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Will coastal reservoirs dominate future Australian water supplies?

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A coastal reservoir is a reservoir designed to store floodwaters in a seawater environment. The first generation of this technology has been successfully applied in China, Singapore, Hong Kong and Korea, but the water quality is generally not as good as that from inland reservoirs. The second generation of coastal reservoirs has been developed and its water quality is comparable with the water available from conventional urban water supply reservoirs. The conceptual design of coastal reservoirs for Australia's capital cities is outlined.

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Abstract: Next to air, fresh water has been always considered as the most important resource, central to economic development as well as to human physiological needs. Currently the total world population is about 7 billion, and by 2050, it is projected to be 9 billion. By that time, an additional 40 Nile Rivers will be needed. Historically, inland dams have successfully solved the water deficit problems in many places, but more and more countries are resorting to emerging technologies like desalination, wastewater recycling and rainwater tanks which are needed to replace inland dams for a number of geomorphological, environmental and social reasons. These new technologies require a paradigm shift in the water supply industry: global water consumption is only 5-6% of annual runoff - as it is in Australia - so the coming shortage is not of water, but of storage.

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Keywords: urban water supply, coastal reservoir, inter-basin water diversion, inland dams, water quality

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1 Introduction

According to Kummu *et al.* [1], the population under water scarcity since the 1900s has increased by nearly 16-time, but total population has increased only 4-fold over the same period. Alavian *et al.* [2] show that 80 countries now have water shortages, and 2 billion people do not have sufficient clean water, with at least 1 billion people not having their basic water needs. The current world population of 7.2 billion is estimated to be increasing by 1 billion every 12 years, about 50% of the total population will soon be affected by severe water shortages. Most of them will live in coastal cities due to urbanization. An example of global water crisis can be seen in Australia, the driest inhabited continent in the world with 24 million people in 2016 spread over 7.7 million km², where desert makes up about 18% of the mainland. Not only is the continent dry, but its rivers generally flow with less regularity and predictability than those of other continents [3,4]. The largest river system (the Murray-Darling river basin) is similar in area to that of the Ganges River in India (about 1 million km²), but during Australia's Millennium Drought (2000-2009), the Ganges River flow was 200 times higher than that in the Murray-Darling system.

In 2013-2014, Australia used 24×10^3 GL/a of industrial and household water [5]. Compared with the annual runoff to the sea which is about 400×10^3 GL/a, the consumed water was

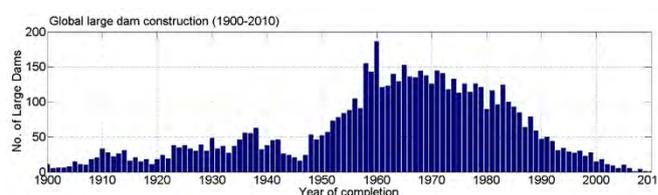


Figure 1. Number of large dams constructed in the world by year.

only 6% of total runoff, similar to the rest areas in the world. In the next 100 years, only 1-2% of additional runoff is needed to sustain Australia's growth in water demand. More and more countries are realising that on-stream dams are not the future for water development, so new technologies are required. These ideas and solutions have been tested in Australia to ensure security of supply:

1) Inland dams. In the 20th century, the dam industry played a leading role in securing water supply such that Australia has the highest storage per capita in the world. In the 21st century, it is now hard to find dam sites which are economically suitable for development. Further, there is much more technical and public recognition of the negative impacts on riverine ecosystems. Consequently, governments, research communities and the public are shifting to other alternatives to locating water storages on significant watercourses.

2) Wastewater reuse. This technology was first highlighted

by its success in low-rainfall Windhoek, Namibia and has been applied in Singapore and Brisbane^[6]. The Western Corridor Project in Brisbane cost \$ 2.7 billion in 2008, but in September 2013, then Premier Peter Beattie admitted that the scheme was a “tragic error of judgment” because the public rejected drinking recycled sewage because of its “yuk factor”.

3) Desalination plants. This has been seen as a promising way to supplement climate/weather-dependent water supplies during droughts, especially for island countries like Singapore and Australia. There are 92 desalination plants in Australia but experience from Melbourne and Sydney plants indicates they are economic “white elephants”, whatever their technological and political benefits.

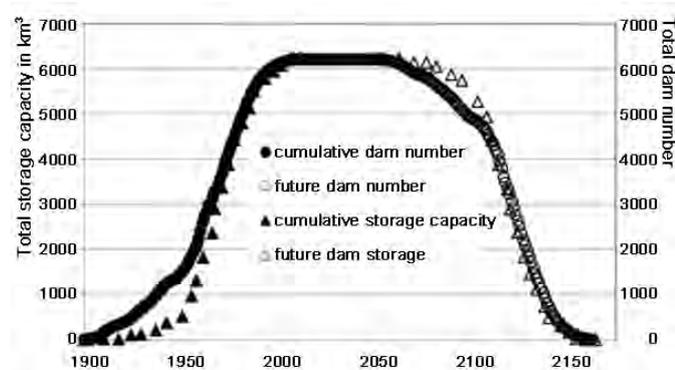


Figure 2. Number of operating large dams in the world and their total water storage in km^3 based on the assumption of 150-year dam life spans. Filled symbols are historical and open symbols are future estimates assuming average sedimentation occurs.

4) Demand management. In the late 20th century, Australia started the swing from supply management - governments delivering the water wanted by society and industry - to demand management - customers reducing water wastage and unnecessary consumption. This move has reduced the immediate demand for more storages to be built but increasing demand by more population will eventually reignite the need for greater water supply and storage.

5) “Operation Plowshare” was an American program to use nuclear explosions for peaceful purposes, a section of the Australian water industry toyed with the idea of blasting several subterranean, sealed-by-molten-rock vessels into which flood flows in Queensland Channel Country would be directed by surface windrows into the vessels via large diameter bores. A central vessel would then be heated by a later nuclear explosion to generate steam for a surface power plant to supply electricity to raise water from surrounding vessels by pumps. It was understood that the nuclear devices would have been supplied free of cost.

6) Adelaide and Perth have considered towing Antarctic icebergs north to have them melt into impervious liners, perhaps aided with a covering of carbon black or similar^[7].

2 Problems with Dams

The problem of all dams is that the dam sites with suitable location with near demand centres have been developed in the post-WW2 40-year era of dam building. The remaining dam sites are generally not suitable for development. Consequently, there is no much new dams after 2000 as shown in Figure 1^[8].

