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A coastal reservoir for Greater Sydney water supply in Shoalhaven river – a preliminary study

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ABSTRACT

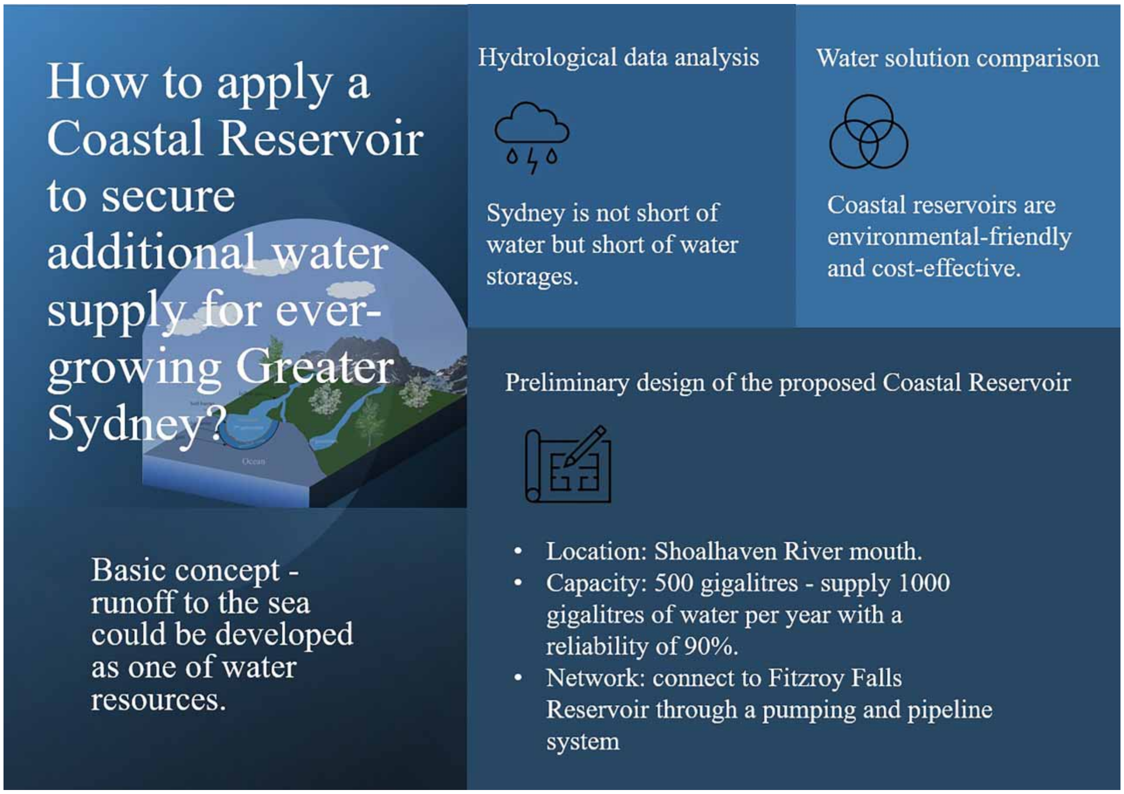
Australia is the driest inhabited continent on earth, and most of its population is concentrated along the coastal line. In recent years, extreme climate events such as floods and droughts have occurred more frequently. Sydney, as the largest city in Australia, requires a reliable water supply. Many solutions have been conducted to secure its water supply. This paper is focused on future water supply for the Greater Sydney area. The analysis supports the concept that in runoff-rich regions like Greater Sydney, there is no water shortage but a lack of water storage. The novel technology, coastal reservoirs, can increase the storage capacity of freshwater in the sea. The average annual discharge at Shoalhaven River mouth is estimated as 1,334 gigalitres. By comparison, the average annual inflow to the Warragamba Dam, which supplies 80% of Sydney's drinking water, is 1,069 gigalitres. This paper discusses how to apply a Coastal Reservoir at the Shoalhaven River mouth to secure additional water supply for ever-growing Greater Sydney. The proposed reservoir with a capacity of 500 gigalitres could supply 1,000 gigalitres of water per year with a reliability of 90%. A preliminary design of the reservoir is demonstrated.

Key words: coastal reservoir, freshwater, Greater Sydney, water solutions, water storage

HIGHLIGHTS

- Review the water solutions for Greater Sydney.
- Apply Coastal Reservoir technology to Greater Sydney's water supply.
- Compare the difference between Coastal Reservoir and other water solutions.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The water crisis is one of the top ten world risks ranked in the Global Risk Report concerning both impact and likelihood to occur (World Economic Forum 2021). However, freshwater is a very limited resource. Although nearly 70% of the world is covered by water, only around 0.025–0.01% of the water on earth is readily accessible freshwater (Hotlos 2008). UN Water (2021) predicted that from 2000 to 2050, the water demand would increase by 55% due to population growth and economic development, and a 40% global water deficit would occur by 2030. Therefore, the security of water supply faces enormous challenges in the foreseeable future around the world.

Australia, as the driest continent on the earth, is inevitably suffering from water crisis, especially during extended periods of drought. Across the Australian continent, the distribution of water resources is uneven. A thin wet margin and a dry interior could be used to summarise the water distribution of Australia (Prosser 2011). Cities and towns are concentrated along the Australian coastal line, especially the major cities, such as Sydney and Melbourne. Hence, the concern of freshwater supply is also focused on coastal areas of Australia. After experiencing three major drought periods (the Federation Drought 1895–1903, the World War II Drought 1937–1945, and the Millennium Drought 2001–2010), Australia launched a series of projects to cope with the water crisis. These projects, such as dams built in the 20th century and desalination plants built in the 21st century, combined with temporally water restrictions in the dry periods, makes the water demand of Australia barely satisfied for now. However, with a population of over 25 million (more than 80% live within coastal areas) and an annual growth rate of 0.9% (Australian Bureau of Statistics 2021), the annual water demand of Australia could increase to 40,000 gigalitres by 2050 (Pigram 2006), which is almost double the current water use. Australia urgently needs measures to increase the availability of freshwater.

Sydney is the largest city in Australia with a population of five million, which is one-fifth of the Australian population. Within the next 50 years, the population of Sydney is predicted to increase to more than nine million (Australian Bureau of Statistics 2021). Water supply for the Greater Sydney area has always been a contentious issue. The shift of rainfall patterns caused by climate change is exacerbating the erraticness and uncertainty of the water supply. During the Millennium

Drought, the level of Sydney's major drinking water supply dam – the Warragamba Dam – fell to less than 33% of its capacity. On the other hand, another water-related disaster, floods, also keep challenging Sydney's water supply system. According to the Australian Bureau of Meteorology's records, from 16th March to 23rd March in 2021 Sydney area received 400–600 mm of rainfall, which equals almost half of the average annual rainfall of Sydney. The water released from the Warragamba Dam spillway was 450 gigalitres per day (WaterNSW 2021a). By comparison, the annual water consumption of Sydney in 2019–2020 was 535 gigalitres (Sydney Water 2020). Similar situations exist in other catchments in the Great Sydney area, such as, in August 2020, the Tallowa Dam spilled about 20 years' worth of local water use in just 24 hours. Hence during high rainfall periods, a significant amount of flow is being released to downstream and ends up in the seas without being captured. UN Water (2021) emphasised that the frequency and severity of droughts and floods are expected to increase, caused by climate change. The possibility of a more prolonged and more intense monsoon would lead people to think about whether Sydney is short of water or short of reservoirs. If the answer is the latter, how to capture and store the surplus water during floods to enhance the water supply during droughts should be addressed.

The vast sea could provide a new solution to capture freshwater. The dam constructed in the ocean near the river mouth preventing runoff mixing with seawater could form a reservoir to capture and store freshwater runoff. This kind of freshwater reservoir is called a coastal reservoir. Coastal reservoirs have been widely used around the world to capture freshwater during floods, such as in China, South Korea, Singapore, and the Netherlands. Coastal reservoirs have many advantages (Liu *et al.* 2013; Sitharam 2017), such as being eco-friendly and cost-effective. Currently, several published studies have demonstrated the feasibility of coastal reservoirs around Australia (Yang 2017; Yang & French 2018; Khalil *et al.* 2020; Sitharam *et al.* 2020).

This paper will review water solutions for Greater Sydney and substantiate the water availability by comparing two main catchments in the Greater Sydney area, Shoalhaven River catchment and Warragamba catchment. Subsequently, this paper will demonstrate a preliminary design of Shoalhaven Coastal Reservoir for Greater Sydney's water supply.

2. BACKGROUND AND HISTORICAL REVIEW OF GREATER SYDNEY'S WATER SOLUTIONS

The water supply of Sydney started from the Tank Stream in 1789–90, then in 1826 from Lachlan Swamps. This was followed by the development of dams in the 20th century. In the 21st century, besides dams, water restrictions, water recycling and desalination have been added into the water solutions for Sydney. The timeline and features of different water sources are shown in Table 1. The development and drawbacks of these water solutions are discussed in detail in the following parts. Currently, WaterNSW supplies water to Greater Sydney's customers through a water supply system that stretches from Shoalhaven to the Blue Mountains, as shown in Figure 1. This complex network includes dams, reservoirs, water filtration plants, water recycling plants, Sydney Desalination Plant, pumping stations and pipelines.

2.1. The early era

According to the water supply historical timeline published on the website of WaterNSW (2021b), the history of Sydney water supply in the early era is summarised as follows.

