sea due to insufficient storage facilities. Coastal reservoirs enable the storage of excess river flood waters near the coast for future use. This paper discusses current water supply solutions available in the country, and the efficacy of coastal reservoirs along with feasibility implications. The associated rewards and challenges are also discussed. The paper presents details of existing coastal reservoirs worldwide and recent feasibility studies envisaging coastal reservoirs in India.

Key words | coastal reservoir, India, runoff, sarovarmala, water demand

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INTRODUCTION

In many parts of developing countries like India, women and children walk miles to fetch water. The water from aquifers, which provides water for one-third of the world's population, is being used up before nature can complement it. It is expected that, by 2025, 1.8 billion people will be living in countries or regions with outright water scarcity, and two-thirds of the world population will be under water-stress conditions (UNESCO 2012). As about 66% of the world population would be confronted with water-shortage by 2020, water scarcity is already a focus of attention all over the world. Though average annual rainfall has not changed significantly over the last 100 years, demand for water keeps on increasing day by day. Increase in population and lifestyle changes are the reasons for water scarcity, but the inefficient management of the precipitation received stands as the major cause. On average, India receives 1,172 mm of rainfall annually, which amounts to a total volume of 4,000 billion cubic metres (BCM) on the Indian landmass (MoWR, http://www.wrmin.nic.in). Most of India's rainfall emanates over a four-month period from June to September. India also experiences years of excess monsoons and floods, followed by below-average or late monsoons along with droughts. Despite abundant rains in June to September, some regions face a shortage of drinking water, while some other parts of the country receive excessive rains resulting in floods. This geographical and time variance in the availability of natural water versus the year-round demand for irrigation, drinking and industrial water creates a demand–supply gap that keeps worsening with rising population.

India is a peninsula surrounded by ocean on three sides. India enjoys a lot of monsoon rainfall because of its physical features. However, due to climate change, very intense rainfall

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events are causing floods in many regions in India. The southwest monsoon accounts for most of the precipitation and different regions receive different amounts of rainfall. Despite that, India has a massive network of both perennial and seasonal rivers that form a network within the country. India also has various water-storing and conservation structures. India is the third largest dam-building country in the world after the USA and China. India has built more than 4,800 dams which are taller than 15 m and the majority of them (>80%) are earthen dams. Various storage structures lie at conflicting spots and hinder the socioeconomic condition of people whenever there is a problem. Even these structures act as hotspots at both national and international borders. Inter-state water disputes have increased in recent times. As per Government of India information, there are eight major inter-state water disputes in the country.

The currently available water solutions are unable to satisfy people's increasing need for water. As far as rainwater is concerned, one area receives too much rain in the wet season thereby causing floods and excess rainwater discharge into the sea, while receiving a shortage of rainfall in the dry season. The changes in the hydrological cycle across the world and uneven, uncertain rainfall also are responsible for the scarcity of water inland. Hence, the solution lies in utilizing or conserving the abundant monsoon water which runs off into the ocean in coastal reservoirs. It is essential to harness the excess river flood water by constructing impermeable sea dikes and creating reservoirs to preserve and distribute fresh water for various purposes. These coastal reservoirs have a unique role in storing freshwater and have characteristic linkages to other environmental entities such as wetlands (natural and manmade), freshwater or brackish water, which provide numerous ecological services. The primary objective of the present paper is to present a method for developing a sustainable water source for managing rainwater and highlight the potential of coastal reservoirs for storing flood water.

SCENARIO IN INDIA

Water demand

In India, the projected water demand for the year 2050 is 1,180 BCM as per the National Commission of Integrated Water Resources Development (NCIWRD) and 1,447 BCM as per the Ministry of Water Resources (Govt of India 2006). Table 1 presents the projected water demand in India for various sectors. Estimates of the utilizable water resources are 1,110 BCM as per the Central Water Commission (CWC), 1,209 to 1,255 BCM as per NCIWRD and 1,122 BCM as per the National Water Policy of India. Garg & Hassan (2007) reported overestimation in the data reported by these agencies and calculated the utilizable water resources as 668 BCM. The consequence will be alarming as the projected demand cannot be met even after the full development of utilizable water resources. Several studies revealed that almost all the basins would be in water-deficit, and this raises a big question about the availability of water through inter-basin transfer. It is also shown that the groundwater has already been overexploited as far back as 1997–98.

Rainfall and utilizable water resources

The Indian peninsula receives an average 1,172 mm of rainfall every year and this number has not changed much in the last 100 years (Figure 1). Water received on the Indian landmass in the form of rainfall in a year amounts to 4,000 BCM of water. The runoff flowing into Indian river systems from neighboring countries brings about another 400 BCM of inflow, and then the total water resources availability in India is up to 4,400 BCM annually. Even the severe drought year of 2014, with rainfall of 1,040 mm (12% below average), yielded about 3,400 BCM. Of the 4,000 BCM of the long-term average rainfall, Indian rivers drain over

Table 1 | Projected water demand in India for various sectors (Govt of India 2006)

Sector	**Standing Sub-Committee of MOWR**			**NCIWRD**		
Year	**2010**	**2025**	**2050**	**2010**	**2025**	**2050**
Irrigation	688	910	1,072	557	611	807
Drinking water	56	73	102	43	62	111
Industry	12	23	63	37	67	81
Energy	5	15	130	19	33	70
Other	52	72	80	54	70	111
	813	**1,093**	**1,447**	**710**	**843**	**1,180**

All values in BCM.