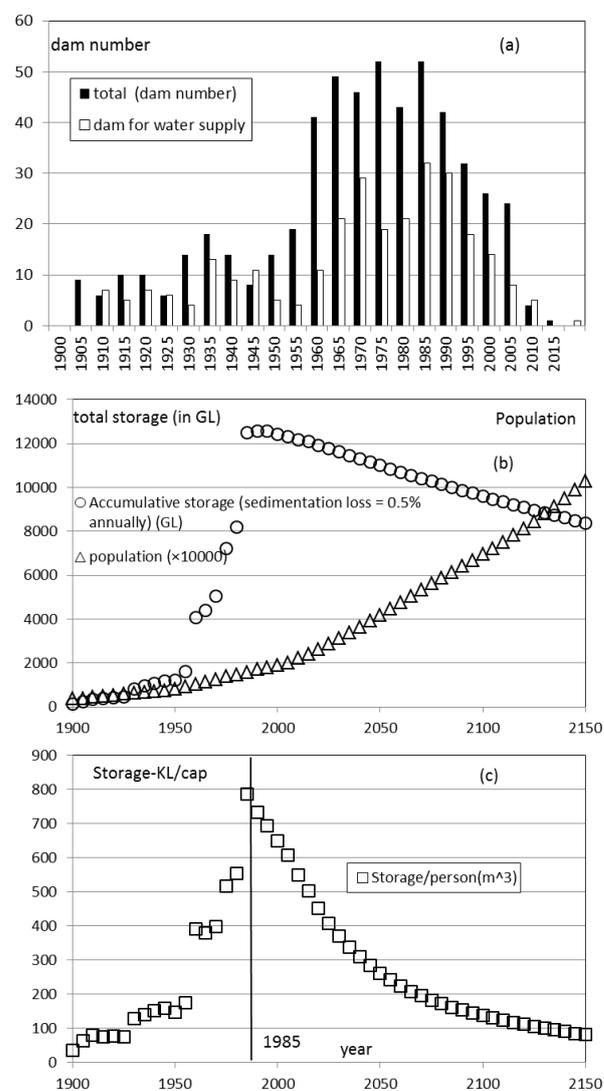


Figure 3. The effect of not increasing Australia’s water storage. (a) Number of dams constructed and number for water supplies. (b) Population growth and total storage capacity. (c) Storage capacity per capita from 1900-2150.

Another problem with dams is sedimentation^[9]. The total sediment yield in the world is estimated to be 13.5×10^9 t/a or $150 \text{ t/km}^2/\text{year}$ and about 25% of this is transported into the seas and oceans and 75% is trapped in the lakes, reservoirs and river systems^[10]. UN experts warn that a fifth of the current storage capacity of reservoirs worldwide will be gradually lost over the coming decades as a result of sedimentation^[11]. Further, global warming may increase the severity of storms

and rains which would accelerate the natural erosion rates that feed reservoirs. The life span of world reservoirs depends on the sedimentation rate which is reducing their storage capacities by more than 1-1.5% per year^[12]. A concrete dam's design life span is about 100-200 years, so assuming an average life span of to be 150 years, the future operating dam numbers and total storage can be calculated. The results are shown in Figure 2, which clearly indicates that by 2150, all reservoirs will have been abandoned as effective water storages. Figure 2 clearly shows that our water crisis is being intensified by sedimentation quite separately from demand.

3 How Those Problems Affect Australia

Australia's dam construction is shown in Figure 3a which is based on the data available in The Australian National Committee on Large Dams' (ANCOLD) website. It has the same post-WW2 boom as in Figure 1, the six-fold peak rate of building over the pre-WW2 average but a 10-year later peak and return to pre-WW2 numbers. More than a half of the dams were designed for purposes other than water supply like irrigation, flood control and hydro-power. A problem for siting Australian dams is that we don't have the high mountains and deep valleys common on other continents to provide narrow dam sites with extensive upstream storage topography. Our flat land not only deprives us water storage in winter snowpacks but makes our reservoirs comparatively shallow with a large water surface, so they are prone to evaporation losses and greater sediment deposition. This is why the benefit of dam construction in Australia often cannot cover its cost. For example, the Ord River Scheme in Western Australia cost A\$ 613 million between 1958 and 1991, but the benefits were just A\$ 102 million in the same period^[8]. The benefit-cost ratio of 0.17 is far below the 1.3 or so needed for governments to recover their outlays through taxes and charges.

Australia has the highest population growth among the major developed countries^[13] as shown in Figure 3b. White estimates the mean annual sedimentation rate for Australia is about 0.27% of reservoir's storage, about 1/4 of the world's average^[12]. In other words, dam operators in 185 years' time can expect to be working with perhaps only 50% of their original storage. This means that, if no new dams are constructed, the storage volume per capita will be decreased significantly as shown in Figure 3c.

Australia's 500 large dams yield the highest per capita surface water storage in the world at 800 kL/capital in 1985. Such storage is needed because Australian rivers are characterised by low discharges and the highest variability of all the continents^[3,4]. However, this storage has been effectively waning since 1985 due to increasing demand from a growing population and to sedimentation. Figure 3c reveals that we have already lost 1/3 of our storage capacity, and by 2050, our storage capacity per capita is projected to shrink to WW2 levels. Obviously, we need more storage for an increased population to survive during droughts like the Millennium Drought of 2000-

2009.

For the above two reasons, it is clear that dam-building era from the 1950s to the 1980s is over, never to return. But perhaps dam-building only needs to change the way it does business.

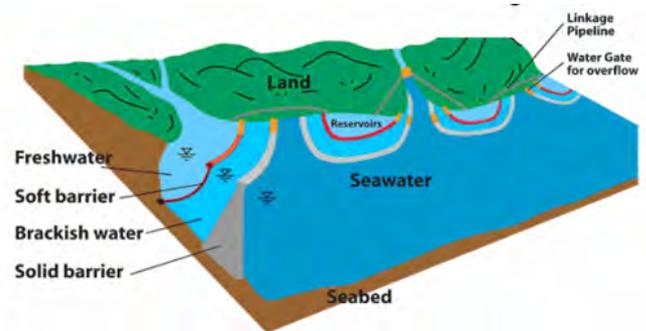


Figure 4. Scenarios for second generation coastal reservoirs^[20], the intake system is shown as an orange square, which can divert good quality river water to the reservoir for storage in flood seasons.

4 Coastal Reservoirs

Coastal reservoirs are the result of siting dams inside seawater. They are similar to inland dams in that they are constructed to high standards of strength and impermeability and for the shortest practical length to minimise costs. They have an advantage over inland dams because they have the potential to collect every single drop of runoff from their catchment. That advantage is also a disadvantage because they have the potential to collect every micro-pollutant from their catchment. As a result, some coastal reservoirs in Table 1 have become wastewater reservoirs, such as the Sihwa Lake in South Korea^[14]. Because the volume of wastewater maintains the same growth rate as population (as does the usage of fertilizer and pesticides), it can be predicted that the raw water quality in these coastal reservoirs will never meet drinking water standards unless new technology solves the problem of non-point source pollution.

