A preliminary feasibility study for a backup water supply-coastal reservoir in Southeast Queensland, Australia

Shu-Qing Yang

ABSTRACT

Australia is the driest inhabited continent in the world, and Southeast Queensland has experienced extreme water scarcity. Intensive research has been conducted and many solutions have been proposed in order to secure its water supply, such as more inland reservoirs, wastewater recycle and reuse, and desalination plants, etc., but after the Millennium drought some of these measures are not readily accepted by the public and government, thus alternative water sources to secure its future demands are urgently needed. By analyzing the natural conditions it is found that coastal reservoirs could be useful for this region, and their feasibility is discussed and analyzed. The new solution is compared with previous proposals based on their sustainability, impacts on environment and ecosystem, construction and operation cost, and greenhouse gas emission. It is found that the strategy of coastal reservoirs meets the regional water demand well, and it is sustainable, environmentally friendly and cost-effective. Most importantly, the example shows that the proposed strategy may eliminate the need of desalination in other runoff-rich regions in the world.

Key words | coastal reservoir, desalination plants, stormwater harvesting, water crisis, water pollution

Shu-Qing Yang
School of Civil, Mining and Environmental
      Engineering,
University of Wollongong,
Wollongong, NSW 2522,
Australia
E-mail: *shuqing@uow.edu.au*

INTRODUCTION

Water is one of the most important resources, and clean water has been and continues to be one of the major challenges for human society. The world's water supplies are facing threats due to population growth and economic development, thus the access to clean water was selected as one of the great challenges for the 21st century by the National Academy of Engineering, USA. This is understandable, as in 2013 UN-Water declared that 1,800 million people will live in countries with absolute water scarcity by 2025 and two-thirds of the world's population could be under severe water stress conditions. To meet the crop demand projected for 2025, an additional 192 cubic miles of water per year could be required – a volume nearly equivalent to the annual flow of the Nile 10 times over (Gleick 2001). Therefore, water shortage is a major socio-economic problem facing society today and will soon become one of the major constraints for future economic development. Severe water shortages have particularly struck arid and semi-arid areas like Australia where it is often said that the story of Australia is the story of the search for and use of water.

Australia is the driest inhabited continent on Earth (Donohue *et al.* 2009). Its semi-arid area (annual rainfall is less than 600 mm) makes up about 80% of the mainland and the arid area (annual rainfall <300 mm) covers 60% of the total 7.7 million km^2 which is almost the same size as the USA (excluding Alaska). Its long-term average rainfall across the whole country is 457 mm, on average, 90% of its rainfall is directly evaporated back to the atmosphere due to the dry climate; only 10% becomes runoff into rivers or recharge into groundwater aquifers. The variability of spatial and temporal rainfall in Australia is high, it may vary from zero for several years to extreme hydrological events, e.g., 515 mm in 6 hours at Dapto, New South Wales in 1984 (Chanson 2001). Most rainfall events occur in a wet season associated with intense fall, and the rest of the year is very

dry. In dry periods the monthly averaged rainfall ranges from 0 to 100 mm only.

Since the early European settlement in Australia, water has been one of the main constraints for its development. For two centuries, Australia's economy has been highly centralized in coastal areas because of the water availability. Among 3,508,000 GL average annual precipitation, the mean annual runoff (MAR) is 385,924 GL. The country's water supply mainly comes from about 500 large dams whose storage capacity is about 93,656 GL or 25% of MAR. Today, more than 90% of Australian people are settled in the coastal areas. Total water use is nearly 80 billion m^3, with about 75% of this water being returned to the environment following in-stream uses such as hydroelectric power generation. The total water consumption is 20,870 GL (i.e., 5% of MAR), with more than 65% of water consumption being for agricultural use, 11% for household and 11% for industry. Similar to other countries, the overcrowded coastal areas have led to a continuing increase in the demand for potable water, thus the deficit between the constant supply capacity and increasing demand has become a major problem for Australia's development.

In recent years, Australia has experienced the Millennium drought and the onset of climate change, with dwindling water supplies resulting in water restrictions. This hardship has brought to the fore reality that the Australia population is growing and needs to develop more water resources. During the drought, former Prime Minister John Howard emphasized that Australians should not have to endure water restrictions on a long-term basis: 'Having a city on permanent water restrictions makes about as much sense as having a city on permanent power restrictions… We would not tolerate it with electricity and we should not tolerate it with water. Part of the solution is better pricing, but the real issue is better management and adequate investment in water infrastructure.' Since that time many solutions and new technologies to solve the 'water crisis' have been suggested and implemented, such as inland reservoir development, stormwater harvest, seawater desalination, and wastewater recycling, etc.

Traditionally, the method of surface water resources development has been to build large-scale dams in upstream gorges, but this method is no longer useful to provide large amounts of freshwater as the topography of Australia is relatively flat and new dam sites for large-scale reservoirs are rare after two centuries of development. CSIRO's (2008) global climate models indicate that by 2030 the average inland rainwater availability will have reduced by 9%, and the average period between high flows increase by 29%; however, the good aspect is that coastal areas will become wetter. Obviously, more inland reservoirs cannot significantly alleviate Australia's water stress. Besides, the overdevelopment of surface water by dams in the upstream generally has a negative impact on the ecosystem, especially the downstream environment; and there is now an extensive literature devoted to the general ecological impacts of dams on rivers (Collier *et al.* 1996).

Stormwater harvesting has been widely adopted in Australia, and rainwater tanks collecting rainwater from roofs are emerging countrywide. This strategy intercepts water from the roof which is going to recharge the ground, thus stormwater harvesting could lead to the degradation of the environment. The quality of harvested stormwater has been allocated for non-potable use, but it does indeed increase water availability (Stoeglehner *et al.* 2011).

As the strategies of water restrictions, inland reservoir development and stormwater harvesting cannot effectively quench Australian's thirst, the Australian government was forced to resort to seawater desalination. Now desalination appears in almost every large city, such as Sydney, Melbourne, Brisbane and Gold Coast, Perth, Adelaide, etc. A plant supplies an output of about 61 GL/year (Stamatov & Stamatov 2010) of desalinated water to the Gold Coast in Southeast Queensland (SEQ). Desalination is energy intensive and it uses significantly more energy than traditional storage and pipe network systems. This means that alternative water sources (if they exist) other than desalination can dramatically reduce greenhouse gas emissions. The accumulative brine discharged from desalination plants may have significantly negative effects on the marine environment, e.g., the abundance and distribution of flora and fauna species. Therefore, other methods such as wastewater reuse and recycling have been proposed and implemented.

The epitome of Australian water shortfall can be seen in SEQ, which covers about 22,000 km^2 extending 240 km from the Gold Coast north, and 140 km from the coastline

to the Great Divide Range in the west (see Figure 1). This region's average rainfall is around 1,200 mm/year. Rainfall patterns vary, from a dry period which receives only around 400 mm/year, to a wet season (January–May) that gets twice as much rain, about 800 mm/year. The population of SEQ is estimated to be approximately 2.77 million, about one-eighth of the country's total population. Two-thirds of the state's population live in the three largest population centers of Brisbane, Gold Coast, and Sunshine Coast. This region combines the most rapid population growth in Australia. The population increased by 27% between 1996 and 2006, and is almost 25% of Australia's total population growth during this period. The region is expected to experience rapid population growth in the coming decades, and the demand for water will increase with the growth of the population, thus intensive research has emerged to augment its water supply (Hurlimamm & Dolnicar 2010; Radcliffe 2010; Yuen et al. 2013; Horne

2013). The rush of new solutions implemented during the Millennium drought has proved to have limited effectiveness (Bertone & Stewart 2011).