On 26th January 1788, the British landed at Botany Bay and settled around the stream that emptied into Sydney Cove. Since in Britain it rained all year round and its rivers always flowed, they had little knowledge of conserving or storing water. The dry summer of 1789–90 attacked Sydney. To cope with the drought, Governor Arthur Phillip had tanks carved into the sandstone banks of a stream to store water, which was known as the Tank Stream. This was the start of the search for a reliable and permanent water supply for Sydney. With the development of Sydney, the Tank Stream was abandoned as a water supply due to pollution in 1826. People began to use well water and carted water from the Lachlan Swamps (now Centennial Park).

In 1837, a 3.4 km tunnel, named Busby's Bore, was built to transport water from Lachlan Swamps to the city racecourse (now Hyde Park), then the water was piped to the carts at the corner of Park and Elizabeth Street. The price of water from Busby's Bore was extremely high during the dry period in 1838–1839. In 1844, the first reticulation pipes were built to connect about 70 houses directly to Busby's Bore. To draw more water from the Lachlan Swamp to supply Busbys' Bore, a steam-powered pump was installed in 1854. At the same time, the Botany Swamps Water Supply Scheme began to construct, which drained water from the east of the city into swamps on Botany Bay. To meet the growing water demand, the system was continually updated since it was operated in 1859. Nevertheless, up to 1886, the storage of the Botany Swamps Scheme only met 10 days of Sydney's water demand.

Table 1 | Summary of Greater Sydney's water supply sources timeline

The early era	Primary water source		Commissioned	Demolished	Remarks
	Tank	Tank stream	1,790	1,826	Abandoned due to pollution
	Swamps	Lachlan Swamps	1,826	1,859	Water price was extremely high due to the drought
		Botany Swamps	1,859	1,896	The capacity could not meet the increasing demand
The era of dams	**Primary water source**		**Commissioned**	**Capacity (GL)**	**Remarks**
	Dams	Prospect Reservoir	1,888	33.33	First earth-fill embankment dam in Australia
		Cataract Dam	1,907	97.19	Largest engineering project in Australia at that time
		Lake Medlow Dam	1,907	0.33	First thin arch high stress concrete dam in NSW, and one of the thinnest dam walls in the world
		Middle Cascade Dam	1,908	0.17	Provide water for the upper and middle Blue Mountains
		Cordeaux Dam	1,926	93.64	Built due to the 1901–1902 drought
		Lower Cascade Dam	1,926	0.3	Supplement Middle Cascade Dam
		Avon Dam	1,927	146.7	Second largest dam after Warragamba in Sydney
		Woodford Creek Dam	1,928		
		Nepean Dam	1,935	67.73	Built due to the 1901–1902 drought
		Upper Cascade Dam	1,938	1.79	Supplement Middle Cascade Dam
		Woronora Dam	1,941	71.79	Built due to the growing residential, industrial and commercial development
		Greaves Creek Dam	1,942	0.3	Supplement Cascade Dams
		Warragamba Dam	1,960	2027	One of the largest dams in the world and the world's largest domestic water supply dam at that time
		Tallowa Dam	1,976	90	Provided more than 30% of Greater Sydney's water during the Millennium Drought
The recent era	**Supplementary solutions,**		**Commissioned**	**Capacity (ML/day)**	**Remarks**
	Water Restrictions	Water Wise Guidelines	2,009	0.4/person	Long term rules replacing the previous restrictions
	Water recycling	Rouse Hill Water Recycling Plant	2,001	24	The largest residential dual reticulation recycling scheme in Australia
		Wollongong Water Recycling Plant	2,004	49.8	Replace the drinking water that previously came from Avon Dam
		Fairfield Recycled Water Plant	2,011	20	The first scheme delivered by the private sector in Sydney
		St Marys Advanced Water Recycling Plant	2,018	60	Replace the environmental release from Warragamba Dam by 60 megalitres per day
		Other water recycling plants owned or operated by Sydney Water	–	126	
	Desalination	Kurnell Seawater Desalination Plant	2,010	250	Operated when dam levels fall below 60%

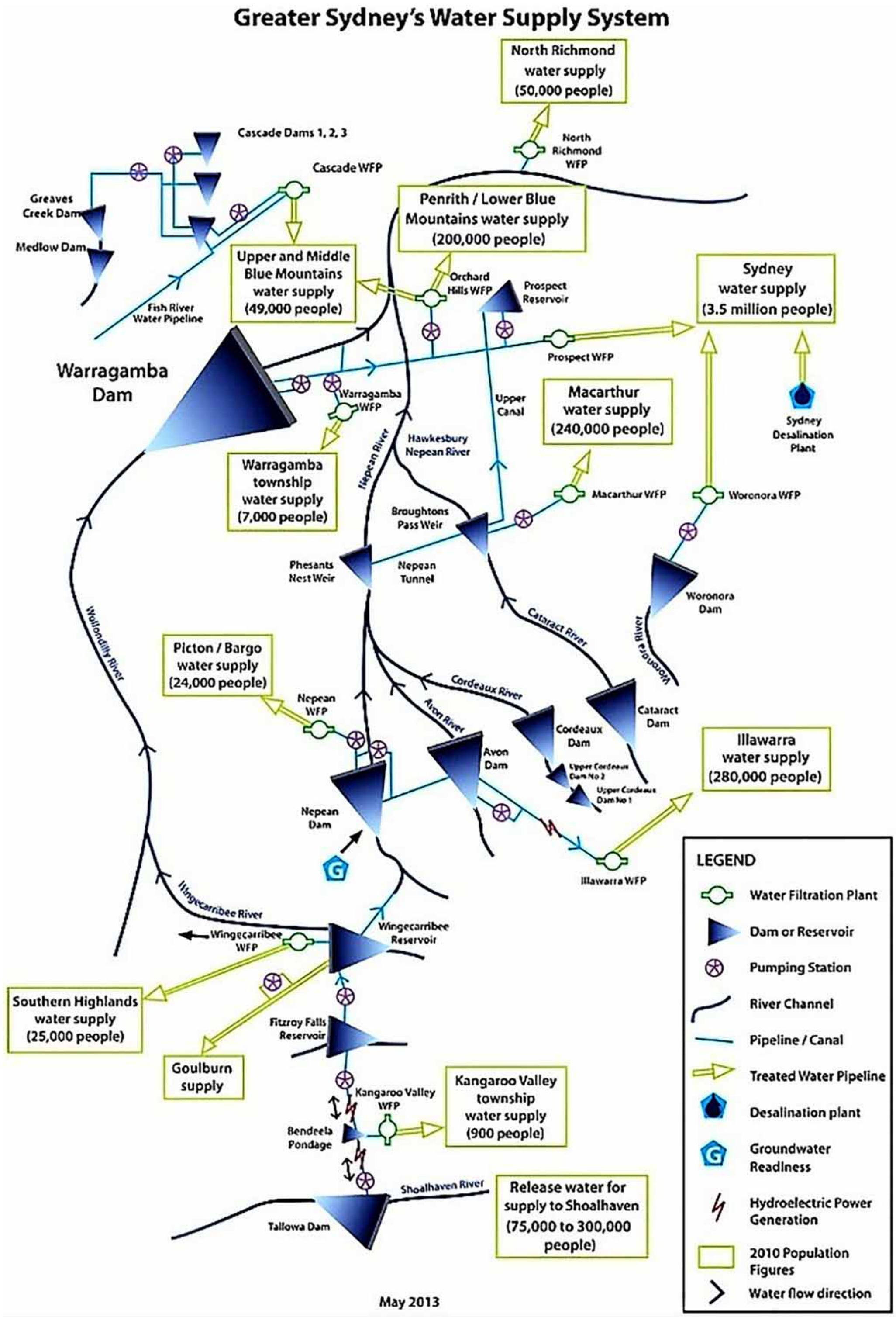


Figure 1 | Greater Sydney's water and wastewater network (Source: WaterNSW 2019).

2.2. The era of dams

To meet the ever-increasing water demand of Sydney, Prospect Reservoir, the first earth-fill embankment dam in Australia, was completed as part of the Upper Nepean Scheme in 1888. This was the start of dam construction. In the following 100 years, the number of dams constructed increased dramatically. Cataract Dam (completed in 1907), Cordeaux Dam (completed in 1926), Avon Dam (completed in 1927) and Nepean Dam (completed in 1935) were constructed to support the Upper Nepean Scheme. In the Blue Mountains, the first dam is Lake Medlow, which was completed in 1907, followed by Middle Cascade Dam (completed in 1908), Lower Cascade Dam (completed in 1926), Woodford Creek Dam (completed in 1928), Upper Cascade Dam (completed in 1938) and Greaves Creek Dam (completed in 1942). To supply the southern suburbs of Sydney, the Woronora Dam was built between 1927 and 1941. As early as 1845, the gorge of the Warragamba River at the exit to Burragorang Valley was identified as an ideal place for a dam. However, due to the engineering and economic constraints, after a century, the Warragamba Dam was completed in 1960. Warragamba Dam was one of the largest dams in the world and the world's largest domestic water supply dam at that time. As a part of the Shoalhaven Scheme, Tallowa Dam was completed in 1976, which is the last dam built in Sydney's drinking water catchment.