These first generation barrages are normal to the flow direction, which cuts off ships' navigation and fish migration, and causes significant environmental impacts. An in-stream coastal reservoir has a fixed storage capacity, which may not be able to match the designed water demands; the accumulative contamination in the reservoir may deteriorate its water quality. Another problem of the first generation coastal reservoir is caused by a high evaporation loss, the example can be seen from Australia's first coastal reservoir formed by five barrages at Lake Alexandrina outlets, it was intended to change its brackish water into a freshwater lake using Murray River water. The high evaporation over very large surface areas, coupled with low river flow in the Millennium Drought, led to its salinity becoming an undrinkable 6,000 mg/L in mid-2010.

The first coastal reservoir in the world was built in the Netherlands in 1932 and it took five years for its originally saline water to be replaced with freshwater. In 1968, Plover

Table 1. World's existing coastal reservoirs.

Name	Catchment (km ²)	Dam length (km)	Capacity (GL)	Year completed	Construction cost (US\$ B)	Country – River
Zuider Zee	170,000	33.00	5,600	1932	N.A.	Netherlands
Lakes Alexandrina & Albert	1.1 × 10 ⁶	7.60	1,600	1940	N.A.	Australia – Murray
Plover Cove	46	2.00	230	1968	0.07	Hong Kong
Baogang/Shanghai	1.8 × 10 ⁶	3.70	12	1985	N.A.	China – Yangtze
West Sea Barrage	20,000	7.80	2,700	1986	1.80	N. Korea – Taedong
Chen Hang/Shanghai	1.8 × 10 ⁶	4.70	8	1992	N.A.	China – Yangtze
Sihwa	476	12.40	323	1994	0.30	South Korea
Yu Huan	170	1.00	64	1998	0.10	China – Zhejiang
Marina Barrage	110	0.35		2008	0.20	Singapore
Qingcaosha/Shanghai	1.8 × 10 ⁶	43.00	550	2011	2.80	China – Yangtze
Saemanguem	330	33.00	530	2011	2.10	South Korea

note: N.A. = not available

Cove in Hong Kong became the first coastal reservoir in the world for drinking water purposes. Most reservoirs in Singapore are coastal reservoirs: Pandan, Kranji and Marina Bay. In China, Shanghai constructed the Baogang coastal reservoir in 1985 and Chen Hang coastal reservoir in 1992. Currently, its water supply mainly comes from the 527 GL Qingchaosha coastal reservoir, which is by far the largest coastal reservoir in the world for drinking water purposes. Its construction cost in 2011 was US\$ 2.8 billion to supply 2,600 GL/a for 24 million people.

In Table 1, except for Shanghai coastal reservoirs, all existing reservoir barrage alignments are normal to the river flow direction. This alignment is the same as inland dams and significantly changes the river flow regime, causing many environmental and ecological problems for navigation, passage of migratory fish etc. Sihwa coastal reservoir in South Korea, for instance, was abandoned for water supply because of accumulative non-point-source contamination^[15].

It is predicted that coastal reservoirs that totally cut off the river flow from the sea would not be approved by any government in the future. It would have been necessary to develop the second generation of coastal reservoirs which should avoid the mentioned disadvantages, thus its water development is technically feasible, economically viable, environmentally sustainable and socially acceptable.

5 Second Generation Coastal Reservoirs

These coastal reservoirs (Figure 4) aim to solve the problems with first generation coastal reservoirs by:

- 1) Potentially reducing construction costs.
- 2) Reducing operating costs especially in terms of maintaining quality standards.
- 3) Reducing the adverse impacts of coastal reservoirs on ecosystems to levels acceptable to the public and to govern-

ments.

4) Bypassing polluted water or opening rivers to navigation and fish passage without interruption, so quality of the stored water is enhanced to levels acceptable to the public and water authorities. The most important feature of the second generation coastal reservoir is its capability to select high quality water for storage.

5) Eliminating dislocation of people caused by land inundation, cessation of agricultural activities, disruption of transport corridors etc.

6) More flexibility in design, construction and operation of barrages for existing conditions as well as future changes in demand, quality standards, environmental expectations etc.

5.1 Solid Barrier

As the sea is the biggest reservoir on the planet, the coastal reservoir can be constructed in any place in the sea, even totally offshore if the coast must remain undisturbed. The primary barrier is located, at least in part, in a body of seawater (see Figure 4). It goes without saying that coastal reservoirs are designed to have the shortest practical barrage length for minimum construction cost, commensurate with providing the required storage volume, seafloor shape, geology etc.. The primary, solid barrier of a coastal reservoir must be of sufficient height to withstand tidal surges and wave action, but it needs not to be as sturdy as the walls of inland dams because the water pressure differential across the wall is usually less than 10 m whereas that across a conventional dam may be in excess of 100 m. It may be constructed as a concrete wall, stone breakwater, a row of caissons, earth/rock dike or a pile of huge sandbags. For example, a 170 km long dike was constructed in 2002 to protect the navigation channel in the Yangtze estuary using prefabricated caissons and sandbags/geosynthetic tubes^[16], where the water depth ranges from 5.0 to 8.5 m, wave height is 3.3 to 5.9 m^[17]. The total cost including dredging of 0.3 × 10⁹ m³ soil was US\$ 2.5 billion; that is, 15 million US\$/km. Huge sandbags are used in the construction of dike

Table 2. Difference between inland reservoirs and coastal reservoirs.

Aspect	Inland reservoirs	First generation coastal reservoirs	Second generation coastal reservoirs
Water quality	Good (from protected catchments)	Poor (collect and store all contaminants)	Good (only collect clean water, bypass 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° to flow direction	90° to flow direction	Small angle to flow direction
Dam site	Limited (narrow dam sites with)	Limited (only inside a river mouth)	Unlimited (inside or outside river mouth)
Dam design	Concrete, earth/rock to withstand high water pressure	Concrete, earth/rock to withstand low water pressure but with wave/ tidal surges	Concrete, earth/rock to withstand low water pressure but with wave/tidal surge, with/without soft dam
Dam length	Short	Short	Long
Environmental impacts	High	Medium (obstruction to floodwater, 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	None	None
Water extraction	By gravity	By pump	By pump
Water catchment	10~50%	100%	100%

in Qingcaosha coastal reservoir, Shanghai.