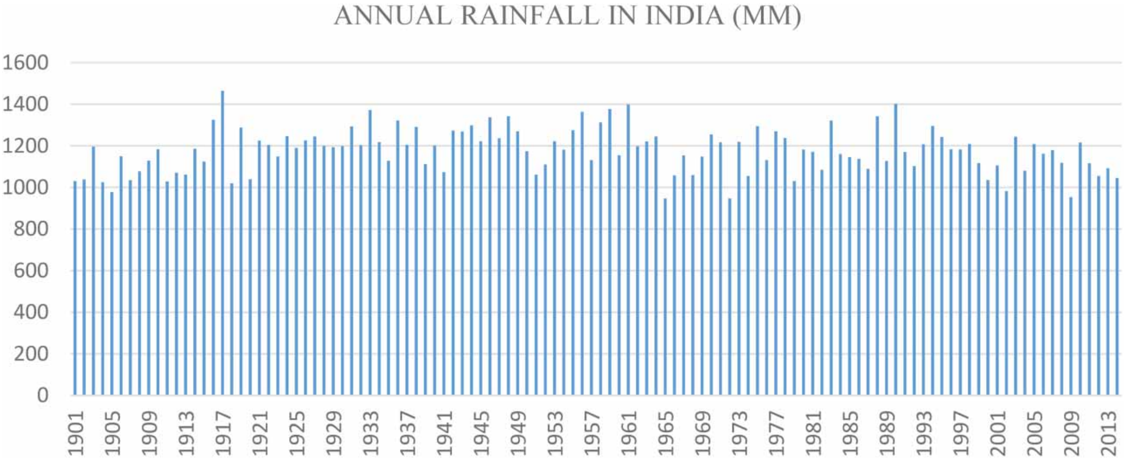

Figure 1 | Annual rainfall In India (mm) from 1901 to 2013 (average is 1,172 mm).

1,900 BCM. Usable totals are 700 BCM of surface water and 400 BCM of groundwater out of which about 450 BCM of surface water and 250 BCM of groundwater are presently withdrawn; and a balance potential of 250 BCM of surface water remains untapped due to various issues (Thatte 2017). To meet the ultimate needs of 1,180 BCM of water resources, it is high time to look at the potential of utilizing at least a small percentage of the water that gets drained into the ocean.

Current water solutions

The primary renewable source of freshwater is rainfall. Rainwater forms a surface/subsurface flow. Groundwater and seawater are other sources of water available for water supply options. The alternatives practiced worldwide to address water scarcity are inland reservoirs, interlinking of rivers to optimize the surface water, groundwater, desalination plants, wastewater reuse facilities and coastal reservoirs.

Status of dams

As the available freshwater sources are much less throughout the world, there is stress upon the available sources and conservation structures. Very few large dams have been built after the year 2000 as countries have realized the problems of large dam construction on land such as displacement of people, the silting process which reduces storage etc. In addition, erratic distribution of rainfall events in the upland catchments makes it difficult for inland dams to tap the river water. India is the third largest dam-building nation in the world with 4,877 large dams. India is a land of agriculture and is second to China in population explosion. Also, the northeastern states of India are prone to yearly flooding, which affects people's lives, property, and their livelihood. So, the requirement of water at least to meet the basic amenities for the people and their safety is to be paid heed to, for which the dams are to be working in good condition. There have been many dams constructed in India and yet, people face hardships with water-related issues. At the time of Independence, there were around 300 dams across India. By the year 2000 there were more than 4,000 large dams and the majority were built during the period from 1970 to 1989. While a few of the dams are constructed for hydro-electric power generations, water supply, and flood control, the primary purpose of Indian dams (96%) remains for irrigation. Currently, in early 2018, construction of 4,877 large dams has been completed and 313 are under construction (as per CWC) and water stored in these large dams amounts to about 305 BCM.

Implications of desalination

Desalination of seawater is a quite high-cost alternative, usually employed as the last choice. Continuous improvements in membrane technology are bringing down the costs and research needs to be stepped up in this area. For a developing country like India, it is very difficult to make a huge investment in projects like desalination, which requires a high maintenance cost. On average, the cost of conversion of seawater into desalinated water is 0.8 to 1.5 USD per kilolitre of water produced (DAE 2010). There are about 1,000 desalination plants operational in India and the total capacity is about 291,820 cubic metres per day. Gujarat and Tamil Nadu are in the forefront of the setting up of desalination plants compared with other coastal states. Though it is costly, these states depend on desalination due to acute water scarcity and non-availability of other alternatives. Desalination is not environmentally viable as it affects marine life where waste water is released.

Interlinking of rivers

The National River-linking Project seeks to interlink the Himalayan and peninsular rivers through 30 interlinking canal systems, of which 14 are in the Himalayan component and 16 are in the peninsular component (NWDA 1982; Shiva & Jalees 2003). It is envisaged that surplus flood waters, which flow unutilized to the sea, would be productively utilized for providing additional irrigation, domestic and industrial waste supply, hydropower generation, navigational facilities etc. This proposed project has raised a lot of controversies and debates since its formulation as such a water resources development strategy has many disadvantages and adverse impacts on the river ecosystem in countries like Russia, China, Kazakhstan, Israel and Turkey, which have taken up the gigantic task of water diversions (Misra *et al.* 2007). The interlinking project will have to face many potential inter-state conflicts (Bandyopadhyay & Perveen 2003). The ability of the river-linking project to address the issue of domestic water security in all drier areas of the country is questionable. Nigam *et al.* (1997) highlighted that if the precipitation available within concerned watersheds or river basins is harvested and stored, the supply of domestic water would not pose a severe issue in most parts of the country. Highlighting the need for looking beyond the grand interlinking project proposal, Verghese (2003) stated that the river-linking project is not a single standalone remedy for the country's water problem but the peak of advancement of integrated micro- to mega-measures in an overall unarticulated national water strategy.

Necessity of alternative water storage strategy

Due to various climatic factors, the total rainfall that should be received throughout the year is received in just 30–40 days. This results in torrential rainfall and flash floods during the monsoon. This precipitation water ultimately will mix in the ocean without being utilized for future need. Because of the lack of storage capacity within the country (even with around 5,000 large dams), there is a burning need for more storage structures to cater to water demands during times of drought. Even though land-based reservoirs like dams have various advantages, they have their own disadvantages like land acquisition, clearing of forest area, loss of bio-diversity, submergence of land and forests, diversion works during construction etc. Per capita storage of water in India for domestic purposes is too small when compared with developed countries.