After Tallowa Dam, the dam construction boom in Sydney ended. To increase the water supply, the Welcome Reef Dam was proposed to be constructed on the Shoalhaven River in 1980. But finally, in 2004, the proposal was rejected by the Shoalhaven Council. The rejection of the Welcome Reef Dam proposal could reflect the difficulty of building a new dam. The first limitation is costly from a financial and environmental perspective. The estimated cost of the Welcome Reef Dam is over $2,000 million with more than ten years of construction. Meanwhile, more than 15,000 hectares of potentially prime land on either side of the Shoalhaven River would be submerged due to water storage in the dam (Smith 2004). The second limitation is hydrological conditions. Considering the site of the proposed Welcome Reef Dam – its catchment only covers half of the whole Shoalhaven River catchment, and the Welcome Reef is in a rainshadow – it would take up to 30 years to reach its capacity under drought conditions (Andre 2016). The third limitation is public protests. These limitations of dams made the Welcome Reef Dam discussion most unwelcome. The construction of new dams had been under a difficult circumstance.

Moreover, there is evidence that climate change is affecting the inflow of existing dams. Average annual dam inflows for the period 1949–1990 were over 300% higher than for the period 1990–2006 (Nicholson 2012). The rainfall trend in the Warragamba catchment, which supplies 80% of Sydney's drinking water, shows a decrease at 2.52 mm/year (Shrestha *et al.* 2009). Although the quantum of rainfall in the inland catchments shows a decreasing trend, it is increasing in coastal areas (Pigram 2006). Therefore, massive amounts return to the ocean as stormwater runoff without harvesting for use (Warner 2009).

2.3. The recent era

At the beginning of the 21st century, Sydney entered the Millennium Drought. Other feasible options were urgently needed to meet the increasing water demand.

2.3.1. Water restrictions

In 2002, two years of low rainfall made the dam levels fall to below 60% of capacity. Water restrictions were introduced in 2003 in Sydney, beginning with Level 1 then updated to Level 2 in 2004. Due to the ongoing drought, these restrictions did not release the stress of the city's water supply, and the dam levels further reduced to below 40% of capacity in 2005. The toughest restriction, Level 3 water restrictions, was enforced from 1st June 2005. The restrictions were replaced with Water Wise Rules four years later in 2009.

Since the introduction of the Water Wise Rules, Sydney's water demand has remained at a relatively lower level with around 300 litres per person per day, compared to more than 400 litres per person per day before 2003. However, the water supply for Sydney is still threatened by the growing population and climate change.

2.3.2. Water recycling

In 2001, Rouse Hill Water Recycling Plant was commissioned to deliver recycled water to residents to be used for toilet flushing and outdoor watering. It is the largest residential dual reticulation recycling scheme in Australia. The Metropolitan Water Plan was released by the NSW government in 2004, which largely expanded the wastewater recycling schemes. The water quality targets for recycled water schemes vary depending on the end-use. The common end-uses include heavy industry, golf courses, homes, and river flow supplementary. In 2005, the Wollongong Sewage Treatment Plant started to send 20 megalitres/day of recycled water to BlueScope Steel Steelworks. In 2011, Fairfield Recycled Water Plant as part of the Rosehill Recycled Water Scheme, the first scheme delivered by the private sector, was completed to supply 20 megalitres/day of recycled water to customers in Western Sydney. St Marys Advanced Water Recycling Plant, as a part of the Replacement Flows Project, replaced the drinking water released from Warragamba Dam into the Hawkesbury-Nepean River by 60 megalitres/day from 2018. Presently, there are about 20 largescale water recycling schemes and 150 smaller local-scale projects running in Greater Sydney.

In 2020–21, the operation of Sydney Water's water recycling schemes cost A$32 million, resulting in the production of 37.7 gigalitres recycled water and a reduction of 12.7 gigalitres drinking water demand (Sydney Water 2021). Although the water reusing reduces the demand for drinking water, the cost of operation is the major impediment. The issue of storage also limits water recycling.

2.3.3. Desalination

In the Sydney Metropolitan Water Plan, the construction of a desalination plant if dam levels fell to around 30% was proposed. The construction of the Sydney Desalination Plant at Kurnell began in 2007 and came online in January 2010. The plant's capacity is 250 megalitres per day, which can provide up to 15% of Sydney's drinking water. The plant is operated under the Metropolitan Water Plan to supply Sydney Water area of operations when dam levels fall below 60% and continue to do so until dam levels rise to 70%. The yearly cost of the Sydney Desalination Plant per customer is more than A$130 in operation mode and around A$90 in shutdown mode (Boxall *et al.* 2017).

Due to the drought in 2019, dam levels dropped to 43.1%. The NSW Government proposed to expand Sydney's desalination plant to double its size. The sea is an almost infinite water resource, but the supply of water from this resource has created a great deal of public debate due to the cost and environmental impacts of the treatment processes. Moreover, due to the heavy and continuous rain that followed this drought in February 2020, questions were raised about whether the Sydney region is lacking water.

3. COMPARISON OF WARRAGAMBA CATCHMENT AND SHOALHAVEN RIVER CATCHMENT

The Hawkesbury River and Shoalhaven River are two of the major rivers in the Sydney Basin. Figure 2 shows the map of Warragmaba catchment and Shoalhaven River catchment. Warragamba catchment, which is Sydney's largest drinking water catchment, is part of the Hawkesbury River catchment. It covers an area of 9,050 km^2, from north of Lithgow to south of Goulburn. Warragamba Dam is located at the east edge of the catchment in a narrow gorge on the Warragamba River to capture water from the catchment. The capacity of the Warragamba Dam is 2,027 gigalitres, supplying 80% of Sydney's water. Shoalhaven River catchment is bordered on the south of Warragamba catchment, covering an area of 7,151 km^2. Tallowa Dam collects water from a 5,750 km^2 catchment within Shoalhaven River catchment from Kangaroo Valley in the north-east to the upper Shoalhaven River south-west of Braidwood. The capacity of Tallowa Dam is 90 gigalitres, of which 7.5 gigalitres is available to be transferred to Sydney.

3.1. Water quantity

Water availability in the two catchments relies heavily on rainfall. Currently, there are 89 opened rainfall gauge stations located in Warragamba and Shoalhaven River catchment. Considering the data period, data from 17 rainfall stations in Warragamba Catchment and 12 rainfall stations in Shoalhaven River Catchment are selected to estimate the areal rainfall. Table 2 shows the number and name of the selected rainfall stations. The arithmetic average rainfall of Warragamba Catchment and Shoalhaven River Catchment from 1887 to 2021 is shown in Figure 3. Descriptive statistics of the annual rainfall are presented in Table 3. The mean annual rainfall of Warragamba Catchment and Shoalhaven River Catchment is 868.6 mm per year and 951.6 mm per year, respectively. According to this, the annual rainfall volume received in the catchment is estimated as 7,861 gigalitres (Warragamba) and 6,805 gigalitres (Shoalhaven River), respectively. Although the catchment area of Shoalhaven River is smaller than Warragamba, higher rainfall makes the water received in these two catchments comparable. However, not all rain could become runoff. Runoff, which could be captured by a reservoir, is generated after the rainfall exceeds the soil's infiltration capacity. According to WaterNSW's report (2020), the annual average inflow to Warragamba Dam and Tollowa Dam is 1,069 and 1,071 gigalitres, respectively. By applying the Rational Method ($Q=CIA$, where Q is the runoff, C is the runoff coefficient, and I is the rainfall, A is the catchment area), the runoff coefficient of Warragamba Dam and Tallowa Dam catchment is 0.136 and 0.196, respectively. Assuming the whole Shoalhaven River catchment has the same runoff coefficient as the Tallowa Dam catchment, the runoff of the Shoalhaven River to the sea is estimated as 1,334 gigalitres annually. Table 4 summarises the catchment area, rainfall and runoff details of Warragamba Catchment and Shoalhaven River Catchment. The higher rainfall and runoff coefficient indicate that the water availability in the Shoalhaven River catchment would be more significant than in the Warragamba catchment. However, the capacity of Tallowa