The current Prime Minister, Tony Abbott, and his government, have not invested in desalination plants, but have the intention of investing $30 billion to construct dams after the Millennium drought. Therefore, it is interesting to discuss where these dams should be constructed to yield the highest benefits, and this may be a key question for the new government in approving new proposals. It is necessary to review existing strategy before a new suggestion is made.

REVIEW OF EXISTING SOLUTIONS IN SEQ

The rainfall in the recent drought from 2002 to 2009 was below average, which resulted in a decrease of runoff captured in dams from 411 GL to between 297 and 362 GL.
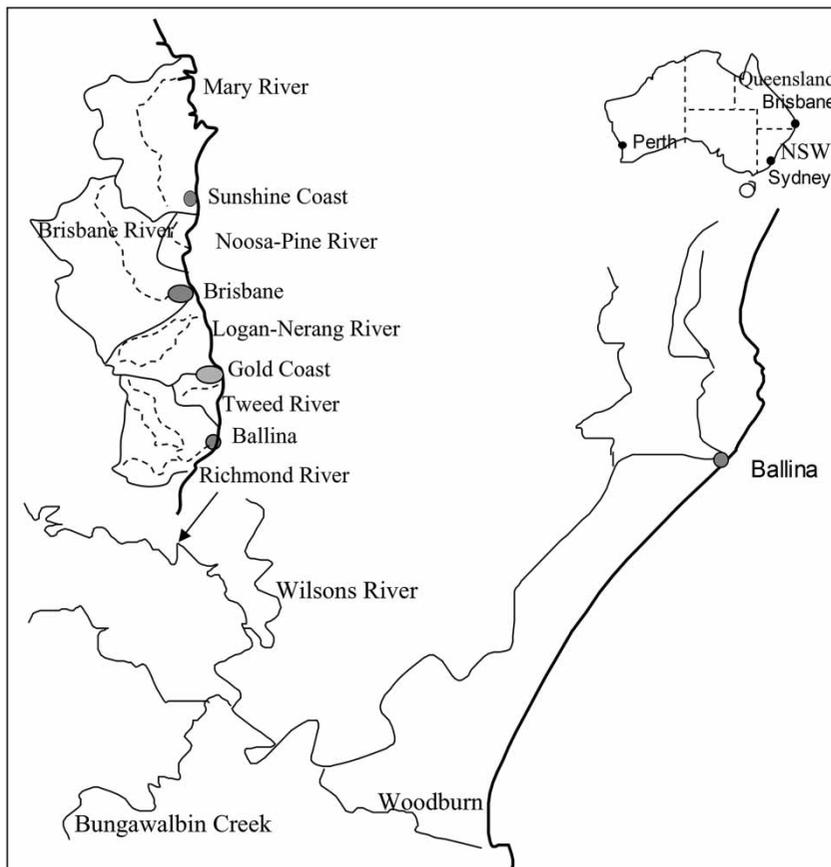

Figure 1 | River basins and Richmond River in SEQ, Australia. NSW stands for the state of New South Wales and Queensland for the state of Queensland.

This region needs an additional 217–283 GL of water from other sources with the current population and economic activity (Stoeglehner *et al.* 2011). In 2056, SEQ Water predicts water demand will have increased to 985 GL/year. The SEQ government had responded with a number of plans to supplement existing water suppliers in the region (see Table 1), such as construction of new dams, wastewater re-use, and desalination plants.

To increase the water supply, the Traveston Crossing Dam was proposed to be constructed on the Mary River, approximately 160 km north of Brisbane. It can only capture water from 22% of its catchment where the annual rainfall is around 1,600–2,000 mm/a. However, the proposed dam aroused opposition from many groups and organizations, from local farmers and fishermen to environmentalists and politicians. In recent years, almost all new dams proposed for the capital city's water supplies have been forced to be canceled or delayed due to public protests. Therefore, to upgrade the existing dams has become a feasible option

Table 1 │ Supply from existing and committed sources

Dams	River system	Supply (GL/a)
Baroon Pocket Dam	Mary	33.0
Somerset Dam and Wivenhoe Dam	Brisbane	263.3
Cressbrook, Perseverance and Cooby Dams	Brisbane	9.0
Enoggera Dam	Brisbane	1.1
Ewen Maddock Dam	Brisbane	2.5
Hinze and Little Nerang Dams	Logan-Nerang	58.2
Leslie Harrison Dam	Brisbane	5.3
Maroon Dam	Logan	29.5
Borumba Dam	Mary	70.0
North Pine Dam, Lake Kurwongbah and Caboolture Weir	Brisbane	43.3
Total dam supplies		525.7
Groundwater	Bribie Island, Brisbane, etc.	28.0
Desalination facility	Gold Coast	60.9
Western Corridor Recycled Water Project	From Brisbane's east to Wivenhoe Dam	84.7
Total		700

for the government. The Hinze dam is the primary source of water for the Gold Coast. This dam on the Logan-Nerang River was built in the 1970s, and in 2007 was upgraded to double its capacity by raising the dam by 15 m. The Queensland Water Commission or QWC (2008) admitted that there are limited opportunities to develop new dams in SEQ to substantially increase the water supply, due to a lack of appropriate sites for the construction of new dams. Groundwater resources in SEQ are almost fully developed, and in some cases they are already considered overdeveloped. Therefore, other water supply options need to be considered.

The government also implemented the purified recycled water (PRW) scheme in 2008, i.e., to treat wastewater up to drinking water standard to meet the supply gap. Producing water from wastewater treatment plants and pumping it to a dam in the upstream Brisbane River could augment the supply up to 85 GL/year for Brisbane. The government invested A\$2.5 billion for this Western Corridor Project, in which the purified wastewater was pumped from the wastewater treatment plants to dams in the Western mountains via 200 km pipelines (Rowe 2009). This is Australia's largest water recycling scheme and the third-largest advanced water treatment project in the world.

Another option is to construct desalination plants which have been seen as a main solution to future shortfalls. The government had investigated various potential sites for desalination plants and a desalination plant was constructed at Gold Coast in 2009 with the capacity of 46 GL/year. The treatment process is highly energy intensive, and its future operation costs will be heavily influenced by the energy cost that is anticipated to increase significantly with time (Hoang *et al.* 2009).

The Queensland Government has considered diverting water supplies from North Eastern NSW, but this was found to be not economically viable, and there were also numerous social, environmental, and interstate issues that were considered to be insurmountable (QWC 2008). Water could potentially be diverted from Northern Queensland. However, this would involve very high construction costs and should only be considered if no alternative water sources are available locally. The supply options considered by the QWC as the best potential sources are listed in Table 2.

Table 2 | Possible water solutions recommended by QWC (2008)

Type of source	Potential source	Volume of additional water supply (GL/year)
New inland dams and weirs	Borumba Dam Traveston Crossing Dam Raised operating levels in Wivenhoe Dam Small surface water upgrades (including additional water harvesting into dams, off stream storages, and raisings of Wappa Dam and Mt Crosby Weir)	120
PRW schemes	Augmentation of supply: From Hinze Dam From dams in Brisbane River At Sunshine Coast At Toowomba	100 (allowing for reduced sewer flow during drought)
New desalination plants	Located at the mouth of the Brisbane River and other places	

Following the prolonged drought which commenced in 2002, in 2011 this region experienced its second highest flood since the beginning of the 20th century (Van den Honert & McAneney 2011), and subsequently, the state government established SeqWater in 2013. A decision made by SeqWater was to shut down the Western Corridor Recycled Water Scheme. Some politicians commented that the scheme had been a $2.7 billion white elephant, and former State Premier, Peter Beattie, admitted that the scheme was a 'tragic error of judgment'.