In India, more than 25% of people live in coastal areas and major urbanization is happening in India on the coastlines. Figure 2 shows the coastal belt and coastal states in India and Table 2 presents a database on the coastal states of India. There is a rapid migration of people to coastal areas because of the job opportunities. There will be a rapid increase in population and the demand for water will increase exponentially. Presently, the solution for this issue would be a coastal reservoir, i.e. a reservoir in the sea to store a portion of the river flood waters which join the ocean in the monsoon period and use it during the drought periods.

CONCEPT OF THE COASTAL RESERVOIR TO STORE FLOOD WATER

The coastal reservoir is a unique structure constructed at an estuary, gulf, or bay or in the sea (at the point where a river meets a sea) to store the portion of excess water at flood times. This seawall or dike structure may run for kilometres together in the coastline. These coastal reservoirs and coastal wetlands to ensure the quality of water play a critical role for the rural coastal population. The coastal reservoir has many advantages such as no land acquisition problems, and no land submergence or forest submergence like in inland reservoirs. They are already put to work in countries like the

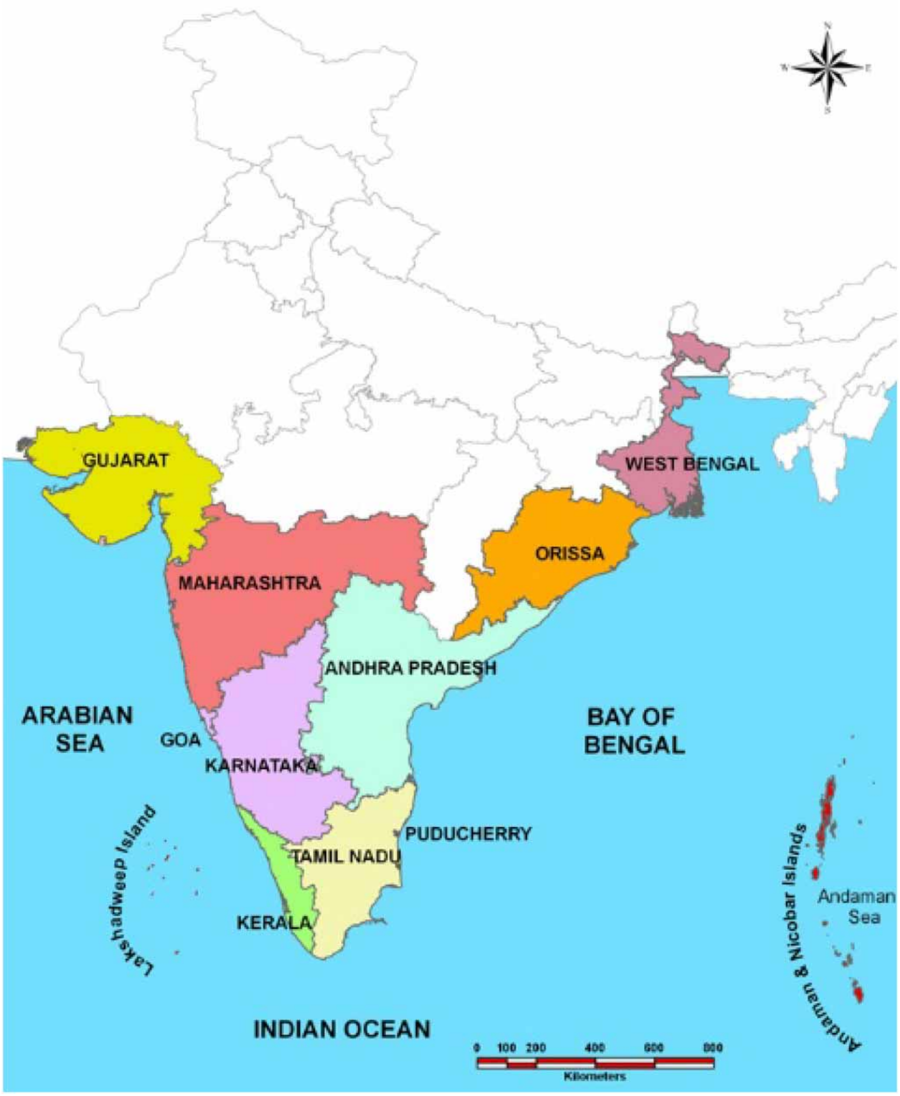

Figure 2 | Coastal states of India (source: Centre for Coastal Zone Management and Coastal Shelter Belt).

Netherlands, Singapore, China, South Korea, Hong Kong, etc. and are proven to be beneficial. They are designed with gates so that the excess flood water that is more than the capacity of the reservoir can be discharged into the sea. Even inlet and outlets are controlled such that only good quality water enters the reservoir with very little stagnation of water. One can adopt very innovative designs with a smart sensor network to operate the coastal reservoirs efficiently. Coastal wetlands, which include water bodies like lakes/reservoirs, estuaries, floodplains and tidal mudflats, play a vital role in ensuring both the quantity and quality of water for human beings and the entire range of flora and fauna. These coastal reservoirs provide freshwater for agriculture, livestock and domestic consumption, water for industry, and recharge the groundwater levels, which are under immense strain of over-exploitation.