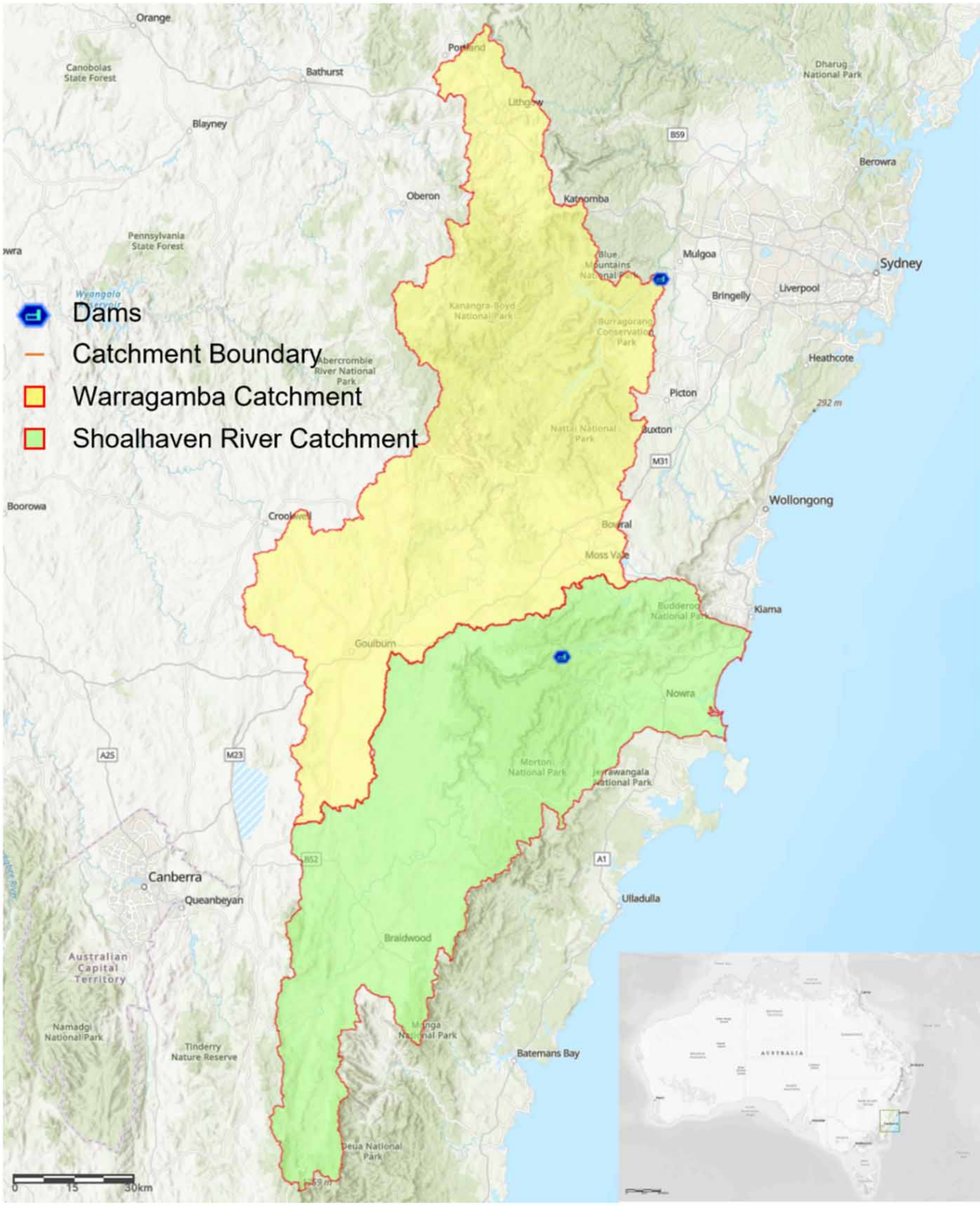


Figure 2 | Shoalhaven River catchment and Warragamba catchment map, showing both are similar in size.

Dam is only 4% of the capacity of Warragamba dam. Therefore, a large amount of runoff in the Shoalhaven River is discharged to the South Pacific Ocean, which can be potentially captured. It could answer the question of whether Sydney is lacking water. The water crisis for Greater Sydney is not a lack of water, rather a lack of reservoirs to capture and store water.

Table 2 | Rainfall stations

Warragamba Catchment		Shoalhaven River catchment	
Station No.	**Station Name**	**Station No.**	**Station Name**
63036	Oberon (Jenolan Caves)	68003	Berry Masonic Village
63039	Katoomba (NarrowNeck Rd	68036	Kangaroo Valley (Main Rd)
63049	Lowther Park	68048	Nowra Treatment Works
63093	Wombeyan Caves	68083	Culburra Treatment Works
63132	Lidsdale (Maddox Lane)	68197	Foxground Road
63146	Cheetham Flats (Jundas)	69010	Braidwood (Wallace Street)
63226	Lithgow (Cooerwull)	69041	Charleyong (Nerriga Road)
68044	Mittagong (Alfred Street)	69049	Nerriga Composite
68045	Moss Vale (Hoskins Street)	70012	Bungonia (Inverary Park)
70036	Lake Bathurst (Somerton)	70057	Braidwood (Krawarree)
70040	Goulburn (Cherryton)	70060	Lower Boro (Calderwood)
70069	Crookwell (Gundowringa)	70219	Braidwood (Khan Yunis)
70071	Goulburn (Pomeroy)		
70077	Goulburn (Springfield)		
70080	Taralga Post Office		
70119	Big Hill (Glen Dusk)		
70131	Woodhouselee (Leeston)		

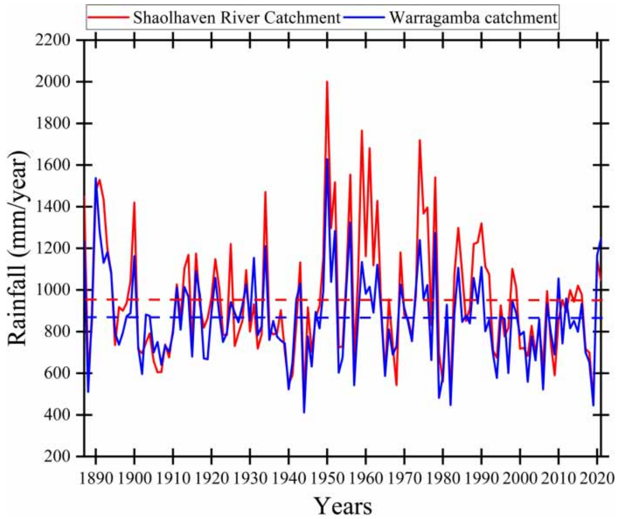


Figure 3 | Average rainfall of Warragamba and Shoalhaven River catchment from 1887 to 2021.

Table 3 | Descriptive statistics of the annual rainfall

Catchment	Mean (mm)	Median (mm)	Standard deviation	Coefficient of variation	Skewness
Warragamba	868.6	855.9	213.78	0.25	0.56
Shoalhaven River	951.6	897.1	291.68	0.33	0.99

Table 4 | Water availability comparison between Warragamba and Shoalhaven River catchment

Catchment	Area (km^2)	Rainfall volume (GL/year)	Runoff (GL/year)	Runoff coefficient	Major Inland dams
Warragamba	9,050	7,861	1,069	0.136	Warragamba Dam
Shoalhaven River	7,151	6,805	1,334	0.196	Tallowa Dam

While the long-term data could provide statistical evidence, people tend to focus more on the drought period. Figure 4 compares the runoff in the Warragamba catchment and Shoalhaven River catchment during two recent drought periods (2001–2010 and 2017–2019). The five sites' discharge data from Real-time-data WaterNSW (2021c) are used to conduct the comparison. Warragamba dam inflow is the sum of discharge of Coxs River at Kelpie Point, Kowmung River at Cedar Ford, Wollondilly River at Jooriland, and Nattai River at the Causeway. The discharge of Shoalhaven River is estimated from the discharge measured at the gauge Shoalhaven River Downstream Tallowa Dam (the discharge at Tallowa Dam is 80% of the whole Shoalhaven River discharge based on the catchment area proportion). From 2001 to 2010, the average annual inflow of the Warragamba Dam was 308 gigalitres, and the annual discharge of the Shoalhaven River was 396 gigalitres. From 2017 to 2019, the average annual inflow of the Warragamba Dam was 113 gigalitres, and the annual discharge of the Shoalhaven River was 267 gigalitres. If there would be a reservoir to capture the discharge of Shoalhaven River without influence on the environmental flow, it could substantially ease the water crisis of Greater Sydney during the drought period.

3.2. Water quality

The water quality in a catchment is highly affected by land uses. Runoff from different types of land use may be enriched with different kinds of contaminants (Sitharam *et al.* 2020). For example, total nitrogen, total phosphorus and Fecal coliform are positively related to residential and agricultural lands and negatively related to forest land use (Tong & Chen 2002). Generally speaking, the runoff in forests and other areas with good vegetation cover and little disturbance from humans is fairly steady with relatively high quality, but in built-up areas the runoff is highly variable with poorer water quality.

The Warragamba catchment includes the major towns of Oberon, Wallerawang, Lithgow, Katoomba, Goulburn, Bowral and Mittagong. These areas contribute to a total population of 81,583 people (2016 Census) for the catchment area. The Shoalhaven River catchment includes the main towns of Nowra, Bomaderry, Braidwood and Berry, totalling a population of only 30,865 (2016 Census), about 1/3 of the former. The Warragamba catchment population density is double the Shoalhaven River catchment population intensity. Figure 5 shows the land-use comparison between the Warragamba catchment and the Shoalhaven River catchment. Most of the Warragamba catchment is in a conservation area, which accounts for 52.3% of the total catchment area. By restricting or prohibiting public access to the Special Areas, the potentially harmful substances could be stopped from entering the water storage. In comparison, the conservation area covers 32.04% of the Shoalhaven River catchment. The percentage of forestry area in Shoalhaven River catchment is much higher than it is in