However, the water shortage problem still exists. Researchers (Stoeglehner et al. 2011; Sahin et al. 2014) reaffirm that the minimum water deficit in 30 years from now will be about 30% of the current SEQ accessible storage capacity, the maximum 45.2%. At the end of 100 years, the annual water demand ranges from 1,860 to 3,650 GL per year (Stoeglehner et al. 2011), but this region's sustainable water yield is only 580 GL/year. The existing measures proposed or used by the government have been proved to have limited effectiveness (Stewart 2011; Siems et al. 2013). The public opposition to these projects was fuelled by campaigns from opposition groups such as Citizens Against Drinking Sewage and Australian Conservation Foundation (Ross et al. 2014). Now, the

government is even talking about selling these infrastructures (personal communication with former senior officer of Queensland Water Commission). Therefore, as future drought is inevitable, it is necessary to investigate the feasibility of other innovative solutions for this region to match future water demand.

Recently, Yang (2003, 2004, 2007, 2009) proposed the concept of a coastal reservoir, i.e., a freshwater reservoir in seawater near a river mouth to capture the sustainable river flow. This paper discusses the feasibility of this new strategy and compares it with the existing proposals in terms of sustainability, environmental impact, and cost-effectiveness. To simplify the discussion it is assumed that in future the water deficit in this region will be about 500 GL/year.

COASTAL RESERVOIR: DEFINITION AND PROBLEMS

Relative to water from seawater desalination processes, rainwater is a natural resource. The existing strategy of stormwater harvesting is to collect rainwater in house yards, streets, and parks, but its storage capacity is very small due to the structural constraints and the water quality means it can be used for non-potable purposes only (Cook et al. 2013). Different from inland rainwater strategy, a coastal reservoir harvests the runoff in the sea, and its water source from a river means the reservoir has the potential to catch every single drop of rainwater in a catchment. The so-called coastal reservoir can be classified into various categories, in terms of location, barrage, and water quality, etc. Existing freshwater lakes or lagoons on the shore can be regarded as special or natural coastal reservoirs. The main differences between coastal reservoirs and inland reservoirs are summarized in Table 3.

Currently, there exist many coastal reservoirs in the world, as listed in Table 4. The time required for the reservoir to convert from brackish to freshwater generally ranges from 0.5 (e.g., Qingcaosha) to 5 years (e.g., Zuider Zee), and the average period is about 2 years (e.g., Marina Barrage). It can be predicted that coastal reservoirs will play a more and more important role in freshwater resources development in the near future, because of the following:

1. Water demand in coastal regions grows rapidly relative to the inland regions coupled with very few new dam sites

**Table 3** | Differences between inland reservoirs and coastal reservoirs

Item	Inland reservoir	Coastal reservoir
Dam site	Valley	Coast
Water level	Above sea level	At sea level
Pressure	High pressure	Low pressure but with wave surge
Seepage	By head difference	By density difference
Pollutant	Land based	Land based and seawater
Emigrant cost	High	No
Water supply	By gravity	By pump

Table 4 | Basic information for coastal reservoirs (Yang 2009)

Name	Basin (km^2)	Dam length (m)	Capacity (GL)	Cost US$ billion	Year comp.
Zuider Zee, The Netherlands	170 k	32,000	5,600		1937
Qingchaosha reservoir, Shanghai	1.8 m	43,000	553	2.8	2011
Saemangeum, Korea	332	33,000	530	2.1	2006
Marina Bay, Singapore	113	350	42.5	0.15	2008
Plover Cove, Hong Kong	45.9	2,000	230	0.07	1968

with good hydrogeological and topographic conditions and this has been experienced in Australia. Also, after so many years' development, there are almost no new dam sites remaining with the ideal combination of topography and hydrogeology.

2. Soil erosion keeps reducing the storage capacity of the world's inland reservoirs by more than 1% annually. Investigation by James & Chanson (1999) shows that 'Australian reservoirs were subject to very high siltation rates that are comparable to overseas extreme siltation rates'. In the future, soil erosion and reservoir sedimentation rates would be accelerated due to the severity of storms and rains as a result of global warming (UNEP 2001). This means that all existing inland reservoirs may lose their capacity in about 100 years.

3. Most of the existing coastal reservoirs in the world are successful in operation, but some coastal reservoirs fall short of expectation for freshwater supply, one example being the coastal reservoir of Sihwa lake that is located in the mid-western region of the Korean Peninsula (Figure 2). The 56.5 km^2 freshwater lake was created from the sea in 1994 (Bae et al. 2010), and was originally designed to supply freshwater to the capital city, Seoul. Soon after the embankment was constructed, it was found that the reservoir was heavily polluted by incoming
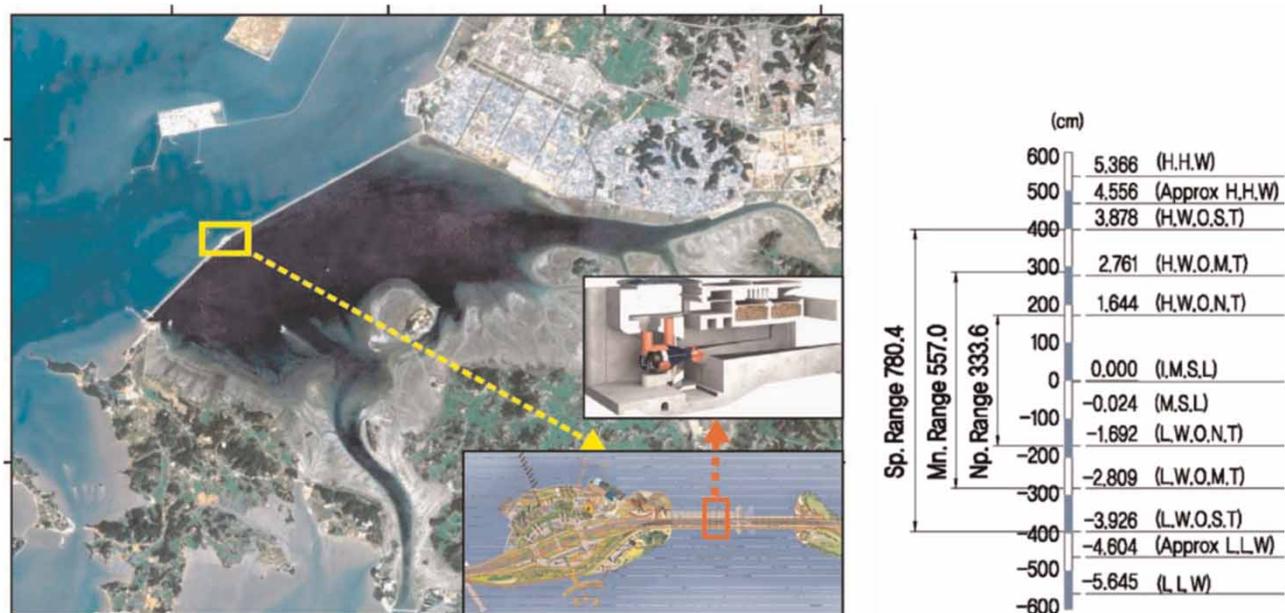
Figure 2 | Location of the Sihwa coastal reservoir and tidal power plant with tidal datum planes (after Bae et al. 2010).

wastewater, and so now the reservoir no longer functions as a freshwater supplier, but has been changed to a tidal power plant. This failure demonstrates that coastal reservoir design must be innovative, and special attention must be paid to water quality because the coastal reservoir – different from the inland reservoirs that are located in remote mountainous areas and only collect rainwater from virgin areas – is located at a river mouth and all pollutants from the catchment are collected and stored, and it could be a reservoir of wastewater.