5.2 Soft Barrier

Seepage for an inland dam can be a big problem, but for a coastal reservoir this is insignificant because the water pressure differences are small, and most of the time the reservoir's water level is slightly higher than the sea level. The sea water intrusion can be further prevented by introducing a soft barrier as shown in Figure 4. The soft barrier is an impermeable curtain suspended from a boom on the water surface^[18]. It extends to the sea bed to separate fresh from brackish water contaminated by seawater from either wave action at the surface or any seepage of groundwater of seawater. The soft barrier can effectively prevent pollution of seawater from seepage in the seabed or overtopping by surging waves in extreme weather conditions. It should be highlighted that a soft barrier is not a must for the second generation of coastal reservoirs.

5.3 Bypass Gates & Water Quality Management

The most important feature of the second generation coastal reservoir is its capability to select good quality for storage and to discharge polluted runoff out of the reservoir without mixing. The existing coastal reservoirs like Singapore Marina Barrage generally receive polluted water (i.e., first flush), but discharge clean water to the sea (after sedimentation). By using the SPP (Separation, Prevention and Protection) strategy^[19], water quality could be improved by separating freshwater and seawater by a barrier, clean water from polluted river water using intake regulation, and only good quality water is allowed to enter the reservoir via the intake regulation as shown in Figure 4. The collected fresh water needs to be protected against external pollution from the river and the sea. Seawater intrusion

into the stored fresh water should be prevented. The SPP strategy is effective in collecting good quality water, because the intake gates in Figure 4 will be closed when poor quality water or first flush flows appear, so the polluted water flows to the sea via a bypass channel without entering the reservoir. A wetland pretreatment is also suggested to purify the river flow prior to its storage.

Generally, good quality water appears during flood seasons except its first flush that should not be allowed to enter the coastal reservoir, as the first flush transports majority of contaminants like total nitrogen (TN) and total phosphorus (TP) and other nutrients and heavy metals. These pollutants generally come from non-point sources over a land surface, particularly after a long spell of dry weather. Normally, it is not necessary to collect all runoff, as globally only additional 1~2% of runoff is enough for human's water demand. For very large river basins, it is suggested that multiple pre-treatment wetland is applied to reduce TN, TP and other nutrients to ensure the reservoir's water quality. The intake/tidal gates can be inflatable rubber dams as those used in Singapore Marina Barrage.

The second generation coastal reservoirs have the capacity to select water for storage and to bypass unwanted water based on its quality in a river. The first generation coastal reservoirs have no bypass channel to discharge polluted water, and poor quality water is stored in the reservoirs, consequently the water inside the reservoirs is deteriorated, like the Sihwa coastal reservoir in South Korea^[15]. Obviously if the bypass channels are used in the reservoir, the Sihwa lake can restore its water quality and function as a water source again.

Like inland dams, all coastal reservoirs will eventually lose its capacity due to sedimentation, but the difference is that another new coastal reservoir can be constructed in the sea near

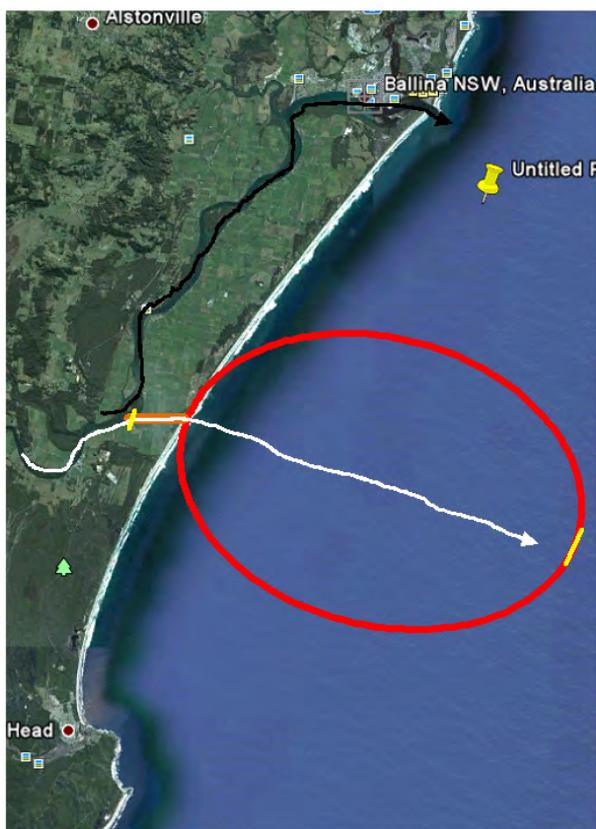


Figure 5. Potential coastal reservoir at Richmond River (100 km north to the Gold Coast).

the silted coastal reservoir, whose land can be developed for industrial and resident purposes, even for agricultural activities without the problem of soil salinization. Therefore, one may conclude that the sites of coastal reservoirs are renewable, but the sites of inland dams are not renewable.

5.4 Environmental Impacts

To discover possible environmental impacts of coastal reservoirs, the writer keyed in “environmental impacts of Zuider Zee” in Web of Science, one of the largest research databases: only one paper by Lammens *et al.* [21] appeared on 18 February 2017. Their research reveals that the impacts of Zuider Zee reservoir include “damming and fixing the water table prevented the development of emergent vegetation and caused steep water-land gradients”, other impacts are “high nutrient loads, which cause phytoplankton blooms, the disappearance of aquatic macrophytes and intensive fishery”. However, when “environmental impacts of Three Gorges Dam” - the largest inland dam in the world completed in 2007, was keyed into the same database, 769 journal papers appeared. When “environmental impacts of desalination” was keyed in the same database, 3,697 journal papers appeared. Eighty-five-year Zuider Zee’s existence is long enough for researchers to infer coastal reservoir’s environmental impacts. Certainly

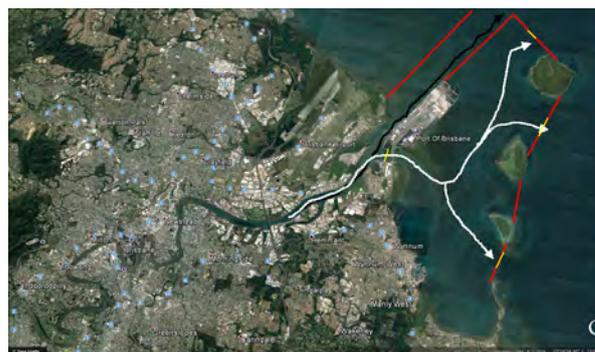


Figure 6. Potential coastal reservoir at Brisbane River mouth.

they attract far less concern than inland dams and desalination plants.

The differences between coastal reservoirs and traditional inland reservoirs are summarized in Table 2. The first generation coastal reservoirs’ shortcomings are also included for comparison, e.g., - poor water quality, high construction costs and inappropriate size. The second generation of coastal reservoir can be designed to overcome these problems so their application to Australia should be discussed.