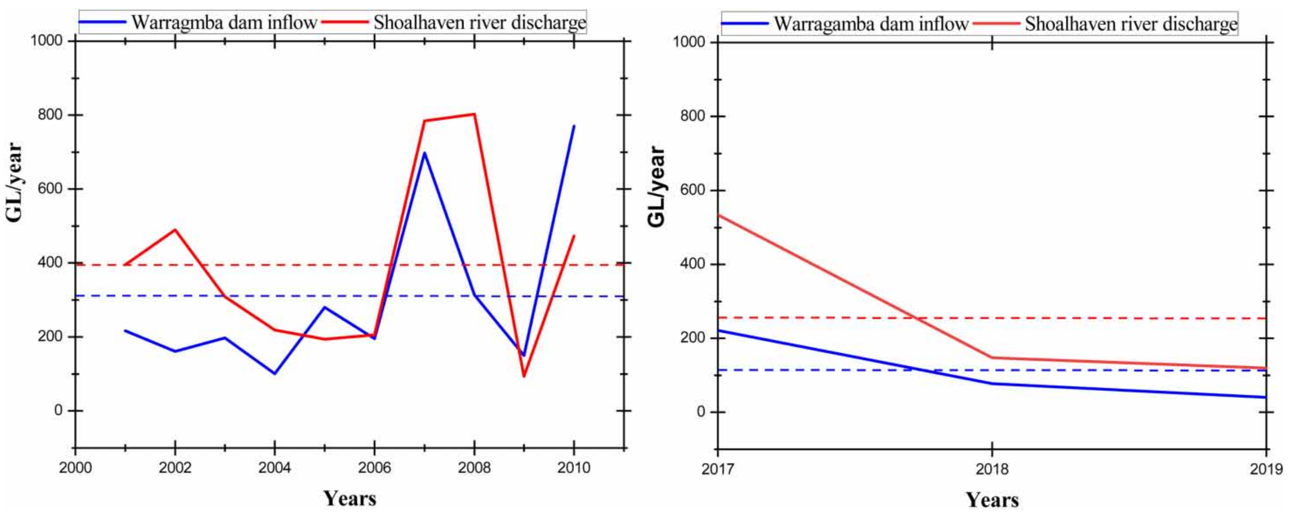


Figure 4 | Drought period runoff comparison between Warragamba catchment and Shoalhaven River catchment.

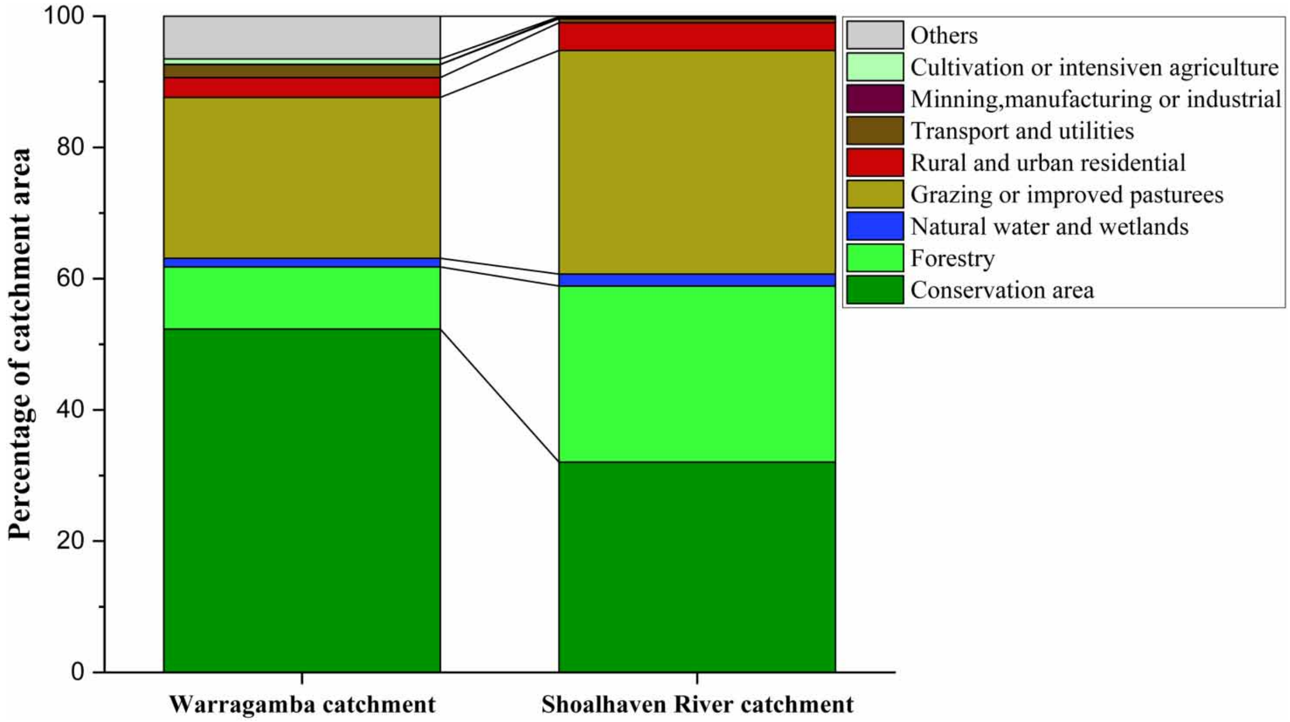


Figure 5 | Land use comparison between Warragamba catchment and Shoalhaven River catchment.

Warragamba catchment, a 26.82 and 9.5%, respectively. Summing up the conservation area, forestry area, and natural water and wetlands area, the total natural process area of Warragamba catchment is 63.1% and of Shoalhaven River catchment is 60.7%. In terms of the area humans affected, there is no significant difference between these two catchments. With the consideration of the population density and land use, the water quality in the Shoalhaven River catchment should be better than, or at least similar to, the water quality in the Warragamba catchment in general.

WaterNSW has a comprehensive surface water quality monitoring program throughout the Sydney Drinking Water Catchment, and Shoalhaven City Council has an online portal to view water quality in Shoalhaven. The long-term water quality monitoring data (DECCW 2010; Shoalhaven City Council 2021) for the Warragamba catchment and Shoalhaven River catchment are compared in Figure 6. Figure 7 shows the location of the water quality monitoring sites, including the site number and site name. WaterNSW benchmarks the water quality for catchment streams against the ANZECC guideline. The benchmark range for conductivity is less than 350 μS/cm, for total nitrogen is less than 0.25 mg/L, for total phosphorus is less than 0.02 mg/L, and for chlorophyll-a is less than five μg/L (WaterNSW 2019). Most of the median conductivity recorded in these two catchments are within the benchmark range. The extremely high median conductivity of Sites 10 and 11 in Shoalhaven River Catchment may be caused by seawater intrusion. Median total nitrogen and median total phosphorus in these two catchments exceed benchmarks, which may be caused by the large proportion of land used for grazing and agriculture. The median chlorophyll a concentration in Wingecarribee River, Mulwaree River, and Wollondilly River in the Warragamba catchment highly exceed the benchmark.

Cyanobacteria, commonly known as blue-green algae, is a type of algae found in freshwater systems. Cyanobacteria blooms could lead to deterioration of water quality, which would disrupt water supplies. High chlorophyll-a combined with high total nitrogen and total phosphorus could enhance the possibility of Cyanobacterial blooms. During 2016–2019, 1266 Cyanobacteria alerts were recorded throughout the Sydney Drinking Water Catchment, of which 73% were recorded in the Warragamba catchment (Eco Logical Australia 2020). The largest algal bloom in Warragamba Dam developed in August 2007, and it covered 75% of the Warragamba dam surface area. That algal bloom made about 500 gigalitres of water in the Warragamba dam unusable.

Fire is a new indicator to determine water quality in a catchment. Although the runoff in forests usually has high quality, the side effects of bushfires cannot be ignored. In recent years, bushfires threatened the Warragamba catchment. The bushfire

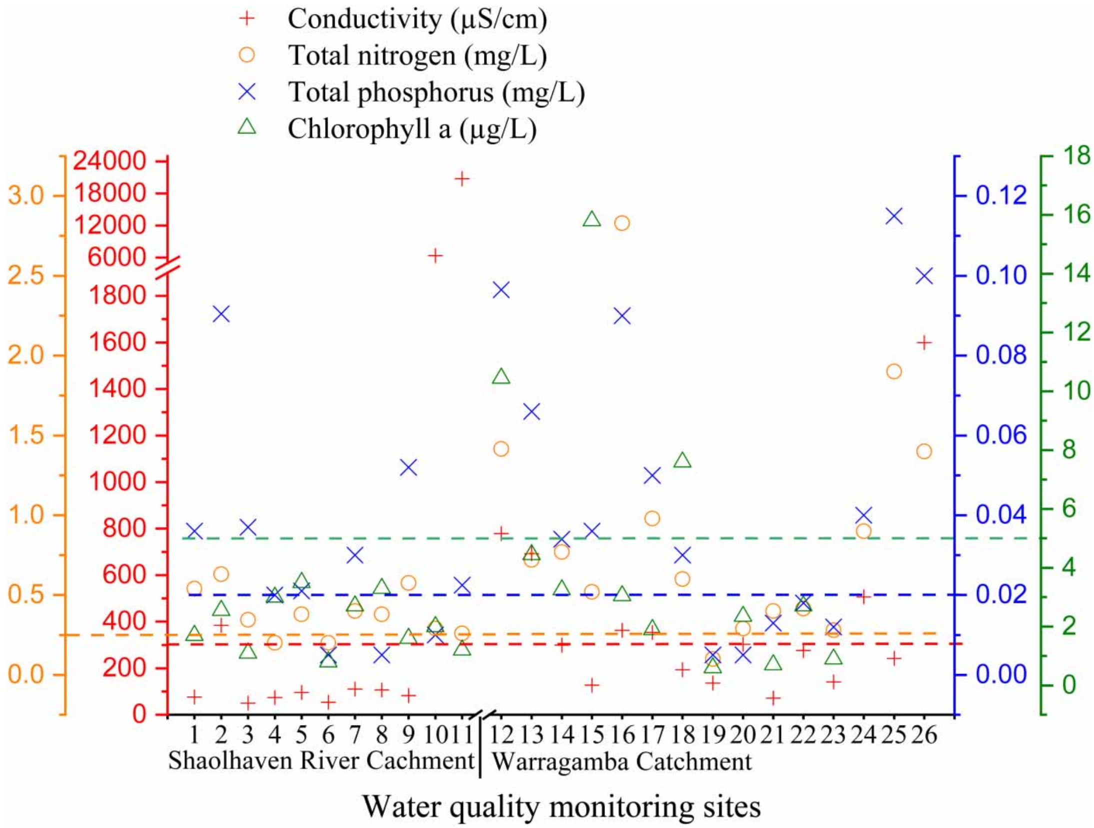


Figure 6 | Long-term water quality monitoring data compared with benchmark.