4. Yang & Liu (2010) comprehensively investigated the water pollution of a large stagnant water body, and proposed a countermeasure for pollution control, i.e., the SPP strategy, which stands for separation of the wastewater from clean freshwater in time and space; prevention of external pollution; and protection of clean water resources stored.

The objective of this paper is to present a new and innovative solution for SEQ's water crisis – the coastal reservoir. Its design and feasibility will be discussed and the comparison of the new solution with the existing methods will be provided.

A COASTAL RESERVOIR IN SEQ: ITS WATER AVAILABILITY

The major river systems in SEQ are listed in Table 5. It indicates that every year the runoff generated is 10,602 GL which is lost to the sea, and the water deficit

of 500 GL/year is only 4.6% of the total runoff. It confirms Yang & Ferguson's (2010) claim that in Australia 'the problem is not a lack of water, rather a lack of ways to capture and store it', thus coastal reservoirs may have the potential to provide an alternative solution for this region.

To demonstrate the feasibility of the new strategy, we take the Richmond River as an example. Its mouth is located approximately 90 km south of Gold Coast. A 2,000 GL coastal reservoir is proposed near the mouth of Richmond River at Ballina, as shown in Figure 3. The proposed reservoir is 30 km long, 4.5 km wide and its average water depth is about 15 m. Current technology has no difficulty in constructing such a dam; one example is the coastal reservoir of Sihwa Lake where the water depth is about 30 m and the tidal height about 10 m.

The Richmond River is a coastal catchment bounded by the Richmond range to the west and the Tweed ranges to the north. It has three main tributaries, the Wilsons River, the Richmond River, and the Bungawalbin Creek. This basin has one of the highest rainfalls in this region. Most of the runoff is generated during the wet season (89–94%) and the greatest monthly rainfall average occurs in February–March (approximately 200 mm/m). Very low stream flow appears in September when the monthly average rainfall is only 40 mm. In a dry hydrological year, the rainfall could be as low as 880 mm or 65% of the average yearly rainfall such as 1994–1995. The largest and most destructive flood on record happened on 19/20 February 1954, when the recorded very heavy rain over the catchment was as high as 600 mm in 24 hours. This basin has a warm summer

Table 5 │ Water resources availability near Gold Coast and Brisbane

| River	Catchment area (km²)	Rainfall (mm/a)	Annual runoff (GL/a)	Inland dams
Mary River	9,595	1,141	2,042	Baroon Pocket, Borumba
Noosa-Pine River	2,270	1,351	600	Lake Samsonvale; Lake Kurwongbah
Brisbane River	13,643	1,100	2,749	Wivenhoe, Somerset
Logan-Nerang River	1,530	700–3,300	818	Hinze Dam/Little Nerang Dam
Tweed River	1,080	1,500–3,000	802	Clarrie Hall, Bray Park Weir
Brunswick River	492	1,600–1,850	246	None
Richmond River	6,940	1,343	3,345	Rocky Creek, Toonumbar
Total	35,550	1,149	10,602	Storage = 525 GL
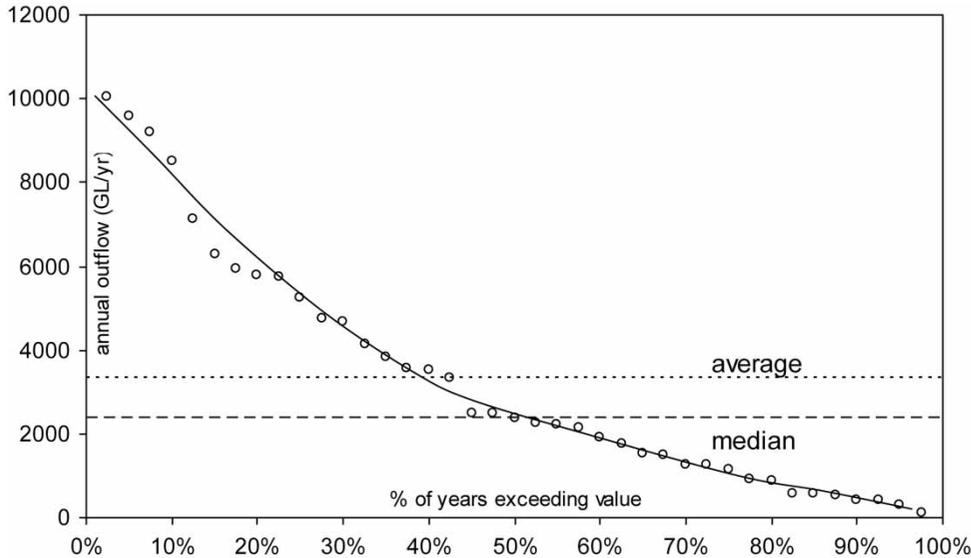
Figure 3 | Estimating reliability from the Richmond duration curve.

temperature of 29 °C and a mild winter temperature of 16 °C.

Analyzing the hydrological data from 1970 to 2008 provided by the state government, the median annual flow rate is $Q = 3,300$ GL/year; standard deviation of annual flow rate at the outlet is 2,800 GL/year; the coefficient of variation is $C_v = 0.84$, which is relatively high compared to the rest of the world ($C_v = 0.43$) (Finlayson & McMahon 1988); the skewness is $g = 0.96$; and the lag one autocorrelation coefficient is $r_1 \approx 0$. The annual outflow duration curve for the river is shown in Figure 3. It can be seen that if all the water from the river can be used, in natural conditions a yearly demand of 2,300 GL can be supplied only about 50% of the time. With pollution caused by seawater intrusion from the sea, this percentage will be much lower. Hence, a reservoir is needed to regulate the river system for its water resources development.

For a reservoir design, it is important to estimate the relationship between the water demand and its reliability. The Gould–Dincer method (McMahon *et al.* 2007) is used

$$\frac{S}{Q} = C_v^2 \left[\frac{\xi_f^2}{4(1-\alpha)} \right] \frac{1+r_1}{1-r_1} \tag{1}$$

where S is the storage capacity, Q is the mean annual flow, α is the annual target demand as a ratio of mean annual flow,

C_v is the coefficient of variation of the annual stream flows, r_1 is lag one autocorrelation coefficient of the annual discharge, ζ_f is the failure deviate which depends on the probability of failure and the statistical properties of the streamflows – the greater the reliability, the larger the ζ_f that can be determined by

$$\zeta_f = \frac{2}{g} \left[1 + \frac{g}{6} (z_f - \frac{g}{6}) \right]^3 - 1 \right] \tag{2}$$

$$z_f \approx -\sqrt{\frac{y^2[(4y+100)y+205]}{[(2y+56)y+192]y+131}} \tag{3}$$

and $y = -\ln[2(1-p)]$ and p is the reliability of water supply.