Figure 3 shows a typical schematic of a coastal reservoir which enables storing of freshwater during river floods. The freshwater reservoir includes an impermeable seawall for containing the freshwater and preventing a mixing of the freshwater with the seawater (Figure 4). The seawall is located on the seabed and has a three-sided structure to prevent ingress of seawater into the freshwater/river course. By keeping out seawater, by the construction of the seawall

Table 2 | Database on coastal states of India (Singh 2003; Venkatraman & Wafar 2005; Sanil Kumar *et al.* 2006)

Coastal data	
Length of coastline	7,516.6 km Mainland: 5,422.6 km Island territories: 2,094 km
Total land area	3,287,263 km²
Area of continental shelf	372,424 km²
Territorial sea (up to 12 nautical miles)	193,834 km²
Exclusive economic zone	2.02 × 106 million km²
Island territories	1. Andaman & Nicobar Islands (Bay of Bengal) 2. Lakshadweep Islands (Arabian Sea)
Total number of coastal districts	69 coastal districts in mainland India, three in Andaman & Nicobar and one in Lakshadweep
Coastal geomorphology (mainland)	
Sandy beach	43%
Rocky coast	11%
Muddy flats	36%
Marshy coast	10%
Coastline affected by erosion	1,624.435 km mainland 132 (islands) (CPDAC)
Population	
Total population of India	1.28 billion (Census 2011)
Population of coastal states and union territories	560 million
Percentage of population in coastal states of India	44%

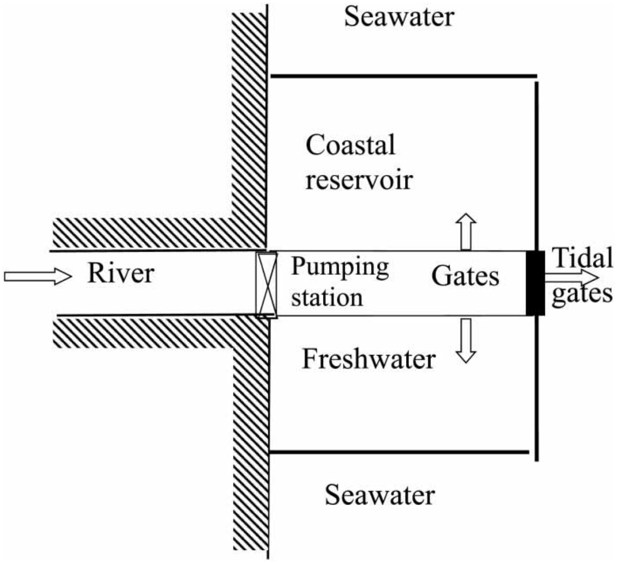

Figure 3 | Schematic of a coastal reservoir that enables storage of freshwater during river floods.

along with one or two barrages (with sluice gates) close to the mouth of the river, the freshwater reservoir is formed in the ocean. The reservoir will be in shallow waters and have an average depth of 10 to 20 m with a maximum depth of about 30 m. When it rains heavily during low-tide, the sea reservoir outflow crest gates will be lowered to release the excess rainwater from the reservoir into the sea. If heavy rain falls during high tide, the outflow crest gates remain closed and a large reservoir can be designed so as to absorb the flood water shocks during high tide and release water out to sea only during low tides. The method further includes interlinking of these reservoirs at different locations across different rivers through underwater subsurface pipes for transferring water from one reservoir to another in shallow seawater (herein called Sarovar Mala™; *sarovar* means freshwater pond in Sanskrit and *mala* means necklace around the land) (Sitharam 2016).

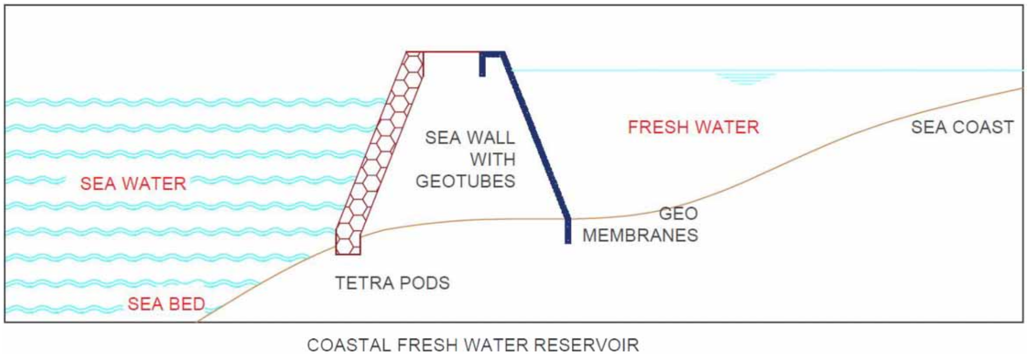

Figure 4 | Typical cross-section of sea dike to impound freshwater in coastal reservoir.

BENEFITS AND CHALLENGES OF THE COASTAL RESERVOIR

The pros and cons of coastal reservoirs compared with other solutions for the provision of water supply are presented in Table 3.

Benefits

The concept of the coastal reservoir enables major hydrological extreme/meteorological extreme (flood) to be fruitfully utilized for the benefit of mankind by storing river flood water in abundance for future use. The coastal reservoir can ensure supply of water at the most economical rates to different regions of the country and interstate water disputes and administrative hitches can be avoided. The Government will make substantial revenue generation by selling the most precious natural resource at the most economical prices. The coastal reservoir can act as a barrier to protect the coast against natural hazards like a tsunami and even in a worse disastrous event of an earthquake, there will be no threat to human habitats unlike in inland dams. The freshwater reservoir has the potential to create a new freshwater ecosystem and can become India's largest freshwater fishing industry hub. New fishing harbors can be built along the seawalls in the deep sea thus facilitating deep water fishing at the sea end of the reservoir. Coastal reservoir demands no diversion of river course, no submergence of land or forest or displacement of people. Agricultural activity can be augmented and people can be insured against famine and hunger.

The coastal area will be benefitted with ample storage of water which is enough for drinking and even irrigation purposes. Solar power can be generated on the side walls of the reservoir and floating solar panels can also be used in the shallow waters making the reservoir self-sufficient in energy. The tides and winds open up additional options for energy generation along the coastal reservoir. Renewable energy can be used for pumping, lighting and other energy requirements. Consultation with renewable energy developers will support the planning phase of the project to achieve cost-effective renewable energy generation. Coastal reservoirs will open up an opportunity to promote water sports on the reservoir and promotion of tourism attracting tourists from worldwide. Freshwater dredging in the reservoir will provide sand for construction. There will be an increase in industrial, recreational and fisheries activity around this freshwater. Roadways over the seawall, freshwater fishing, navigation, and tourism will make the reservoir site be developed as a smart township. The presence of the coastal reservoir will pave the way for improvement in the quality of groundwater (saline water to freshwater) near the coast. In short, the coastal reservoir has the potential to transform a neglected and polluted coastal area into a sustainable freshwater township with self-sufficient energy raising the living standard of people in addition to the supply of freshwater for all. The coastal reservoir will complement the water–energy–food nexus as it facilitates storage of freshwater for drinking as well as irrigation along with ample opportunities for renewable energy production.