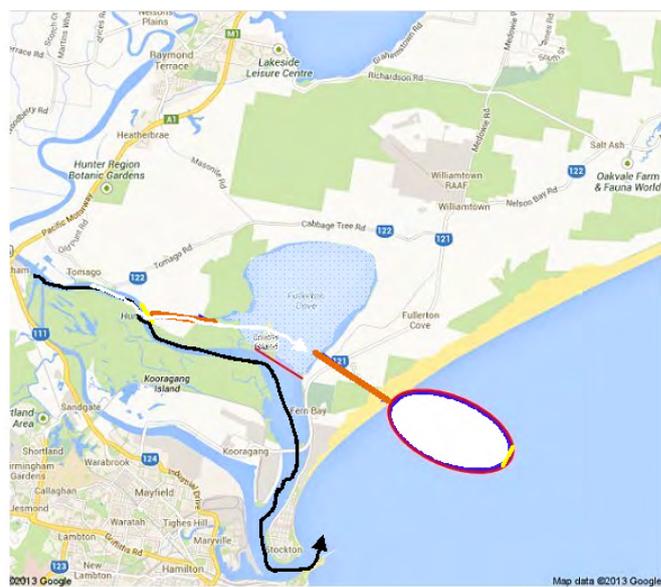


Figure 7. Potential coastal reservoir for Newcastle at Hunter River mouth.

5.5 Financial Comparison

The proposed A\$1.6 billion Traveston Crossing Dam in South-east Queensland would store 161 GL of water and could supply 70 GL/year, and 76 km² of land to be flooded permanently as the reservoir [22]. The design life span of concrete dam and its steel structures is about 100 years, during which span the total water supply is 7,000 GL, thus the capital cost is 0.23 A\$/kL (= 1.6 B A\$ / 7 B m³). Its running cost is much cheaper compared with desalination or wastewater reuse.

Sydney desalination plant invested A\$ 1.8 billion for its output of 90 GL/year. Its design life span is about 20 years, the total water supply in this period is 1,800 GL. Hence, its capital cost is 1.0 A\$/kL. This plant has been in standby mode since its birth in 2010. The taxpayers need to pay 535 m A\$/year for its state of hibernation, or 5.9 A\$/kL (= 535 m A\$ / 90 GL) of manpower cost. This water desalination plant needs the power of 4 kWh/kL [23], thus the energy cost is about A\$1.2/kL, so the total running cost is 7.1 A\$/kL.

The western Corridor Project invested A\$ 2.6 billion for water supply capacity of 130 GL/year, thus its capital cost is 1.0 A\$/kL for 20 year design life span. Its manpower cost is similar to the desalination plant, but its required energy is less, and 0.6 A\$/kL is assumed. This gives that wastewater recycling method's running cost is 5.9 A\$/kL + 0.6 A\$/kL = 6.5 A\$/kL.

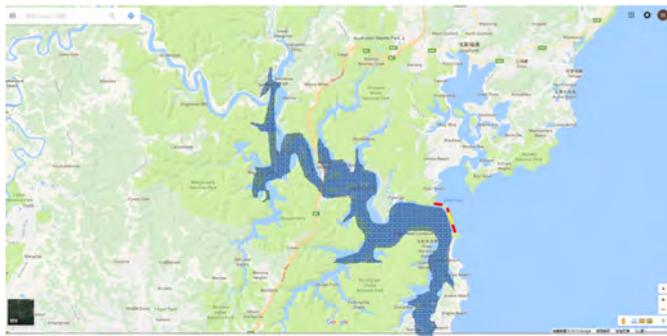


Figure 8. Potential coastal reservoir at the Hawkesbury River mouth by 2.9 km barrage.

The Qingcaosha coastal reservoir in Shanghai spent A\$ 3.7 billion for the construction cost including 45 km long dam, pumping system with the capacity of 200 m³/s or 2,600 GL/year, 114 km long pipeline system and a 7.2 km underground tunnel (about 6 m in diameter), two sluice gates with widths are 70 m and 20 m [24], the design life span of coastal reservoirs is also 100 years, thus its capital cost is 0.01 A\$/kL. Its running cost is very low as the government charges the residence's tap water at 0.4 A\$/kL only.

In this study, inland dams' running cost is assumed to be 0.4 A\$/kL as same as the coastal reservoir. Table 3 provides the comparison of costs among different methods, where the second row shows the projects. The total capital cost in row 6 means the cost at its beginning. Row 5 is its design capacity. Row 6, the capital cost per kL, is obtained by dividing the total capital cost in row 4 with the total water supply in its life span (i.e., the product of data in row 3 and 5). The running cost includes the manpower cost and energy cost. It can be seen that for one kL of water, the capital cost of desalination and wastewater recycling is about 100 times higher than the cost of coastal reservoir, the running cost is about 17 times higher.

6 Coastal Reservoirs for Australian Capital Cities?

In the light of Australia's small water consumption compared with surface runoff, Yang [25-27] claims that our future water crisis will not be caused by water shortage, rather by storage shortage. As dams on rivers are becoming increasingly unattractive for economic, environmental, and social reasons, it may now be time to consider building dams at sea, creating coastal reservoirs to harvest floodwaters otherwise lost to the oceans.

To solve Australian coming urban water crisis, coastal reservoirs for the capital cities are proposed in Figure 5-14. Conceptual designs are indicated as follows: red lines represent solid dams or shoreline of fresh water reservoirs, artificial canals are represented by a thick orange line, intake/tidal gates are represented by short yellow lines. The flow path of high quality river water are represented by white lines with arrow heads, the flow path of poor quality water or by-passed water are represented by black lines with arrow heads.

In Australia, all capital cities except Hobart have faced water crisis, this can be seen from the emergence of desalination plants. Hence it is necessary to analyse whether the water crisis is caused by water shortage or storage shortage, and whether coastal reservoirs can quench Australian thirst.

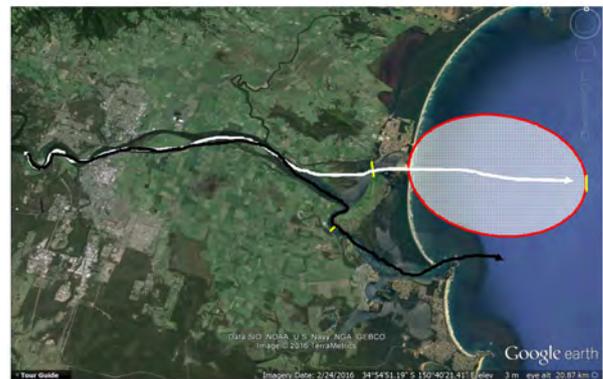


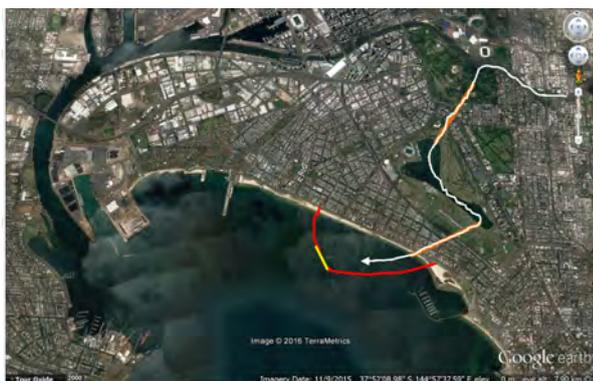
Figure 9. Potential coastal reservoir at the mouth of Shoalhaven River.