If a reservoir of storage capacity $S = 2,000$ GL is proposed, then $S/Q = 2,000/3,300 = 0.6$, the reliability of water supply depends on the water demand, and the calculated results are shown in Table 6. As this region's water deficit is about 500 GL, Table 6 shows that to meet this water demand, the coastal reservoir's supply reliability is 93%; this probability could be higher if coastal reservoirs are built at other river mouths. Hence, the reliability of water supply from coastal reservoirs is comparable with the strategy of desalination, whose failure could be caused by technical problems, power supply, and others. One of the examples is the Gold Coast desalination plant that was

Table 6 │ Water demand and supply reliability from a 2,000 GL coastal reservoir

Water demand in GL	α	ζ_f	z_f	y	$p\%$
100	0.03	1.82	1.61	2.25	95%
500	0.15	1.70	1.53	2.08	93%
1,000	0.3	1.54	1.43	1.88	92%
1,500	0.448	1.37	1.31	1.65	90%
2,000	0.6	1.17	1.16	1.42	88%

forced to shut down in 2008–2009 due to technical problems such as corroded pipes, leaking reverse osmosis, reverse osmosis valve bolt failure, damage to special coated bolts, etc.

## INNOVATIVE DESIGN OF COASTAL RESERVOIR AND ITS POLLUTION PREVENTION

A coastal reservoir at a river mouth can capture every single drop of rainwater, and also has the potential to collect all contaminants yielded from the catchment. If the design is not carefully considered, a coastal reservoir will gradually be transformed into a wastewater reservoir, like the Sihwa Lake, shown in Figure 2.

The dominant land uses in the catchment are grazing of cattle (53%) followed by timber cutting (42%) and cropping (Hossain et al. 2001). There are five towns in the basin, and the largest population centre is Ballina at the river mouth which has approximately 10 times the population (15,000) of the remaining towns combined. This basin has only one sewage treatment plant at Ballina which discharges treated effluent into the river mouth. Williams (1987) identified that the Richmond River has poor water quality compared with other systems in this region. Further study by Eyre & Morrisey (1994) indicates that Ballina plays a main role in the poor quality as it is transporting significant loads of nutrients into the river. The significance of nutrient concentrations in urban stormwater runoff is likely to become more important as water quality deteriorates with the rapid increase in population and associated urban expansion in the region (McKee & Eyre 2000).

Obviously, if the coastal reservoir encloses the river mouth as the Sihwa Lake does, then the accumulated pollutant from the river will eventually lead to the failure of clean water supply. To avoid this failure, Yang & Liu's (2010) SPP strategy is extended to the coastal reservoir design which can be started from the analysis of hydrograph and pollutant loading. The measured hydrograph is shown in Figure 4 in which the ordinate is the ratio of averaged monthly flow rate to the annual flow rate. It can be seen that the runoff is unstable and flood periods always appear from January to May.

McKee et al. (2000) analyzed nitrogen and phosphorus loads in the river mouth. They found that more than 74% of the nitrogen and 84% of the phosphorus load enters the estuary during one month when flooding occurs in the catchment (i.e., first flush). Obviously, the period with high nutrients is
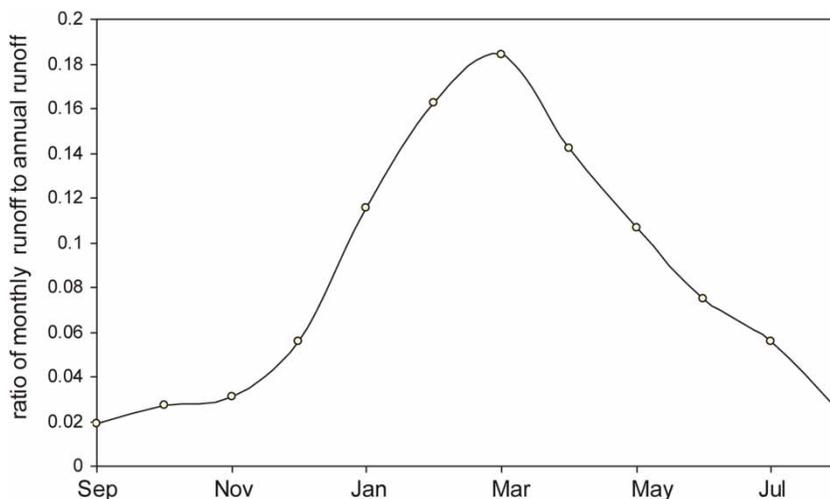
Figure 4 │ Hydrograph of Richmond River at outlet.

not suitable to enter the coastal reservoir, and the intake should be conducted when the water quality is good enough. Based on this consideration, we proposed a 2 km long by-pass canal at approximately 21 km upstream from the river mouth (see Figure 5), and a gate at the canal entrance used to regulate the incoming water; another gate may be needed to regulate the reservoir water to the sea. Only good quality water will be allowed to enter into the coastal reservoir. All poor quality water will drain to the ocean via the original river course, and this will minimize the impact of the coastal reservoir on the ecosystem and marine wildlife, also preventing pollution by land-based contaminants.

Hence, we use the sluice gates to separate the clean water and polluted water (temporal separation); the clean water is stored in the reservoir, but the polluted water is discharged into the sea (spatial separation). The clean water in

Figure 5 │ Proposed coastal reservoir for Richmond River, solid lines are the dam wall and canal that divert the stormwater to the coastal reservoir (solid lines are proposed works).

the reservoir is protected by the dam and the gates prevent the external pollution. In other words, the SPP strategy avoids the similar failure by land-base pollutants as occurred in the Sihwa reservoir.

However, the proposed coastal reservoir shown in Figure 5 can be easily polluted by the seawater whose intrusion into the upstream is driven by the tidal flow and density stratification. Therefore, it is necessary to investigate the salinity variation at the entrance of the by-pass canal. The Richmond River estuary can be classified as a well-mixed type (Davies 1973; Hayes 1975) with tidal amplitudes from about 0.5–1.5 m for neap tides and about 0.2–2 m for spring tides. During the dry season the estuary extends about 60 km from its entrance at Ballina and remains well mixed; however, during high flows the estuary flushes freshwater at its mouth (Hossain & Eyre 1996), thus it is necessary to estimate the seawater intrusion length at the entrance of the by-pass channel at the mean flow.

The Richmond River estuary is about 60 km long and 4–5 m deep (Hossain & Eyre 1996). The river width is about 280 m at the ocean end and an average of 500 m in the course from the outlet to the reservoir intake, and cross-sectional peak tidal velocities in the estuary average 0.71 m/s during flood tides and 1.22 m/s during ebb tides.

For a well-mixed river mouth, Ippen's (1966) model can be used to estimate the salinity at distance x from the river mouth and any time t, i.e., $s_{(x, t)}$

$$\frac{s_{(x,t)}}{s_o} = \exp\left\{ -\frac{u_f}{2D'_O B}[N_1 - (N_1 - x)\mathrm{e}^{\frac{a_o}{h}(1 - \cos \sigma t)} + B]^2 \right\}$$

(4)

where $N_1 = hu_o/(a_o\sigma)$, $h = $ water depth, $u_o = $ maximum velocity at the ocean end, $a_o = $ the tidal amplitude, $\sigma = $ wave angular frequency, $U_f = $ fresh water velocity, $B = $ distance at low tide to maximum salinity from a river mouth, $D'_o = $ diffusion coefficient at a river mouth. The maximum intrusion of salinity occurs at high tide for $\sigma t = \pi$. Specifying the intrusion length by a salinity of 1% of that in the ocean, the maximum intrusion length can be solved for $x = L_t$

$$L_t = \frac{hu_o}{a_o\sigma}(1 - \mathrm{e}^{-(2a_o/h)}) + \mathrm{e}^{-(2a_o/h)}B\left(3\sqrt{\frac{D'_O}{U_f B}} - 1 \right)$$

(5)

The minimum intrusion length L_l at low tide is

$$L_l = B\left(3\sqrt{\frac{D'_O}{U_f B}} - 1\right) \tag{6}$$

where $B \cong u_o/\sigma(1\text{-}\cos \sigma t_B)$, $t_B =$ time interval from low tide to the arrival of the maximum salinity at $x = 0$, $D'_o = U_f B/(2 \ln s_o/\bar{s}_{min})$, where $\bar{s}_{min} =$ the minimum average salinity at low tide at $x = 0$.