Table 3 | Pros and cons of different water supply solutions compared with coastal reservoirs

Water supply solution	Pros	Cons
Conventional dams	1) Mature technology	1) Limited lifecycle 2) Devastating environmental impact (flooding) 3) Far from demand – high cost for pipes 4) Ineffective water harvesting
Desalination plant	1) Unlimited water from the sea 2) Ideal for no or very limited rain	1) Limited lifecycle 2) Requires enormous amount of energy 3) Large amount of waste (salt) 4) Very expensive to build, maintain and operate
Storm water harvesting	1) Low-cost water harvesting 2) Long lifecycle	1) Land conversion (environmental impact) 2) Limited storage capabilities 3) Redundant during drought
Wastewater reuse	1) Low-cost water harvesting 2) Long lifecycle 3) Consistent supply	1) Not suitable for human consumption 2) Limited maximum output 3) Expensive to build, maintain and operate
Groundwater	1) High chances of quality water 2) Low-cost water harvesting	1) Groundwater depletion 2) Sinking of land 3) Intrusion of salt water 4) Exposed to contamination
Coastal reservoirs	1) No land acquisition 2) Cost effective 3) Sustainable 4) Effective method to harvest water 5) Multi-functional 6) Harvest of energy 7) Free of risk like dam breaching 8) Recreational and urban regeneration 9) Additional space would be created and new cities around the freshwater body can be created	1) Transportation of water can be costly to towns uphill 2) Proper care needs to be taken to allow fish breeding in rivers 3) Regular desilting required 4) Issue of environmental clearance

Challenges

Though the rewards associated with a coastal reservoir are high, the construction of a coastal reservoir will also face challenges which need to be addressed in a sustainable manner. It is a little-explored and challenging methodology of storing the flood waters in a sea reservoir by building a seawall which may lead to possible vulnerability of coastal ecosystems, including marine ecology. The existing means of fishery livelihoods may be affected. The coastal reservoir has huge financial implications in terms of investment though it is much less compared with inland reservoirs and desalination. It is challenging to prevent saltwater intrusion into the command area of the proposed freshwater reservoirs within the sea. Regular de-silting of a sea-based reservoir may need to be carried out economically and efficiently. Administrative and environmental clearances from various statutory bodies would be another challenge. There would be possible resistance from environmental/political activists and local communities which need to be addressed with proper awareness of the concept of the coastal reservoir supported by a scientific rationale.

GLOBAL STATUS OF COASTAL RESERVOIRS

Many countries such as Singapore, South Korea, the Netherlands, China, Hong Kong, Australia etc. have constructed coastal reservoirs (Yang *et al.* 2013; Yang 2015; Yang & Kelly 2015) for supplying water to domestic, industries, irrigation, and other ecological needs. Apart from this, these sea-based freshwater reservoirs function as flood control measures and have other recreational benefits including promoting water sports, tourism, deep sea harbors, solar and ocean wave energy generation, etc. Table 4 presents the existing coastal reservoirs in the world along with their purpose.

Singapore successfully constructed a sea-based freshwater reservoir in 2008 called the Marina Barrage to augment the water supply to Singapore and to control floods. The Marina Barrage divides freshwater in the Marina Bay Reservoir from the salty waters of the South China Sea. When the barrage was first erected, the reservoir contained a mixture of freshwater and seawater. The desalination of the reservoir's initial water was achieved through the natural process of replacement by rainwater. The reservoir is cleaned daily to remove any litter and maintain a high quality of drinking water (Schmid 2015).

Table 4 | Existing sea-based reservoirs around the world (modified after Yang & Kelly 2015)

Country	Name	Purpose
Netherlands	1. Afsluitdijk in the Ijsselmeer, 1932 2. Zuider Zee, 1937	Flood control Flood control
India	Thanneermukkom bund, 1974	Agriculture
South Korea	1. Sihwa, 1994 2. Saemanguem, 2010	Tidal energy Land reclamation and freshwater
Hong Kong	1. Shek pik, 1963 2. Plover Cove, 1968 3. High Island, 1978	Freshwater
China	1. Qingcaosha, 2011 2. Chenhang, 1992 3. Baogang, 1985	Freshwater
Singapore	Marina barrage, 2008	Freshwater
United Kingdom	Cardiff Bay project	Freshwater and coastal area development

At planning stage: 1. Pluit Reservoir Revitalization Project, Jakarta, Indonesia, 2. Kalpasar Project, Gulf of Kambhat, Indian Water Project, Gujarat, 3. Sydney and other coastal cities, Australia, 4. New York, USA, 5. Netravati River Project, Mangalore, India.

The Saemangeum Reclamation Project was launched as a national project in 1991 to reclaim a large coastal area by constructing a 33.9-km-long dike. The Saemangeum seawall encloses 401 square kilometres (160 square miles) of seawater or tidal mudflats, about two-thirds the size of Seoul.

Water supply in Hong Kong initially came only from local sources, including numerous small dams. Providing an adequate water supply for Hong Kong has always been difficult because the region has few natural lakes and rivers, inadequate groundwater sources, a high population density, and extreme seasonable variations in rainfall. Thus about 70% of water demand is met by importing water from the Dongjiang River in neighboring Guangdong province. In addition, freshwater demand is curtailed by the use of seawater for toilet flushing, using a separate distribution system. Three sea-based reservoirs have been constructed, namely 1. Shek Pik (1963), 2. Plover Cove (1968), and 3. High Island (1978). Water rationing was renewed for the last time in 1980–81. Between 1965 and 1982 water had to be rationed seven times, often for many months with interruptions of up to 16 hours per day (Chau 1993).