Southeast Queensland This region has a population of 1.9 million people spread over the 240 km from the Gold Coast to the Sunshine Coast, west to the Great Dividing Range and includes cities of Gold Coast, Brisbane and Sunshine Coast. To reliably supply this region's 300 GL/a [28] demand, coastal reservoirs are suggested for the mouths of the Richmond River and the Brisbane River, as shown in Figure 5 and 6. The annual runoff of Richmond River is 3,300 GL/a and that of the Brisbane River is about 2,500 GL/a [29]. The available water is 20 times more than the water demand. In Figure 6, the total length of dike is 16.3 km, the water surface area of coastal reservoir is 66 km².

NSW Its total population in 2015 was 7.7 million, with Sydney 4.9 million or 64%, and Newcastle Maitland 0.4 million or 5.6%. During the Millennium Drought (2000-2009),

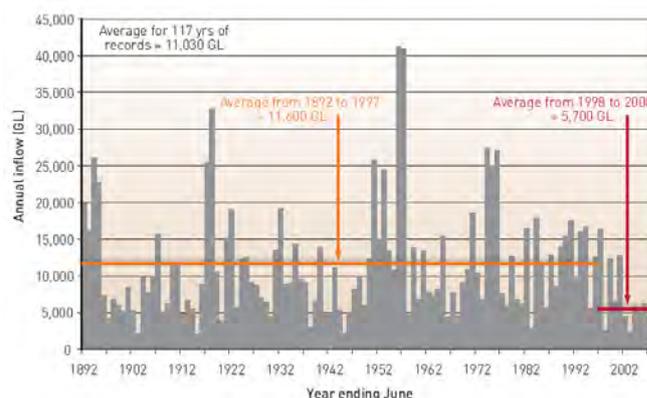
Table 3. Cost comparison among different methods of water supply for per kL of water.

	Inland dams	Desalination plant	Wastewater reuse	Coastal reservoir
Project discussed	Traveston Crossing Dam in QLD in 2007	Sydney desal. Plant in 2010	West Corridor Project in QLD in 2008	Qingcaosha in Shanghai in 2010
Design life span (year)	100.00	20.00	20.00	100.00
Total capital cost (A\$ billion)	1.60	1.83	2.60	3.70
Water supply (GL/year)	70.00	90.00	130.00	2,600.00
Capital cost (A\$/kL)	0.23	1.00	1.00	0.01
Running cost (A\$/kL)	0.40	7.10	6.50	0.40

**Figure 10.** A potential coastal reservoir to develop the wetland pre-treated water from Yarra River using pipelines or underground tunnel.

water in Warragamba Dam, the largest dam for Sydney's water supply, dropped to its lowest recorded level of 33.8% on 9-10 February 2007. Warragamba Dam's catchment is only 9,000 km², but the catchment areas of the Hunter River, Hawkesbury River and Shoalhaven River are 22,000 km², 21,600 km² and 7,000 km², respectively. If the coastal reservoirs proposed in Figures 7-9 are applied, the total catchment is as high as 44,300 km², which is 50 times larger than Warragamba Dam's catchment. It is certain that these regions' water supply can be secured. In Figure 7, the Fullerton Cove receives good quality water in flood seasons, and its shallow cove can be used as a wetland to pre-treat the river water that is stored in the coastal reservoir in the sea. Figure 8 shows that two barrages at the outlets of Hawkesbury River mouth can create a reservoir with 50 km². These barrages can be also used for road transport like freeway or high speed train rails. If average water depth is 10 m, then the storage is about 500 GL. Its annual flow rate is about 4,600 GL/a. As the catchment is covered by forest, thus the water quality should be good enough and the wastewater bypass channel may be unnecessary. Figure 9 shows the coastal reservoir of Shoalhaven River, whose flow is regulated by two hydraulic gates, these barrages can be also used for land transport. This reservoir can be a backup water source for Sydney, Wollongong, Nowra and Canberra in extreme dry years in future.

Melbourne Its annual rainfall is about 650 mm/a. Its largest dam, the Thomson River Dam is capable of holding around 60% of Melbourne's water capacity. The total storage capacity of the 10 reservoirs that supply Melbourne is 1,800 GL, and the water comes from 1,600 km² protected catchments in the Yarra Ranges. The annual flow from the catchment to these reservoirs is about 600 GL, but during 1997-2009, this dropped to 380 GL/a. On 1 July 2009, the storage was only 26% of fully capacity. Water supply in 2014-2015 was 400 GL. If coastal reservoirs are constructed at the river mouths of the Yarra River (catchment area = 4,100 km²), Bunyip River (4,100 km²), Maribyrnong River (1,500 km²) and Werribee River (2,000 km²), the total catchment is about 11,600 km², and total runoff from these four catchment is 2,000 GL/a. An example of a coastal reservoir for Melbourne is shown in Figure 10 where the intake at the Yarra River is open only when the river flow has high quality water, the lake in the city can be used as a wetland to pre-treat the river water. The treated water is stored in the coastal reservoir.

**Figure 11.** Murray-Darling River runoff into Lake Alexandrina from 1892 to 2008.

Adelaide Its local inland reservoirs provided 32 GL/a water during the Millennium Drought (2000-2009), and the catchments of these inland dams are small relative to the coastal reservoirs' catchment like Torrens River and Onkaparinga River. Hence, if coastal reservoirs were constructed at the river mouths, the local reservoirs could provide more water to Adelaide, say 100-200 GL/a. In dry years, Adelaide's water sup-

ply depends heavily on water transfer from the Murray River, up to 90%. Lake Alexandrina is the first coastal reservoir in Australia as its barrages were constructed in the 1930s to develop its water resources. However, the design purpose is not successfully achieved as it was a saline water body in the Millennium Drought.