2019/2020 affected 35% of the Warragamba catchment. The Warragamba catchment received two major rainfall events during and shortly after the Green Wattle Creek Fire. These events resulted in 800 gigalitres inflows into Burragorang Lake and doubled pre-storm storage levels. These inflows transported large amounts of ash, eroded soil and associated contaminants that generated plumes in the lake and impacted water quality. The water authority temporarily had to shut off Warragamba Dam's supply of raw water to the Prospect Water Filtration Plant for 1 week and used alternative water sources for the city. However, this type of threatening could be eliminated if the coastal reservoir is constructed due to its bypass channel, the CR can bypass the unwanted water, and no polluted water can enter a coastal reservoir for storage.

The long-term monitoring data and significant water quality incidents substantiate the conclusion that the runoff in the Shoalhaven River catchment has higher water quality.

4. COASTAL RESERVOIR

A coastal reservoir is a freshwater reservoir constructed at an estuary, bay, or in the ocean near a river mouth (Liu *et al.* 2013), which plays a vital role in capturing and storing runoff before it flows into the sea. Figure 8 shows the typical schematic diagram of first- and second-generation coastal reservoirs. The freshwater lakes or lagoons that existed on the shore can be regarded as natural coastal reservoirs. The functions of the coastal reservoir include irrigation, industrial and domestic usage depending on the water quality in the reservoir.

Coastal reservoirs as a new generation of water solution have several particular advantages compared to other main water solutions. Compared with inland dams, coastal reservoirs are a more effective method to harvest water since they have the potential to capture all runoff from a catchment (Liu *et al.* 2013), and also, there is no land acquisition concern for coastal reservoirs. Compared with seawater desalination and wastewater treatment, coastal reservoirs are a more cost-effective and sustainable method since the water in coastal reservoir sources from river runoff requires less treatment before supply. On the other hand, some disadvantages of coastal reservoirs mentioned by Kolathayar *et al.* (2019) should be

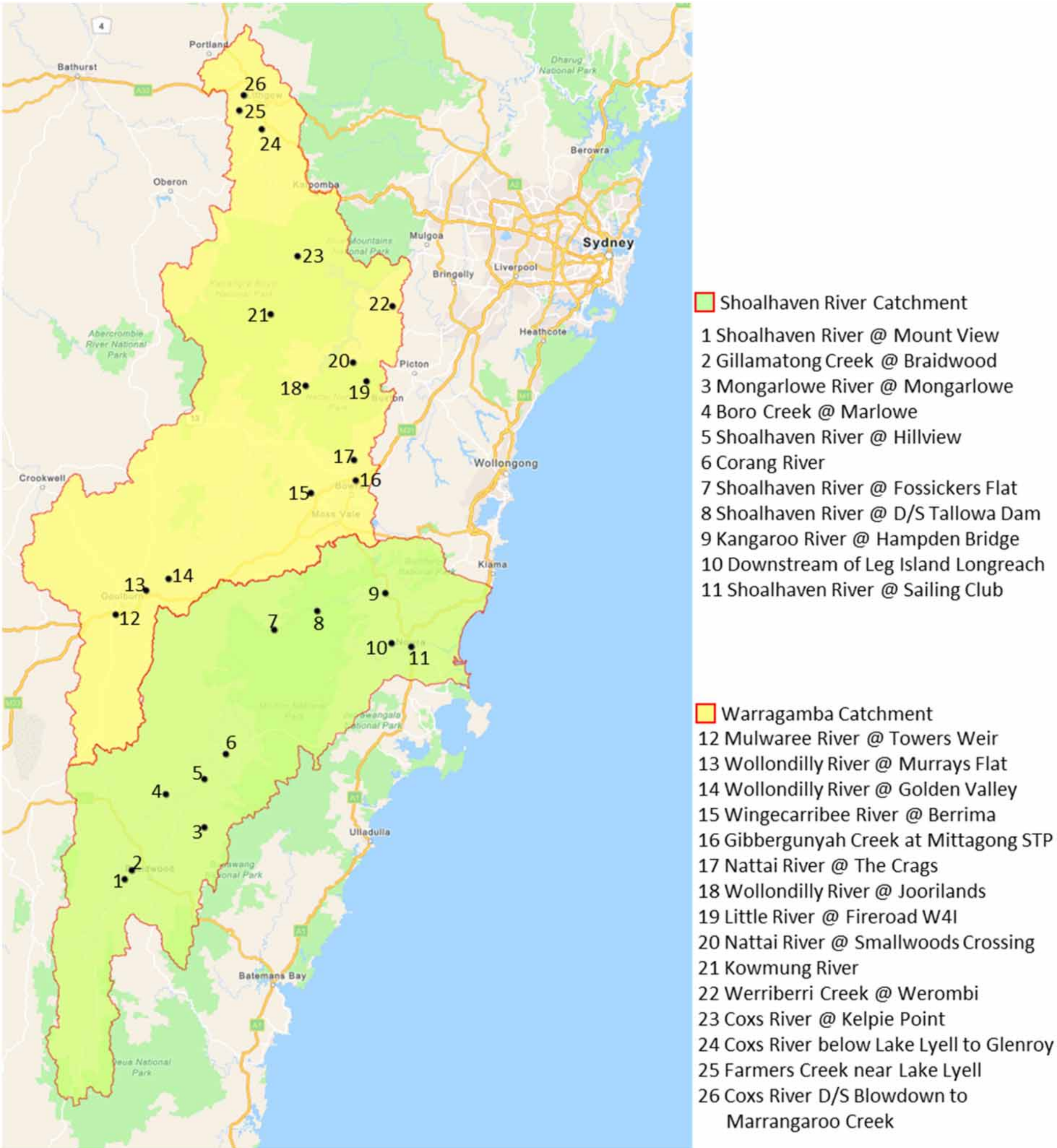


Figure 7 | Map of water quality monitoring sites.

concerned when applying coastal reservoirs, such as costly transportation of water to uphill towns and regular desilting required.

4.1. Existing coastal reservoirs in the world

Currently, several coastal reservoirs exist around the world. Table 5 lists the details of some main coastal reservoirs. Sixty-two per cent of existing coastal reservoirs are used for water supply, 20.3% are designed to prevent seawater intrusion, and the remaining purposes of coastal reservoir development mainly include land reclamation, flood defence and urban regeneration