To consider the worst case with a conservative purpose, the maximum salinity s_o at $x = 0$ is assumed to be 30 kg/m^3, and $\bar{s}_{min} = 10$ kg/m^3 and $t_B = 3$ hours. The amplitude of tidal wave $a_o = 1.0$ m, angular frequency $\sigma = 2\pi/T = 1.45 \times 10^{-4}$ (s^{-1}), where $T =$ tidal wave period $= 12$ hours. The maximum velocity is $u_o = 1.22$ m/s, $U_f = Q_{annual}/bh = (3,300$ GL/year)/500/4.5 $= 0.47$ m/s. Hence, $B = 8.4$ km and $D'_o = 1,800$ (m^2/s) according to the above equations. The estimated

maximum intrusion length at high tide $L_t = 19.6$ km, and minimum intrusion length at low tide $L_l = 8.6$ km.

The above calculation indicates that when the river flow discharge is greater than 105 m^3/s or 3,300 GL/year, water at the intake shown in Figure 5 is freshwater, but if the flow rate is less than this value the salinity at this location could be higher and the water intake gate should be closed to protect the clean water in the coastal reservoir. It should be stressed that the above estimate is valid only for the conceptual design, and more detailed physical and numerical models should be conducted to confirm these preliminary results. It is also suggested that the 280 m width of the river mouth be reduced in order to reduce the driving force of seawater intrusion, and thus the water quality at the proposed intake would be better (see Figure 6); a more detailed study is needed to determine the optimal width of the mouth.

Figure 6 | To reduce seawater pollution in the river, the existing seawalls at Ballina at the mouth of the River Richmond are suggested to be extended into the sea (solid lines are proposed works).

COMPARISON WITH OTHER ALTERNATIVES

To solve the water shortage problem in SEQ, there exist many proposals and much research work has been done, thus it is worthwhile to compare these proposals in terms of sustainability, energy/gas emission, environmental impacts on the ecosystem, life span, and cost, etc. The existing proposals to secure 500 GL/year water deficit include inland dams, wastewater recycle and reuse, desalination plants. The proposal in this paper is the so-called coastal reservoir that aims at available runoff to the sea and noting that the rainfall (1,200 mm/a) in the region is the highest relative to other metropolitans, e.g., London (581 mm/a), Paris (566 mm/a), Moscow (522 mm/a), and Beijing (630 mm/a).

To simplify the calculation, this study assumes the unit cost (energy or gas emission) per GL water remains constant when it is expanded to 500 GL. For example, if one method costs $x/GL, then $500x is needed for the region's 500 GL water demand by expanding this method.

As mentioned, the strategy of inland reservoirs alone is impossible to secure the additional water supply of 500 GL/year in 2050 due to the limitations of dam sites and catchment size. The proposed Traveston Crossing dam will supply 70 GL/year with A$1.6 billion for the dam construction (Turner et al. 2007) and 76 km^2 of land to be flooded. Taken into consideration must be the inundation of prime agricultural land, potential loss of biodiversity, including the Australian lungfish which is listed as vulnerable under legislation (Harland 2009), the impact on the local community, and the fact that once this land is inundated it cannot be returned to its prior state. Hence, to supply 500 GL/year to this region, this strategy should cost A$11.4 billion for the dam's construction and inundation of 543 km^2 of land. The life span of the inland reservoir can be assumed as 100 years based on James & Chanson's (1999) erosion rate survey. The maintenance and operation cost of an inland reservoir is almost zero relative to the desalination plant and wastewater treatment plant. The main environmental impacts of inland reservoirs include loss of freshwater biodiversity, reduction of sediment supply to the estuary, beach erosion, etc. and the damaged ecosystem is not reversible.

The desalination plant in the Gold Coast has a supply capacity of 60.9 GL/year with the construction cost of A$1.13 billion, thus to supply 500 GL/year, this method should spend A$9.28 billion on its construction. This water desalination plant was initially planned to be powered entirely from power stations burning fossil fuels at a rate of 4 kWh/m^3 by Stamatov & Stamatov (2010) and 3.3 kWh/m^3 by Poussade et al. (2011). Therefore, to produce 500 GL of freshwater, the energy required will be 2.0×10^9 kWh. For a desalination plant with the capacity of 150 GL/year, Stamatov & Stamatov (2010) estimated that the extra annual carbon dioxide emission would amount to around 1 million tonnes per year, thus a 500 GL/year desalination plant will produce 3.33 million tons of carbon dioxide, or 13.3% of the Australian industrial carbon dioxide emission (the data for the year 2001 level are 25 million tonnes).

Western Corridor Recycled Water Project is the largest advanced water recycling project in the southern hemisphere. The estimated total cost is about A$2.7 billion with a capacity of 130 GL/year, thus for a 500 GL/year project, the construction cost will be A$10 billion. The treatment process requires electricity consumption of 1.14 kWh/m^3 (Poussade et al. 2011). Then, the required energy and associated greenhouse emissions are 0.57×10^9 kWh, and 1.67 million tons of carbon dioxide, respectively. Similar to the desalination process, the maintenance/operation cost is also very high. There is no significant impact of wastewater treatment on the ecosystem. Its life span can be assumed as the same as desalination plants, i.e., 20 years.

Different from the solutions of desalination and wastewater recycling, the solution of the coastal reservoir uses the natural stormwater and there is no need to separate the freshwater and salt or wastes, thus the energy cost associated with the treatment is zero, nor is there any carbon dioxide emission. When compared with the strategy of inland reservoirs, the method of coastal reservoirs has no cost to cover the inundation of land and relocation of people; normally this is very expensive and could be more than half of a dam's construction cost. The latter also has low negative impacts on the ecosystem as it only develops 15% of runoff; fish still have a smooth passage to go to upstream for breeding. After 100 years, the proposed coastal reservoir could be silted due to sedimentation, then another

coastal reservoir could be created seaward and the river water will be developed again, and thus its life span is infinite. If necessary, the barriers shown in Figure 5 can be removed and the ecosystem can be returned to its original form; thus this strategy is sustainable, because it can meet the current water needs without compromising the ability of future generations to meet their own needs.

As shown in Figures 5 and 6, the construction works include a 34.5 km dam together with a 2 km by-pass canal, a 90 km pipeline system, and seawalls to reduce the width of the river mouth, etc. To estimate the cost, the coastal reservoir in Shanghai, China is analyzed here. Its total construction cost was A$2.8 billion including a 45 km long dam, pumping system with the capacity of 200 m^3/s and 2,600 GL/year, 114 km long pipeline system with a 7.2 km underground tunnel (about 6 m in diameter), two sluice gates with widths of 70 and 20 m. Hence, it is certain that the cost of the coastal reservoir shown in Figure 5 is smaller than the one in Shanghai, and the construction cost should be less or equal to A$2.8 billion. Table 7 clearly indicates that by comparison with other alternatives, the strategy of coastal reservoirs is technically feasible, environmentally friendly, sustainable, and cost-effective.