Similar to Las Vegas whose water supply comes from Hoover Dam by developing water from its nearby river - Colorado River, Adelaide’s desalination plants may be unnecessary if a dam like Hoover Dam existed to develop water from its nearby large river: Murray-Darling River. Figure 11 clearly shows that Adelaide is not short of water, but its storage, as its annual inflow during the Millennium Drought was 5,700 GL/a, but the annual water demand was about 150 GL/a in the same period. Detailed research^[18] shows that if a second generation coastal reservoir is applied inside the Alexandrina Lake, this Australian “Hoover Dam” can supply sufficient high quality water to the Adelaide and South Australia. Their results also show that the coastal reservoir would improve the lake’s ecosystem, as the research shows if there was a coastal reservoir in Figure 12 in the Millennium Drought, the lake’s water level would be higher and its hydraulic residence time would be shorter. This is understandable because the reservoir reduces the stagnant water volume and stores good quality water in flood seasons. The research also shows that it is safe for Adelaide to divert 500 GL/a in dry years like 2007-2009 from the coastal reservoir whose size is about 580 GL located inside the Lake Alexandrina. In flood seasons, the intake gate is open to store high quality water. After that, the intake gate is closed, and river flow by-passes the reservoir entering the lake and the poor quality water is used to improve ecosystem. This design does not use any shoreline of the lake, thus it has little impacts on human society.

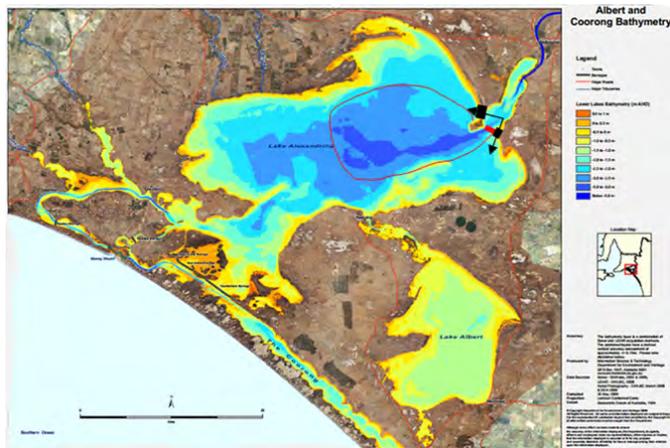


Figure 12. A coastal reservoir proposal in Lake Alexandrina to develop freshwater from the Murray River for Adelaide’s water supply.

Perth Total population in West Australia in 2015 was 2.6 million, 82.7% lived in four coastal cities, i.e., Perth (2.0 million), Bunbury (0.075 million), Busselton (0.036 million), Geraldton (0.040 million). In 2005, Perth had a population of around 1.5 million people, and the city consumed 240 GL/a

of water. It is estimated that the population in Perth in 2026 and 2056 will be 2.27 million and 3.36 million, the required water supply will be 350 GL/a and 520 GL/a, respectively^[13]. Runoff from Swan River (570 GL/a, Murray River (720 GL/a, and 42 km from Perth) can be developed using coastal reservoirs for Perth’s water supply. An example is shown in Figure 13, in which the bypass channel width is about 100 m on average, the estimated surface area of reservoir is about 19 km², and the estimated storage capacity is about 100 GL. Alternatively a barrage can be constructed near Point Walter Reserve and Chidley Reserve. As the polluted water is stored in the reservoir, a water treatment plant with RO technology may be needed to purify the reservoir water to drinking standard, similar to Singapore Marina Barrage.

Darwin The runoff from Adelaide River (1,700 GL/a) in Northern Territory can be developed for Darwin. The 180 km long river is 50 km away from Darwin CBD. Its catchment is about 7,640 km² and its tributaries include Margweret River, Manton River and Marrakai Creek. About 50% of the area was pastoral leasehold land, and 20% of it was Aboriginal land. The topography varies from low escarpment country in the upper reaches of Adelaide River to low lying flat floodplain areas near the coast. Figure 14 shows a conceptual design of coastal reservoir for Darwin’s water supply.

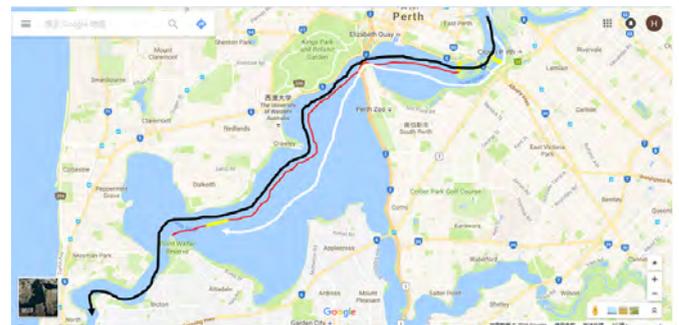


Figure 13. A coastal reservoir proposal at Swan River mouth for Perth’s water supply.

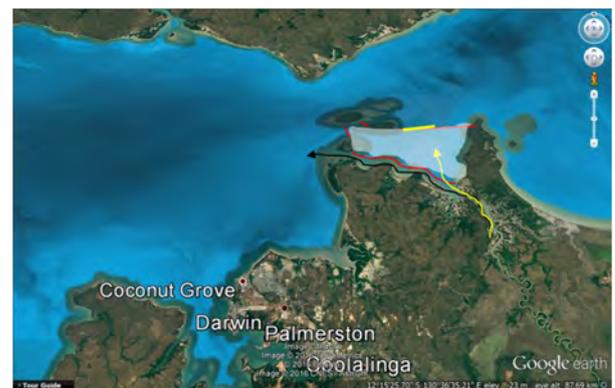


Figure 14. Proposed coastal reservoir at the mouth of Adelaide River (45 km to Darwin).

7 Inter-basin Water Diversion for Inland Regions

Coastal reservoirs can supply sufficient water to coastal cities, and also can provide sufficient water to inland Australia to meet its vast water demand for irrigation and mining industry. This is achievable as the existing large dams for water supply could be used for this purpose, for example, if the capital cities' water supply comes from the coastal reservoirs, then the water in large dams like Warragamba Dam, Wivenhoe Dam and Thomson Dam can be diverted to inland regions across the Great Dividing Range, thus the Murray-Darling River Basin's water could be increased. As mentioned, Australian flat land is bad for inland dams' development, but good for water diversion. Water from some coastal reservoirs can be also diverted into the inland regions as shown in Figure 15, where the proposed coastal reservoirs for water diversion are those blue ovals. The existing inland dams are red solid dots. The existing pipelines in SA and WA are represented by red lines. The proposed water diversion pipeline from Kimberley to Perth is represented by a blue line, and the proposed pipelines are represented by red lines with arrows.

To quantify the feasibility of these water diversion proposals, this study uses the energy required for water diversion to judge whether these water diversion routes are feasible and economic. Examining the pumping energy over long distance pipeline, this study proposed the following empirical equation to express the needed hydraulic head as the follows:

$$H(m) = 0.625X(km) + \Delta h(m) \quad (1)$$

where H is the hydraulic head in m, and X is the length of pipeline in km. Δh = elevation difference between the ending point and its source of route in m. Eq. 1 includes the energy loss by friction and the change of potential energy. In Table 4, the values of X (column 3) and elevations (column 6 and 7) are obtained from the google earth.