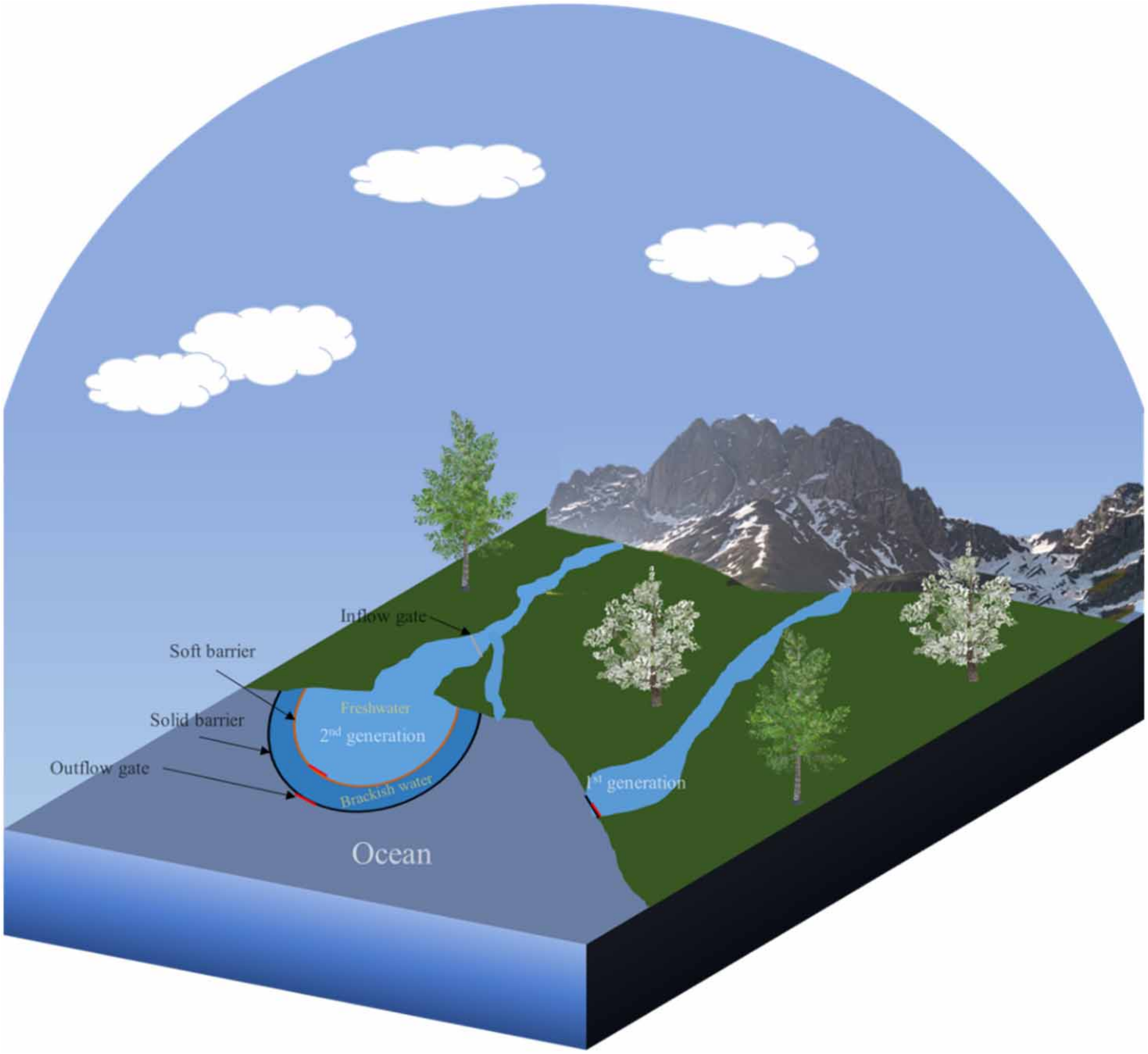


Figure 8 | Schematic diagram of 1st and 2nd generation coastal reservoir.

(Yang 2019). Ijsselmeer reservoir, also known as Lake IJssel, was built in Zuider Zee, Netherlands in 1932 and is usually considered as the first coastal reservoir. A 32 km dam was built in the river estuary to form a shallow freshwater reservoir covering 1,100 km^2 with an average depth of 5.5 m. Agriculture and drinking water are supplied from the Ijsselmeer reservoir.

The coastal reservoirs built inside the river mouth, similar to the Ijsselmeer reservoir, are the first-generation coastal reservoirs. The majority of existing coastal reservoirs are first-generation coastal reservoirs. The dam site of a second-generation coastal reservoir is more flexible, and it could be outside the river mouth in the seawater. The significant improvement of second-generation coastal reservoirs is that they can only capture and store high-quality water and bypass unwanted water. Qingcaosha coastal reservoir built outside the Yangtze River mouth in Shanghai China is a second-generation coastal reservoir. The reservoir was built in 2011 cost A$2.74 billion, and the supply output had the capacity of 200 cubic metres per second. That is equivalent to 2600 gigalitres per year with a design life span of 100 years. This, in turn, results in an overall capital cost of A$0.02 per kilolitres of water supplied in 2021's value. The construction cost of Warragamba Dam and Sydney Desalination Plant was £35.5 million in 1960 and A$1.8 billion in 2010, respectively. Considering the lifespan and the annual water supply, the construction cost turns to A$0.03 and A$1.22 per kilolitres of water supplied in 2021's value. It is thereby

Table 5 | Main existing coastal reservoirs in the world

Name	Catchment (km^2)	Capacity (GL)	Year completed	Construction cost (A$ billion)	Country/Region
Ijsselmeer	170,000	5,600	1932	–	Netherlands
Lake Alexandrine and Albert	1,100,000	1,600	1940	–	Australia
Plover Cove	45.9	230	1968	0.06	Hong Kong
Thanneermukkom Bund	–	–	1974	–	India
Baogang	1,800,000	12	1985	–	China
West Sea Barrage	20,000	2,700	1986	2.77	North Korea
Cheng Hang	1,800,000	8	1992	–	China
Sihwa	476	323	1994	0.39	South Korea
Yu Huan	170	64	1998	0.16	China
Marina Barrage	110	–	2008	0.31	Singapore
Qingchaosha	1,800,000	550	2011	2.74	China
Saemanguem	330	530	2011	2.05	South Korea

evident that although construction costs of coastal reservoirs may be higher than both dams and desalination plants when taking into account both production output and design life, they are the cheaper alternative. Energy cost is another important indicator to compare different water solutions. Since Warragamba Dam supplies raw water to Prospect Water Filtration Plant by gravity, the main energy consumption occurs at water filtration plants used to treat the raw water. According to Sydney Water's report (2007), the energy consumption is 0.28 kilowatt-hours per kilolitres of water treated in water filtration plants. Ignoring other energy consumptions, the energy consumption of Warragamba Dam is 0.28 kilowatt-hours per kilolitres of water supplied. The Sydney Desalination Plant consumed 3.5 kilowatt-hours per kilolitres of water supplied in operation mode (Boxall *et al.* 2017). Qingcaosha Coastal Reservoir delivers 7,080 megalitres of water per day to the water treatment plant by a pump station with a capacity of 83,900 kilowatts. Assuming the energy consumption of the water treatment plant is the same as the Prospect Water Filtration Plant, Qingcaosha Coastal Reservoir consumed 0.56 kilowatt-hours per kilolitres of water supplied. Although the energy cost of Qingcaosha Coastal Reservoir is double that of Warragamba Dam, it is far lower than Sydney Desalination Plant. A summary of cost comparison between Warragamba Dam, Sydney Desalination Plant and Qingcaosha Coastal Reservoir is shown in Table 6. In conclusion, considering both construction cost and energy cost, coastal reservoirs could be the most cost-effective solution for a coastal area with sufficient runoff.

4.2. Preliminary design for Shoalhaven Coastal Reservoir

The Shoalhaven Coastal Reservoir is proposed as a second-generation coastal reservoir, which could bypass the poor-quality water. The Shoalhaven River estuary has two entrances, the Shoalhaven Heads entrance and the Crookhaven Heads entrance. This dual entrance system provides a natural bypass channel for the proposed reservoir. The Shoalhaven Coastal

Table 6 | Cost comparison between Warragamba Dam, Sydney desalination plant and Qingcaosha coastal reservoir

	Lifespan (years)	Water supply (GL/year)	Dam length (km)	Dam height (m)	Construction cost	Construction cost in 2021's value (A $ billion)	Construction cost per kL Water in 2021's value (A$/kL)	Intake pumping head (m)	Supply pumping head (m)	Energy consumption (kWh/kL)
Warragamba dam	100	438	0.35	142	£35.5 million in 1960	1.2	0.03	0	0	0.28
Sydney desalination plant	20	90	–	–	A$1.8 billion in 2010	2.2	1.22	0	20	3.5
Qingcaosha coastal reservoir	100	2,600	48.4	13–19	A$2.74billion in 2011	3.3	0.01	0	70	0.56

Figure 9 | Location and gates of the proposed Shoalhaven Coastal Reservoir.

Reservoir is proposed at Shoalhaven Heads entrance, as shown in Figure 9. In the dry season, due to the lower rainfall and runoff and higher saltwater intrusion (Fan *et al.* 2012), the water quality may be not good enough to store in the reservoir. The intake gate A would be closed, and the poor-quality water could be bypassed through Gate B, then discharged to the ocean directly. The same procedure would be applied to the first flush of stormwater which carries significant contaminants (Perera *et al.* 2021). Otherwise, when the high-quality water comes, Gate B would be closed, and the water would intake from Gate A and be stored in the reservoir. To ensure the inflow water quality accurately, a monitor station could be installed upstream of Gate A. The open or closure of Gate A and Gate B would be based on the real-time monitor data.

Once the Shoalhaven Coastal Reservoir has been constructed, it could provide several different pathways to relieve the stress of Greater Sydney's water supply. The distance from the proposed Shoalhaven Coastal Reservoir to the nearest inland dam, Fitzroy Falls Reservoir, is only around 35 km, and the elevation difference between these two reservoirs is about 600 m. Impeccable pumping and pipeline systems are connecting the Fitzroy Falls Reservoir to the Sydney water supply network. A new pumping station and pipeline are required to transfer water from the proposed reservoir to the Fitzroy Falls Reservoir. This is the first option. Based on this option, the proposed reservoir could also become a backup water supply for Canberra. The distance from the Fitzroy Falls Reservoir to Canberra is about 150 km, and the average elevation of Canberra is 20 m lower than the elevation of Fitzroy Falls Reservoir. Water could be transferred and supplied to Canberra by gravity.

The second option is using under subsea pipelines. According to the current Greater Sydney's water supply system, the WaterNSW supplied 2,418 megalitres of water to the Illawarra area every month (29 gigalitres per year) from the Avon Dam (WaterNSW 2020). The distance from the proposed Shoalhaven Coastal Reservoir to the main city of the Illawarra area, Wollongong, is around 50 km. A submarine pipeline could be constructed to transport water from the proposed reservoir to Wollongong, then supply water for the Illawarra area. If so, the water stored in Avon Dam could supply Sydney with the existing network. The length and elevation differences of possible networks are summarised in Figure 10.