Finally, it is necessary to estimate the pumping energy from the sources of water to the specified area. According to

the plan, the water from the desalination plant at Gold Coast (elevation $Z \approx 0$) needs to be pumped to Brisbane ($Z \approx 30$ m) for distribution via a 100 km pipe. The PRW was scheduled to pump from the Brisbane River mouth ($Z \approx 0$) to the west reservoir ($Z \approx 80$ m) via a 200 km pipeline in order to mix the treated water and the clean water in the reservoir, and thus public health risk could be minimized. Water from the coastal reservoir ($Z \approx 0$) needs to be pumped to Gold Coast (100 km) or Brisbane (200 km) for distribution. The energy equation can be written with the following form:

$$Z_1 + \frac{V_1^2}{2g} + h_{\text{pump}} = Z_2 + \frac{V_2^2}{2g} + h_{\text{loss}} \tag{7}$$

where Z = elevation, V = velocity, g = gravitational acceleration, h = energy head, the subscripts 1 and 2 represent the source and destination of pipeline. The mean velocity at the reservoirs is very small, i.e., $V_1 = V_2 = 0$. The energy loss can be expressed by the Darcy–Weisbach equation

$$h_{\text{loss}} = \left(f \frac{L}{D} + \sum K_i \right) \frac{V^2}{2g} \tag{8}$$

where h_{loss} = head loss, f = friction factor, L = pipe length, D = pipe diameter, V = flow velocity in the pipe ($= Q/A$, for

Table 7 │ Comparison of different proposals to secure 500 GL/year water supply to SEQ region in terms of sustainability, cost, and carbon emission

	Inland dams	Desalination	Recycled wastewater	Coastal reservoir
Treatment energy ($\times 10^9$ kWh)	0	1.65–2.0	0.57	0
Pumping energy for distribution ($\times 10^9$ kWh)		0.26 (to Brisbane)	0.33	0.15 (to Gold Coast); 0.26 (to Brisbane)
Greenhouse emission (carbon dioxide) in million ton	0	3.33	1.67	0
Construction cost (A$ in billion)	11.42	9.28	10	2.8
Maintenance/operation cost	Low	High	High	Low
Impacts on ecosystem	Loss of biodiversity, beach erosion, cool water from reservoir, etc.	Brine results in loss of marine biodiversity and saline fish may be either extinct, threatened, or endangered	Low	Low negative impacts on the ecosystem
Life span	100 years	20 years	20 years	Infinity
Sustainability	The damage on ecosystem cannot be remediated	The damage to the ecosystem is remediable	Damage on ecosystem	Sustainable

Q = discharge, A = cross section area), K = coefficient for minor energy loss that is negligible relative to the friction loss.

If we assume that four concrete pipelines (absolute roughness $\varepsilon = 3$ mm) with diameter of 2.0 m are used to pump the water, the Moody chart shows that the friction factor $f = 0.02$, the discharge Q is 500 GL/year or 15.8 m³/s, and velocity $V = 0.26$ m/s. The required power E can be estimated from

$$E = \rho g Q h_{\text{pump}} \tag{9}$$

where ρ is density of water (=1,000 kg/m³).

The calculated results show that the required pumping energy for the desalination plant and PRW are 0.30 kWh/m³ and 0.66 kWh/m³, respectively. Poussade *et al.* (2011) also estimated the electricity requirements for distributions of desalinated water and purified water, and they are 0.52 kWh/m³ and 0.60 kWh/m³, respectively. It can be seen that the result from Equation (9) is very close to Poussade *et al.*'s (2011) estimation for the Western Corridor Project, but they may overestimate the energy required for the desalination plant, which can be explained by the internal by-pass of seawater required for reaching the appropriate velocity in the discharge diffuser.

The calculated results using Equation (9) show that the required pumping energy is 0.3 kWh/m³ and 0.52 kWh/m³ from the coastal reservoir to Gold Coast and Brisbane, respectively. Obviously, the required pumping energy from the coastal reservoir to Brisbane is lower than the required energy for the water distributions from the desalination plant and PRW plant. Therefore, the government's conclusion may be not correct by claiming that water diversion from northeast NSW is 'not economically viable'. The total energy for seawater desalination and distribution is 3.82 kWh/m³ and PWR amounts to 1.73 kWh/m³ (Poussade *et al.* 2011).

CONCLUSIONS

Australia is the driest inhabited continent in the world, and SEQ has experienced the worst drought in 100 years. The government has responded with a series of measures, such as more inland reservoirs, wastewater recycle and reuse, and desalination plants. With the development of time, it has become difficult for some of these measures to be accepted by the public or government, thus it is necessary to discuss other options for this region to overcome its next drought. The strategy of coastal reservoirs is proposed and analyzed based on the natural and hydrological conditions of this region. This new strategy is highly recommended because of the following:

1. Previous researchers made an assumption that this region is short of water, thus countermeasures to produce more water from seawater or wastewater are needed. By analyzing the rainfall data (1,200 mm/year) and runoff data (10,000 GL/year), it is found that in this region, the shortage is not water, rather a lack of storage capacity. However, the government finds it very difficult to construct very large new dams due to public opposition.

2. To secure the gap between supply and demand, if 5% of the runoff to the sea in this region is developed, then the water demand will be met. To do so, the application of coastal reservoir has been suggested, i.e., to construct a freshwater reservoir in the seawater near a river mouth. The feasibility of coastal reservoirs is investigated and the Richmond River is taken as an example of such a demonstration.

3. The proposal of coastal reservoirs has been justified based on water quality, supply reliability, and technical feasibility. It is found that using the Richmond River mouth alone is sufficient for this region's water crisis, and its supply reliability is comparable with the desalination plants. If the reservoir is deliberately designed against inland and seawater pollution, its water quality is also comparable. Using modern technology, there is no difficulty in building such a reservoir.

4. Preliminary assessment of the proposed coastal reservoir has been conducted and comparison with other alternatives is provided. It is found that among all existing solutions, the coastal reservoir represents the best solution for the region. It uses natural resources and has low negative impacts on the environment and ecosystems. Different from desalination and wastewater reuse, the stormwater development does not waste any energy and has no greenhouse gas emissions. Its construction cost is only one-third of other alternatives. Thus the strategy of coastal reservoirs is sustainable, environmentally friendly and cost-effective.

5. This paper only discusses SEQ, with particular attention being paid to the Richmond River, but it is easy to extend the above conclusions to other places in Australia, even the rest of the world. It is suggested that all regions with abundant runoff to the sea consider the strategy of coastal reservoirs in their planning stage, and make a comparison with other alternatives such as new inland dams, desalination plants, and wastewater reuse before a decision is made in practice.

REFERENCES

Bae, Y. H., Kim, K. O. & Choi, B. H. 2010 Lake Sihwa tidal power plant project. *Ocean Eng.* **37** (1), 454–463.

Bertone, E. & Stewart, R. A. 2011 Framework for enhancing the supply-demand balance of a tri-supply urban water scheme in Australia. *Water* **3**, 976–987.

Chanson, H. 2001 Teaching hydraulic design in an Australian undergraduate civil engineering curriculum. *J. Hydr. Eng.* **127** (12), 1002–1008.

Collier, M., Webb, R. H. & Schmidt, J. C. 1996 Dams and Rivers: A Primer on the Downstream Effects of Dams. Circular 1126, US Geological Survey, p. 94.