Similarly, China has constructed three main sea-based reservoirs, namely Qingcaosha (2011), Chenhang (1992) and Baogang (1985) for different purposes.

In 1987, the Cardiff Bay Barrage Act was passed by the UK Parliament and a 1.4-km-long tidal exclusion barrage was constructed across the mouth of Cardiff Bay, impounding two rivers, namely the Taff and Ely, regenerating an area of over 1,000 hectares and creating a large freshwater lake, connecting the city of Cardiff back to its waterfront.

EXISTING AND PROPOSED COASTAL RESERVOIRS IN INDIA

Thanneermukkom bund

Thanneermukkom bund (Figure 5) was constructed in 1974 as part of the Kuttanad lowland development scheme and creation of a freshwater reservoir in the coastal area of Kerala, India. Thanneermukkom saltwater

Figure 5 | (a) Bird's eye view of Thanneermukkom barrage; (b) location of barrage across Vembanadu Lake.

barrier/bund is considered the largest mud regulator in the country and has been in operation since 1976. It divides Vembanad Lake into a freshwater lake fed by the rivers draining into the lake and a brackish water lake fed by ocean currents into the lowlands of Kuttanad. The four major rivers of Kerala, the Pamba, Meenachil, Achankovil, and Manimala, flow into the region before their confluence into the Arabian Sea. It also has a major portion of the largest lake in Kerala, Vembanad Lake. The lake is fed by ten rivers of which the above four major rivers form the main part. The regions receive a good amount of annual rainfall, which is above 3,000 mm, and these four rivers bring a large quantity of water into the lake before joining the sea. By constructing the saltwater barrier, a coastal reservoir having freshwater has been created for increasing agricultural activities in the area in addition to land development. However, there are reports of environmental and ecological damage such as rampant propagation of water hyacinth in freshwater and deterioration of brackish water fishing in the area. However, these are related to the wrong operation of the reservoir and not the fully functional plan of Thanneermukkom bund. The problems faced by fisherman and the water hyacinth problems need to be addressed with innovative alternative schemes of operations. In fact, this freshwater reservoir needs to be restored to its capacity for the supply of drinking water to nearby areas and also to supply freshwater for irrigation in the lowlands of Kuttanad, which helps farmers.

Kalpasar project

The Gulf of Khambhat Development Project is mainly a water resources project involving the creation of a freshwater reservoir in the Gulf of Khambhat for meeting the demands of irrigation, domestic and industrial water supply. Associated components related to the freshwater reservoir are the use of the top of the dam across the Gulf as a surface transport link, potential development of fisheries, and reclamation of saline land around the freshwater reservoir. The Gulf of Khambhat extends from north to south about 200 km and the width varies from 25 km at the inner end to 150 km at the outer mouth, covering an area of around 17,000 km^2, of which only 2,000 km^2 will be enclosed by constructing a dam across the Gulf between Bhavnagar and Dahej. Figure 6 shows the Kalpasar Project location and detailed Gulf of Khambhat development plan where the coastal reservoir is envisaged in the Gulf of Khambhat, using contour canals to supply water to the entire Gujarat coast. The Kalpasar Project envisages building a dam across the Gulf of Khambhat for establishing a huge freshwater reservoir for irrigation, drinking, and industrial purposes. A ten-lane road link will also be set up over the dam, greatly reducing the distance between Saurashtra and South Gujarat by 225 km. A state government release said the Rs 55,000 crore (US$ 11.7 billion) project will have a vast freshwater reservoir with gross storage of 16,791 million cubic metres of water. Once constructed it will be one of the largest freshwater reservoirs in the sea with the

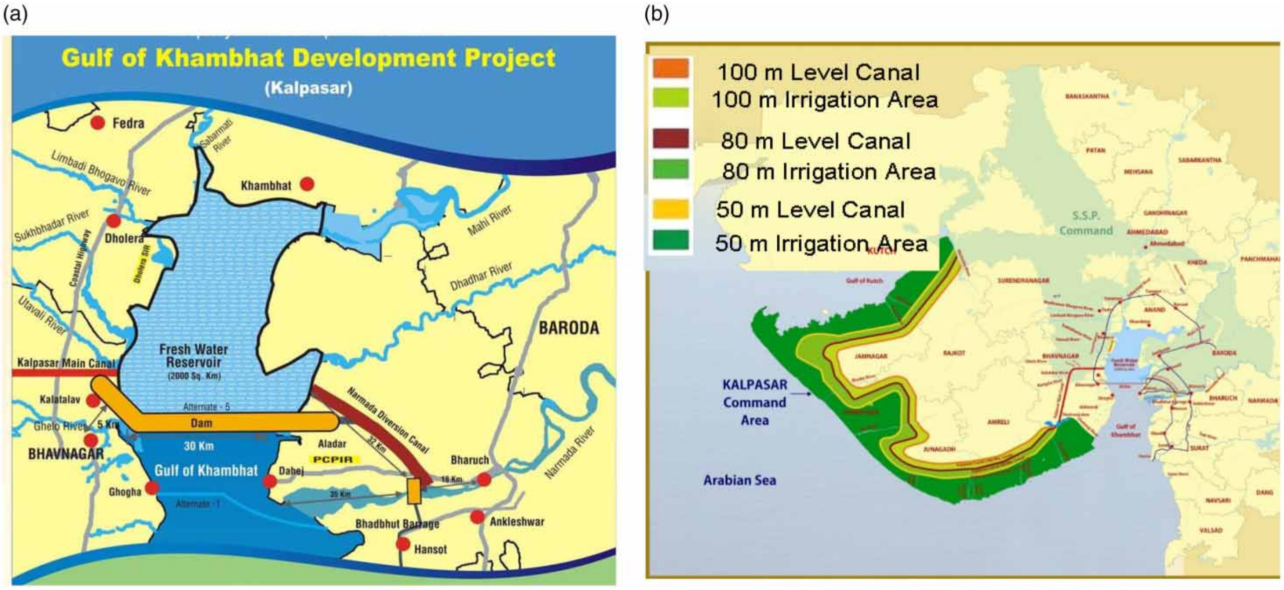

Figure 6 | (a) Coastal reservoir in the Gulf of Khambhat in Gujarat state; (b) developmental plan to supply water for the entire Gujarat coast using the coastal reservoir (Kalpasar 2016).

highest priority for irrigation and drinking water in the region for Saurashtra and the Central Gujarat regions of India.