The supply reliability of the proposed Shoalhaven Coastal Reservoir regarding its storage capacity and the water demand could be estimated by the Gould-Dincer method (Yang 2015):

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

where S is the storage capacity, Q is the mean annual runoff, α is the annual target demand as a ratio of mean annual runoff, C_v is the coefficient of variation of the annual runoff, r_1 is lag one autocorrelation coefficient of the annual runoff, ξ_f is the failure deviate:

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

where g is the skewness of annual runoff, z_f is the standardised normal variate at 100% probability of non-exceedance:

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

$$y = -ln[2(1-p)] \tag{4}$$

where p is reliability of water supply.

The annual runoff of Shoalhaven River is estimated by using the annual rainfall data from 1887 to 2021 discussed before, with a runoff coefficient of 0.196. Analysing the annual runoff of Shoalhaven River, the mean annual runoff is 1,334 gigalitres,

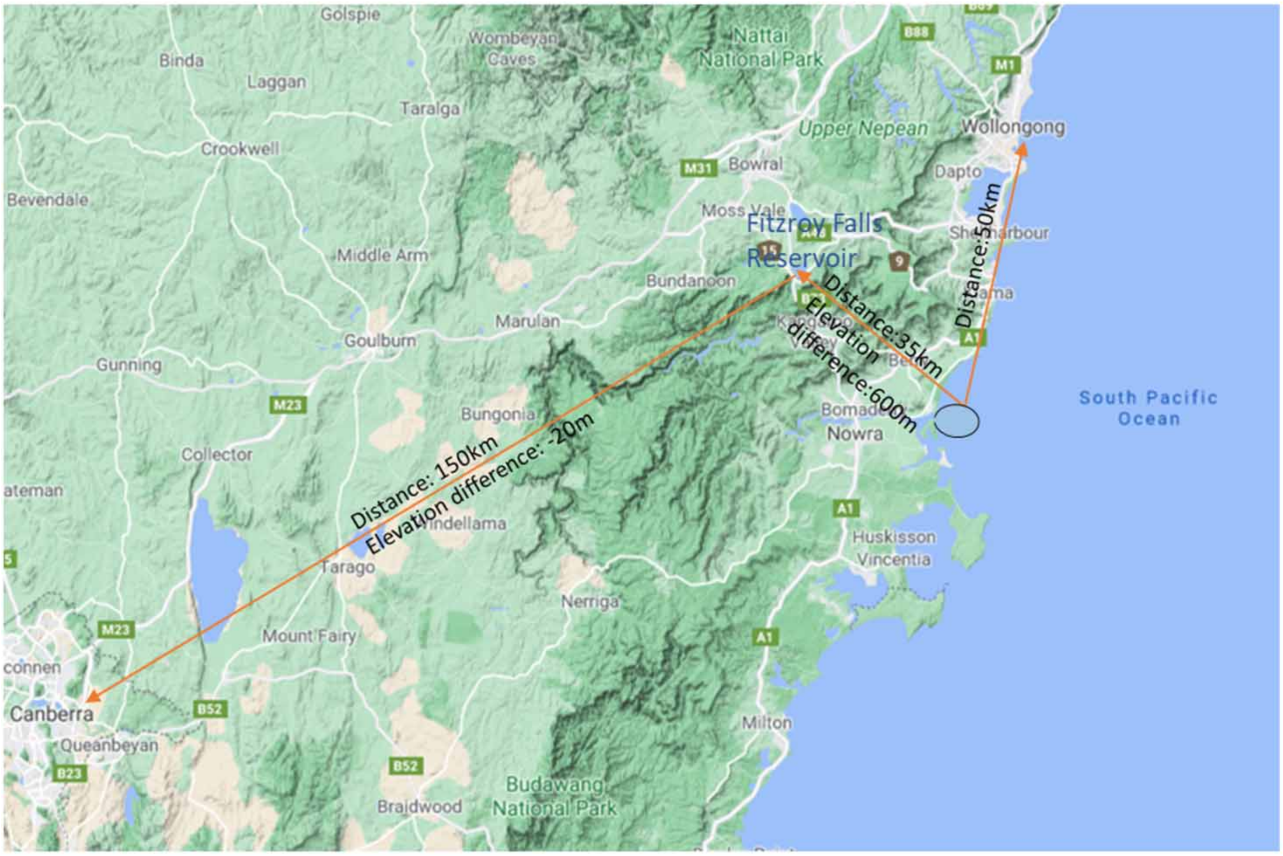


Figure 10 | Possible network for the proposed Shoalhaven Coastal Reservoir.

the median annual runoff is 1,257 gigalitres, the standard deviation is 409 gigalitres, the coefficient of variation is 0.32, the skewness is 0.99, and the lag one autocorrelation coefficient is 0.29. Table 6 shows that to meet Sydney's current water demand, which is around 500 gigalitres per year, the reliability could reach 96% if the proposed storage capacity is 500 gigalitres, and the reliability will be higher if the proposed storage capacity is larger. Although the larger storage capacity in Table 7 shows higher reliability, it does not mean the largest storage capacity, 2,000 gigalitres, is the best option for the proposed reservoir. Coastal Reservoirs have a shallower depth compared to in-land dams. The average water depth in a coastal reservoir usually is less than 10 m. Therefore, a higher storage capacity indicates a higher water surface area of the reservoir. Higher reservoir water surface area could result in a higher evaporation rate (Tian *et al.* 2021). The evaporation rate could not only affect the water efficiency but also affect the water quality in a reservoir. Evaporation could increase the water salinity in a reservoir and enhance the risk of eutrophication. Two primary nutrient indicators, total nitrogen and total phosphorus, in Shoalhaven River, perennially exceed benchmarks. Therefore, it is extremely important to control the evaporation for the proposed reservoir to reduce the chance of toxic algal blooms outbreak. With comprehensive consideration, the proposed Shoalhaven Coastal Reservoir would have a storage capacity of 500 gigalitres which ensures a reliability larger than 90% to the supply of 1,000 gigalitres per year and 1,000 gigalitres per year of water is enough to supply nearly two cities like Sydney's size.

5. DISCUSSION

Sydney is the largest city on the driest inhabited continent on earth, and the security of water supply is crucial to its development. In this paper, water solutions for Greater Sydney are reviewed, and the limitations of each solution are discussed. Water recycling and desalination are rainfall-independent solutions, but the cost of treatment is high. The basic assumption of water recycling and desalination is rainfall is not reliable, and the freshwater resource is not enough. However, the rainfall, runoff, and water quality analysis of two main river basins in Greater Sydney, Warragamba catchment and Shoalhaven River catchment, indicates that the true water crisis for Greater Sydney is not water shortage rather water storage shortage. The annual runoff of the Warragamba catchment and Shoalhaven River catchment is 1,066 and 1,334 gigalitres, respectively. The annual water consumption of Greater Sydney is around 500 gigalitres, which is only 20.8% of runoff in those two catchments. Greater Sydney needs more reservoirs to capture and store this natural freshwater, especially during the flood season. Like other parts of the world, the strict geographical and hydrological requirements and high financial and environmental costs limit the development of in-land dams for Greater Sydney. The coastal reservoir as a reservoir constructed at the river mouth in the ocean could eliminate some of the limitations of the in-land dams, and compared with other water solutions, the coastal reservoir is more cost-effective. The coastal reservoir will be an emerging option to secure the water supply of Greater Sydney in the future.

The Shoalhaven Coastal Reservoir is proposed constructed at the river mouth of Shoalhaven River near Shoalhaven Heads with a capacity of 500 gigalitres. The reservoir could supply 1,000 gigalitres of freshwater with reliability of 90.68%. The reservoir could be connected to the existing water supply system for Greater Sydney by transferring water to Fitzroy Falls Reservoir with a pumping station and pipeline or by transferring water to Wollongong with a submarine pipeline. The quality of water from Shoalhaven Coastal Reservoir is expected to be higher than the quality of water from Warragamba Dam.

Table 7 | Supply reliability of the proposed Shoalhaven River Reservoir with a different storage capacity

Storage (gigalitres)	Demand (gigalitres)	Reliability (%)	Storage (gigalitres)	Demand (gigalitres)	Reliability (%)
2,000	100	99.97	1,000	100	99.67
	500	99.87		500	99.11
	1,000	98.58		1,000	95.64
	1,200	94.18		1,200	88.84
1,500	100	99.91	500	100	98.35
	500	99.68		500	96.77
	1,000	97.61		1,000	90.68
	1,200	92.22		1,200	82.68

However, the social and environmental implications of coastal reservoirs have yet to be properly assessed. More detailed research is required to justify the preliminary design of the proposed reservoir.

6. CONCLUSION

This paper reviews the history of Greater Sydney's water supply and investigates the feasibility of applying coastal reservoir technology at Shoalhaven River mouth. The following conclusions can be drawn:

(1) By reviewing the history of Greater Sydney's water supply, the limitation of current water solutions would lead to insufficient supply in the future or consume high environmental and financial costs. Therefore, alternative solutions are needed to secure the water supply.
(2) According to the analysis of the hydrological data, the average annual runoff of the Warragamba catchment and Shoalhaven River catchment is 1,066 and 1,334 gigalitres, respectively. The capacity of Tallowa Dam (the main dam on Shoalhaven River) is only 4% of the capacity of the Warragamba dam. Therefore, Sydney is not short of water but short of water storage.
(3) Coastal Reservoirs could develop runoff lost to the sea as an environmental-friendly and cost-effective technology. The proposed coastal reservoir is located near the mouth of the Shoalhaven River in the ocean. It could provide sufficient water to Greater Sydney to meet the increasing water demand caused by population growth.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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