Cook, S., Sharma, A. & Chong, M. 2013 Performance analysis of a communal residential rainwater system for potable supply: a case study in Brisbane, Australia. *Water Resour. Manage.* **27**, 4865–4876.

CSIRO 2008 Water availability in the Murrumbidgee. http://www.clw.csiro.au/publications/waterforahealthycountry/mdbsy/pdf/Murrumbidgee-Report.pdf.

Davies, J. L. 1973 Geographic Variation in Coastal Development. Hafner, New York, p. 204.

Donohue, R. J., McVicar, T. R. & Roderick, M. L. 2009 Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. *Global Change Biol.* **15** (4), 1025–1039.

Eyre, E. & Morrisey, B. 1994 Comparison of nutrient loading to a northern NSW estuary from urban runoff and sewage effluent. In *Water down under 94: Adelaide, 21–25 November 1994*, Institution of Engineers, Australia.

Finlayson, B. L. & McMahon, T. A. 1988 Australia versus the World: A comparative analysis of stream characteristics (R. F. Warner, ed.). In: *Fluvial Geomorphology of Australia*. Academic Press, Sydney, pp. 17–40.

Gleick, P. H. 2001 Making every drop count. *Scientific American* **284** (2), 41–45.

Harland, L. 2009 Call for project to be judged on sustainability. *Water Eng. Aus.* **3** (2), 26–27.

Hayes, M. O. 1975 Morphology of sand accumulation in estuaries. In: *Estuarine Research Vol. 2, Geology and Engineering* (L. E. Cronin, ed.). Academic Press, New York, pp. 3–22.

Hoang, M., Bolto, B., Haskard, C., Barron, O., Gray, S. & Leslie, G. 2009 *Desalination in Australia, Water for a Healthy Country Flagship Report Series*. CSIRO, Clayton, Victoria.

Horne, J. 2013 Economic approaches to water management in Australia. *Int. J. Water Resour. Dev.* **29** (4), 526–543.

Hossain, S. & Eyre, B. 1996 Catchment runoff and estuarine water exchange model for the Richmond River northern NSW, Australia. In: *23rd Hydrology and Water Resources Symposium*, Institution of Engineers, Hobart, Australia, pp. 281–285.

Hossain, S., Eyre, B. & McConchie, D. 2001 Suspended sediment transport dynamics in the sub-tropical micro-tidal Richmond River estuary, Australia. *Estuarine Coast. Shelf Sci.* **52**, 529–541.

Hurlimamm, A. & Dolnicar, S. 2010 When public opposition defeats alternative water projects – the case of Toowoomba Australia. *Water Res.* **44**, 287–297.

Ippen, A. T. 1966 *Estuary and Coastline Hydrodynamics*. McGraw-Hill, New York.

James, D. P. & Chanson, H. 1999 A study of extreme reservoir siltation in Australia. In: *Water 99 Joint Congress*, Institution of Engineers, Brisbane, Australia, pp. 1109–1114.

McKee, L. J. & Eyre, B. D. 2000 Nitrogen and phosphorus budgets for the sub-tropical Richmond River catchment, Australia. *Biogeochemistry* **50**, 207–239.

McKee, L. J., Eyre, B. D. & Hossain, S. 2000 Transport and retention of nitrogen and phosphorus in the sub-tropical Richmond River estuary, Australia – a budget approach. *Biogeochemistry* **50**, 241–278.

McMahon, T. A., Vogel, R. M., Pegram, G. G. S. & Peel, M. C. 2007 Review of Gould-Dincer reservoir storage-yield reliability estimate. *Adv. Water Resour.* **30**, 1873–1882.

Poussade, Y., Vince, F. & Robillot, C. 2011 Energy consumption and greenhouse gas emission from the use of alternative water sources in SEQ. *J. Water Sci. Technol. Water Supply* **11** (3), 281–287.

Queensland Water Commission 2008 South East Queensland Water Strategy – Draft [Online] http://www.qwc.qld.gov.au/SEQWS+document.

Radcliffe, J. C. 2010 Evolution of water recycling in Australia cities since 2003. *Water Sci. Technol.* **62** (4), 792–802.

Ross, V. L., Fielding, K. S. & Louis, W. R. 2014 Social trust. Risk perception and public acceptance of recycled water: testing a social-psychological model. *J. Environ. Manage.* **137**, 61–68.

Rowe, L. 2009 Western Corridor. *Water Eng. Aus.* **3** (1), 18–22.

Sahin, O., Siems, R. S., Stewart, R. A. & Porter, M. G. 2014 Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: a system dynamics approach. *Environ. Modell. Softw.* Available from http://dx.doi.org/10.1016/j.envsoft.2014.05.018.

Siems, R., Sahin, O., Talepour, M., Stewart, R. & Hopewell, M. 2013 Energy intensity of decentralized water supply system utilized in addressing water shortages. In: *8th International Conference of the European Water Resources Association, 26–29 June*, FEUP, Porto, Portugal.

Stamatov, V. & Stamatov, A. 2010 Long-term impact of water desalination plants on the energy and carbon dioxide balance

of Victoria, Australia: a case study from Wonthaggi. *Water Environ. J.* **24**, 208–214.

Stewart, R. 2011 *Verifying the End Use Portable Water Savings From Contemporary Residential Water Supply Schemes*. Waterline report. National Water Commission, Canberra, Australia.

Stoeglehner, G., Edwards, P., Daniels, P. & Narodoslawsky, M. 2011 The water supply footprint (WSF): a strategic planning tool for sustainable regional and local water supplies. *J. Clean. Prod.* **19**, 1677–1686.

Turner, A., Hausler, G., Carrard, N., Kazaglis, A., White, S., Hughes, A. & Johnson, T. 2007 *Review of Water Supply-Demand Options for South East Queensland*. Institute for Sustainable Futures, Sydney and Cardno, Brisbane.

UNEP 2001 Felling of forests adding to world's water shortages as dams fill up with silt. http://www.unep.org/Documents. Multilingual/Default.asp?DocumentID=227&ArticleID=2966.

Van den Honert, B. C. & McAneney, J. 2011 The 2011 Brisbane floods: causes, impacts and implications. *Water* **3**, 1149–1173.

Williams, R. 1987 *Water quality in the Richmond River*. State Pollution Control Commission Northern Rivers Study No.4. State Pollution Control Commission, Sydney.

Yang, S. Q. 2003 Potential water resources in Singapore. *J. Water Supply Res. Technol.* **52** (6), 425–434.

Yang, S. Q. 2004 *Global and China's Water Crisis and Its Solutions in the 21st Century*. Tianjing University Press, Tianjing (in Chinese).

Yang, S. Q. 2007 Problems in existing coastal reservoirs and a potential solution by soft dam. In: *The Fourth International Conference on Asian and Pacific Coasts*, World Scientific, Nanjing, China.

Yang, S. Q. 2009 Water resources available in Australian's coastal zones and its development by coastal reservoirs. In: *5th International Conference on Asian and Pacific Coasts*, World Scientific, Singapore.

Yang, S. Q. & Ferguson, S. 2010 Coastal reservoirs can harness stormwater. *Water Eng. Aus.* **4** (5), 25–27.

Yang, S. Q. & Liu, P. W. 2010 Strategy of pollution prevention in Taihu Lake and its effects analysis. *J. Great Lakes Res.* **36** (1), 150–158.

Yuen, E., Jovicich, S. S. & Preston, B. L. 2013 Climate change vulnerability assessment as catalysts for social learning: four case studies in South-eastern Australia. *Mitigation Adapt. Strat. Global Change* **18**, 567–590.