ONGOING FEASIBILITY STUDIES IN INDIA

Coastal reservoir at Mangalore to impound Netravali River flood waters

Mangaluru is blessed with the river Netravati, which carries a large quantity of water during the monsoon and finally ends up in the sea. A project funded by BWSSB, Government of Karnataka, was envisaged to carry out a feasibility study on developing a sustainable water source for Bengaluru and Mangaluru, using the coastal reservoirs as a storage area for Netravati River flood waters. The principal objective of the project was to assess the feasibility of storing freshwater in a reservoir along the coast, by building a sea dike in the Arabian Sea. The results of the feasibility study (Kolathayar *et al.* 2017) state that there is enough water available at the outlet of the Netravati basin for Mangaluru and Bengaluru. The technologies available are elegant for constructing the dikes in the shallow sea and on the soft sediments, and the geotechnical profiles clearly indicate that one can develop the coastal reservoir in and around the mouth of the Netravati River (Parthasarathy *et al.* 2018). Between 1989 and 2013, the average annual runoff in the Netravati basin is estimated to be 388.5 TMC ft (11 BCM). As per studies, the shortfall in demand in Bengaluru for 2051 is 26.16 TMC ft, which is 7% of the average annual runoff through Netravati. In 2021, the shortfall in demand is only 8 TMC ft, which is just 2.1% of the runoff. Enough water is thus available in the river Netravati to cater to the needs of Mangaluru and Bengaluru. Hence, in principle, a small percentage of the runoff of Netravati is more than sufficient to cater to the water requirements of both Mangaluru and Bengaluru.

Formation of a freshwater reservoir in Ashtamudi Lake, Kollam

Sitharam *et al.* (2017) and Sitharam *et al.* (2018) discussed the concept of constructing a dike at the mouth of Ashtamudi Lake, to check seawater intrusion into the lake and to save tiny islands in the lake from the after-effects of sea-level rise. The study reported that conversion of the brackish Ashtamudi Lake to a freshwater reservoir is feasible by building a barrage at the outlet of the lake at the mouth of the Arabian Sea (Neendakara). On one side, it will block freshwater flowing from Kallada River to the lake from being dispersed into the sea. On the other side, the barrage will prevent seawater from entering the lake, avoiding the contamination of the freshwater supply from saltwater. The study presented three different possible schemes to meet the water demands of Kollam city, Kollam district and the entire state of Kerala. Scheme 1 can supply water to the entire Kollam Municipal Corporation, scheme 2 can meet the water demands of Kollam, Cochin and Thiruvananthapuram cities whereas scheme 3 will suffice to supply water to the entire state of Kerala. The annual yield of Kallada River was estimated as 80 TMC ft and hence it was concluded that enough water is available every year to supply freshwater to the proposed schemes in Ashtamudi Lake.

SAROVAR MALA™ (GARLAND OF RESERVOIRS FOR INDIA): A CONCEPT

Sarovar Mala™ (Figure 7) is a concept of linking coastal reservoirs (Sarovars in the ocean) at the mouths of rivers (where a river joins the ocean) in peninsular India. The main objective is to create a large freshwater body for developmental activities including drinking/agricultural/industrial activities in the coastal area and to increase water storage per capita in the coastal areas. This is a strategic plan to increase the water storage per capita in India along the Indian coast by storing the excess flood waters from major rivers in the southern Indian peninsula. These Sarovars can be connected by pipelines/channels along the coast.

Along with the initiative of the Government of India to modernize India's ports, this freshwater reservoir (Sarovar) will aid coastal area development along with new ports. With the increased freshwater availability on the coast, the coastlines can be developed to contribute to India's growth. Sarovar Mala provides good connectivity for non-perennial rivers and will provide a storage plan for freshwater from the excess river flood waters and one can develop industrial clusters and hinterland up to a radius of 100 km resulting in Sarovars becoming the drivers of economic activity in coastal areas.