A feasible project can be seen from the existing water diversion pipelines in South Australia, the detail information is shown in Row 2 of Table 4. The Morgan-Whyalla pipeline is about 360 km long, Mount Lofty Ranges is about 460 m over sea level, and $\Delta h = 60 \text{ m} - 17 \text{ m} = 43 \text{ m}$. Eq. 1 shows that $H = 267 \text{ m}$, and the cost is about $0.24 \text{ A\$/m}^3$ [30]. The distance of water transfer from Wivenhoe dam across the Great Dividing Range is only $X = 70 \text{ km}$ lifting 384 m height, Eq. 1 gives $H = 428 \text{ m}$. The calculated H using Eq. 1 is shown in the last column of Table 4.

Based on the H value, this study broadly divides the water division projects into four groups:

$H < 300 \text{ m}$;	Class I;
$301 \text{ m} \leq H < 600 \text{ m}$;	Class II;
$601 \text{ m} \leq H < 1200 \text{ m}$	Class III;
$H \geq 1200 \text{ m}$	Infeasible

Class I means that a project is simple and easy. A more difficult project is defined as Class II. A very difficult and costly project is defined as Class III. If $H > 1,200 \text{ m}$, the project is

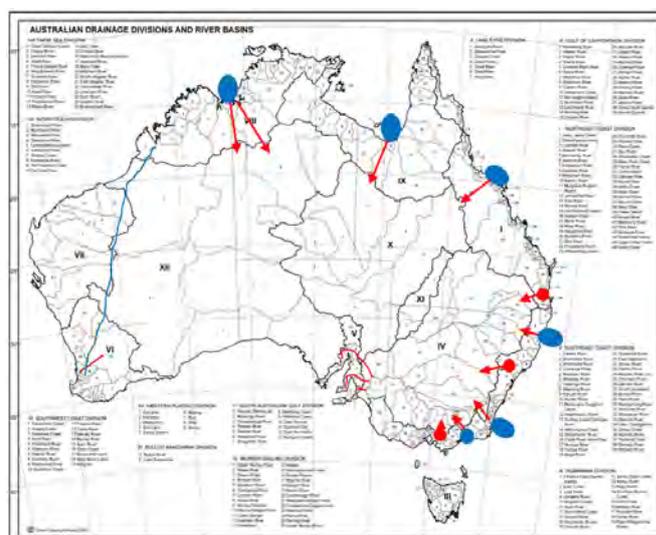


Figure 15. Proposed interbasin water diversion schemes from existing dams (red arrow with red circles), and coastal reservoirs (red arrow with blue ovals).

infeasible. From this criteria, the Morgan-Whyalla pipeline in South Australia is Class I as its $H < 300 \text{ m}$. The project of Mannum-Adelaide pipeline is Class II as its H is higher than 300 m , but less than 600 m . The Perth-Kalgoorlie pipeline is Class III ($601 \text{ m} < H \leq 1,200 \text{ m}$). But the pipeline from Kimberley to Perth is infeasible as its H value is greater than $1,200 \text{ m}$.

Based on the value of calculated H , feasibility of a proposed route of water diversion can be justified. Table 4 shows that water diversion from the coastal reservoir at the Carpentaria to Georgia River has $X = 250 \text{ km}$ and $\Delta h = 350 \text{ m}$, and Eq. 1 gives $H = 506 \text{ m}$, less than 600 m , so the project is feasible with Class II. But Table 4 shows that it is infeasible to divert water from the coastal reservoirs at the river mouths of Be-ga where the distance X to the Great Division Range is only 50 km . Table 4 shows that the diversion routes are feasible but difficult (Class III) from Wellington Lake and Warragamba dam to the Murray-Darling river system. Most of rest diversion routes shown in Figure 15 are also feasible. However, more detail investigation needs to be conducted for the feasibility and environmental impacts of these conceptual proposals.

8 Conclusions

It is not that Australia is running out of water, it is that water is running out of Australia. This paper seeks to start the conversation into how coastal reservoirs may retain water for human use at reasonable cost. That conversation needs to start now because no any new dams have been constructed since the 1990s for Australia's capital cities. Substitutes for storage - desalination plants and wastewater reuse - have emerged in Australia but there are continuing debates as to these projects' economics and sustainability.

If an additional 1-2% of runoff is made available by mean-

Table 4. Basic information for proposed inter-basin water diversion schemes in Figure 15.

Water source	Annual flow (GL/year)	Distance to another river basin, X (km)	Highest elevation of diversion route	Elevation at source in m	Water destination/ elevation in m	Water lifting height H (m)
Morgan of Murray River	75	359	460	17	Whyalla/60	267 (Class I)
Mannum of Murray River	140	60	480	15	Millbrook dam, Adelaide/300	322 (Class II)
Mundaring Weir in Perth	8.4	530	450	130	Kalgoorlie/411.5	612 (Class III)
Kimberley in West Australia	200	1,900	670	30	Perth/300	1,457 (Infeasible)
Burdekin Dam in Burdekin River	7,200	180	400	158	Thomson River in Lake Eyre Division/400	354 (Class II)
Fairbairn Dam in Fitzroy River	3,000	110	590	200	Warrego Condamine-Culgod Rivers/590	458 (Class II)
Wivenhoe Dam in Brisbane River	300	70	484	100	Condamine-Culgoa river/484	428 (Class II)
Warragamba Dam in Hawkesbury River	600	50	800	141	Arthur River/800	690 (Class III)
Thomson Dam in Thomson River	400	25	1,000	435	Goulburn River/1,000	580 (Class II, tunnel)
Lake Argyle in Ord River	3,940	200	400	87	Mackay, Wiso/400	438 (Class II)
Coastal reservoir at Bega River	570	50	1,500	0	Murrumbidgee River /1,500	1,531 (Infeasible)
Coastal reservoir at Clarence River	4,920	80	1,000	0	Border River/1,000	1,050 (Class III)
Wellington Lake	3,600	100	1,000	0	Upper Murray River/1,000	1,062 (Class III)
Coastal Reservoir at Carpentaria	6,530 (Nicholson-Norman River)	250	350	0	Georgia River/350	506 (Class II)
Coastal Reservoir at Fitzroy, WA	6,000	180	186	0	Great Sandy desert/186	298 (Class I)

s of coastal reservoirs, Australia should have sufficient water for its long-term sustainable development. It goes without saying that the coastal storages in this paper would need to be designed and cost to much greater detail before being implemented but their viability seems inevitable.

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