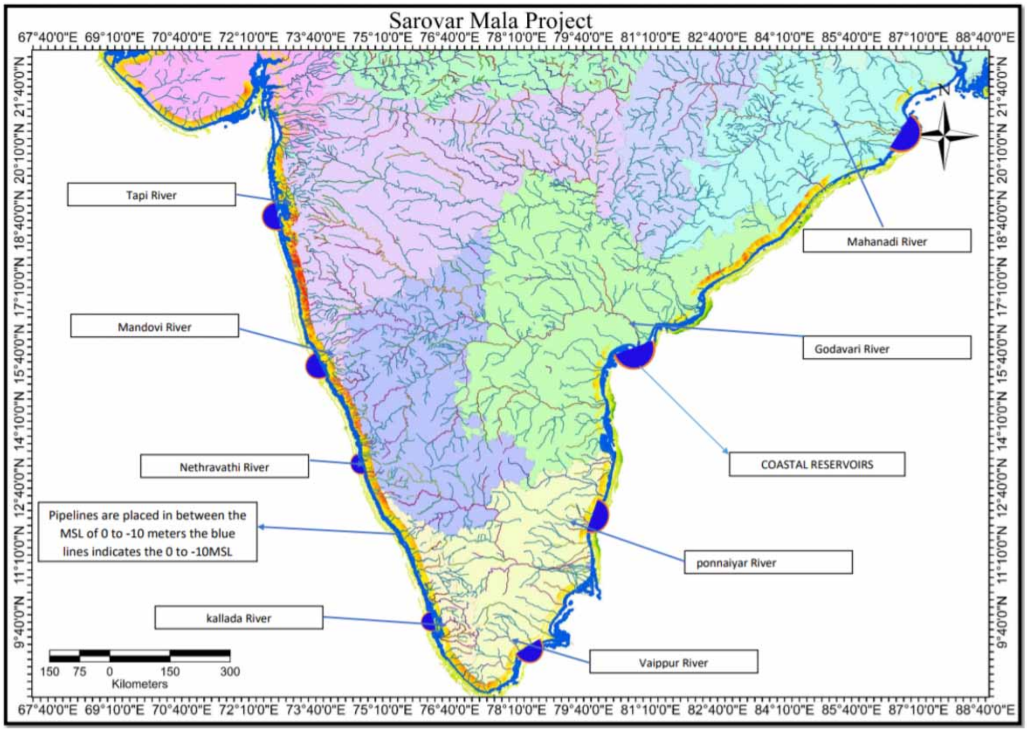

Figure 7 | Sarovar Mala™, a chain of freshwater reservoirs along the coast line of India.

Considering all the above, the solution lies in storing flood water in coastal reservoirs, as this does not submerge lands which are of immense value, and connecting them using shallow water pipelines in the ocean – Sarovar Mala™. Even the sand, silts and salts can join the ocean partly through the coastal reservoir. The coastal reservoir can be constructed in shallow waters at appropriate locations close to the mouth of the river along with a barrage at one or two ends. All these reservoirs will be connected through water pipelines in the ocean which will be a sustainable Sarovar Mala™ around the Indian peninsula for creating a sustainable solution for Indian water requirements specifically in the coastal areas. Seawalls or breakwaters with some modifications are good enough to construct the coastal reservoirs. This concept envisages a coastal reservoir storing freshwater, while the bottom of the reservoir is a mixture of sand and rubble. The emergent vegetation can cover about 20% of the surface area of these artificial reservoirs or ponds, making them environmentally friendly. More species of fish will call these ponds home! This reservoir will increase India's freshwater supply for generations to come and use the rivers flowing into Arabian Sea and Bay of Bengal.

CLASSIFICATION OF COASTAL RESERVOIRS

The strict definition of a coastal reservoir (Yang *et al.* 2013) could be a small fluid body held by artificial structures inside a very large water body, the inside and outside fluids being different in their physical, chemical and biological properties. For water supply purposes, the coastal reservoir can be simply defined as a freshwater body inside a seawater environment with its dam situated in the seawater, and seawater pollution is the main risk for its structural corrosion and water quality maintenance.

Coastal reservoirs can be classified into various categories, in terms of location, type of barrage and water quality. The location of a coastal reservoir can be inside a river mouth, beyond the river mouth or beside the river mouth. The possible types of the dam are concrete, earth or soft dam. Coastal reservoirs can be classified in terms of water quality as freshwater, brackish water, and polluted water. The utilization of water from coastal reservoirs can be for drinking, irrigation or industrial usage.

Broadly, all existing CRs can be divided into the first generation and second generation. The first generation CR uses the barrage to cut off river mouths and forms a water body on the continental side relative to the coastline, and generally, its water quality is not good and social/environmental impacts are severe. The second generation CR uses the sea space to store the freshwater, and its water quality is better than or equivalent to the existing dam water with minimum environmental/social impacts as its river mouth is not closed. It can select the best-quality river water for storage, and by-pass unwanted poor-quality water into the sea. The differences of first and second generation coastal reservoirs compared with inland reservoirs are detailed in Table 5.

For an inland dam's design, the most important parameters are the selection of the dam site and dam height. The hydraulic structures include a spillway to release excessive floods. For the first generation CR, the dam site and height are almost in flexible; one cannot adjust the reservoir size to match its demand.

For the second generation CR design, the dam site is flexible, and its dam is no longer short and straight, but long and curved, and the dam length is important, rather than dam height. So that the reservoir size can exactly match the demand, the enclosed water area should be the minimum or the ratio of water volume to its surface area should be maximum. In its structural design, its bottom water should be released regularly as the seawater has higher density rather than the surface water as from the inland reservoirs' spillway.

SUMMARY AND CONCLUSIONS

To summarize, a solution to India's water shortage lies in conserving the abundant monsoon water available as precipitation, storing it in coastal reservoirs, and using 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. India receives an annual rainfall of 1,172 mm and the volume of water available to India annually from rainfall and runoff from neighboring countries amounts to 4,400 BCM. The water

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, by-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 flood water, fish, navigation)	Low
Seepage	By pressure difference	By density difference	By density difference
Pollutant	Land-based	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%

stored in India's large dams is only 327 BCM. Coastal reservoirs enable the storage of excess river flood waters near the coast for future use in areas known to be drought-prone or at those times of the year when water supplies become scarce. Using this method, the amount of water that is wasted as run-off can be effectively utilized. Construction of a coastal reservoir does not involve many risk factors and disadvantages like relocation which would be there in inland dam construction. The flood water which passes through the man-made wetlands before it is stored in coastal reservoirs can charge aquifers, conserve moisture, act as pollution barriers and are a habitat for biodiversity. This can also help in purification and storage of freshwater, flood control, groundwater replenishment, acting as nurseries for freshwater/marine fish, providing shoreline stabilization and protection, sediment retention, harbors and supporting biological diversity and mitigating effects of climate change.

This paper also presented the concept of Sarovar Mala™, a chain of coastal reservoirs, an innovative concept that has the potential to ensure water availability to India throughout the year. It is wise to invest in storage of this excess flood water, which is reasonably diluted and cleaner, in the coastal reservoirs close to the place where the river joins the sea. There is a need to develop a strategy for effective utilization of the coastal reservoir concept in a holistic approach addressing water needs, energy generation and socio-economic development in India. In this context, coastal reservoirs ensure availability of water for meeting multiple requirements of the ecosystem as a whole.

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