MACLEAY COASTAL SANDS GROUNDWATER SOURCE

Groundwater resource description for Macleay coastal sands

September 2021

NSW Department of Planning, Industry and Environment | dpie.nsw.gov.au

Published by NSW Department of Planning, Industry and Environment

dpie.nsw.gov.au

Title: Groundwater resource description for Macleay coastal sands

ISBN: 978-1-76058-402-3

Department reference number: DOC21/201939

More information

Chris Rumpf, Jess Thompson, Prem Kumar, Sharon Gray – Groundwater Management and Science

Acknowledgements

Cover image: Macleay coastal sands groundwater status sampling program, taken April 2019.

© State of New South Wales through Department of Planning, Industry and Environment 2021. You may copy, distribute, display, download and otherwise freely deal with this publication for any purpose, provided that you attribute the Department of Planning, Industry and Environment as the owner. However, you must obtain permission if you wish to charge others for access to the publication (other than at cost); include the publication in advertising or a product for sale; modify the publication; or republish the publication on a website. You may freely link to the publication on a departmental website.

Disclaimer: The information contained in this publication is based on knowledge and understanding at the time of writing (September 2021) and may not be accurate, current or complete. The State of New South Wales (including the NSW Department of Planning, Industry and Environment), the author and the publisher take no responsibility, and will accept no liability, for the accuracy, currency, reliability or correctness of any information included in the document (including material provided by third parties). Readers should make their own inquiries and rely on their own advice when making decisions related to material contained in this publication.

Executive summary

This report describes the status of the groundwater resources within the Macleay coastal sands groundwater source (MCSGS). The source is located on the mid-north coast of New South Wales (NSW), predominantly between Hat Head and Smokey Cape near South West Rocks. The groundwater source is within sediments deposited in aeolian, fluvial, marginal marine and marine environments.

The groundwater source is managed under the *Water Management Act 2000*, following the introduction of the water sharing plan (WSP) for the North Coast coastal sands groundwater sources in 2016.

There are two different categories of water access licences (aquifer access licence and special purpose access licence) within this groundwater source.

Groundwater extraction is predominantly for town water supply and domestic purposes.

There are 45 groundwater level monitoring sites within the groundwater source. Groundwater is monitored to measure and understand the impacts of groundwater pumping and climate variation on groundwater levels and quality.

This study involved the collection and analysis of samples from groundwater, surface water and rainwater, including 27 groundwater samples, six surface water monitoring locations of swamps and channels, and one sea water sample (site adjacent to a groundwater monitoring site). Groundwater and surface water are typically characterised as fresh, sodium-chloride type water.

Report findings indicate that groundwater elevations and flow respond to rainfall events and climatic variation and show little response to groundwater pumping under the current pumping regime. The monitoring bore data for groundwater level and chemistry (electrical conductivity or EC, total dissolved solids or TDS, and major ions) around the town water supply bores and throughout the MCSGS do not immediately indicate seawater intrusion impacts; however, longer-term water level and quality monitoring is required to validate this.

Contents

Figures

Tables

1. Introduction

The Macleay coastal sands groundwater source (hereafter MCSGS), is located on the mid-north coast of New South Wales, between the towns of South West Rocks to the north and Crescent Head to the south (**Figure 1**). It is centred near the township of Hat Head and covers a narrow, elongated strip along the coast with an area of approximately 179 square kilometres (km^2).

This report describes the location, climate and physical attributes of the coastal sands aquifer and explains its geological and hydrogeological context, environmental assets, groundwater quality and management. It also presents the current status of the groundwater resource covering groundwater rights, dealings (water trades), groundwater behaviour and modelling.

1.1. Description of water source

The water source area encompasses the coastal sands of the Macleay Coast from Crescent Head in the south to South West Rocks in the north, representing an area approximately 30 km in length and 4 km in width at its broadest point. The water source is characterised by dunal systems, the majority of which are within the Hat Head National Park. The National Park was reserved in 1972 and contains 7,220 hectares (ha) of coastal land.

The water source includes all water contained within all sand formations below the surface of the ground within the boundaries of this groundwater source, shown on **Figure 1**.

The MCSGS consists of coastal sands and gravels deposited by coastal advance and regression during periods of sea level fluctuations. The MCSGS can be up to 45 metres (m) thick and is overlain by and abuts the estuarine deposits of the coastal plain.

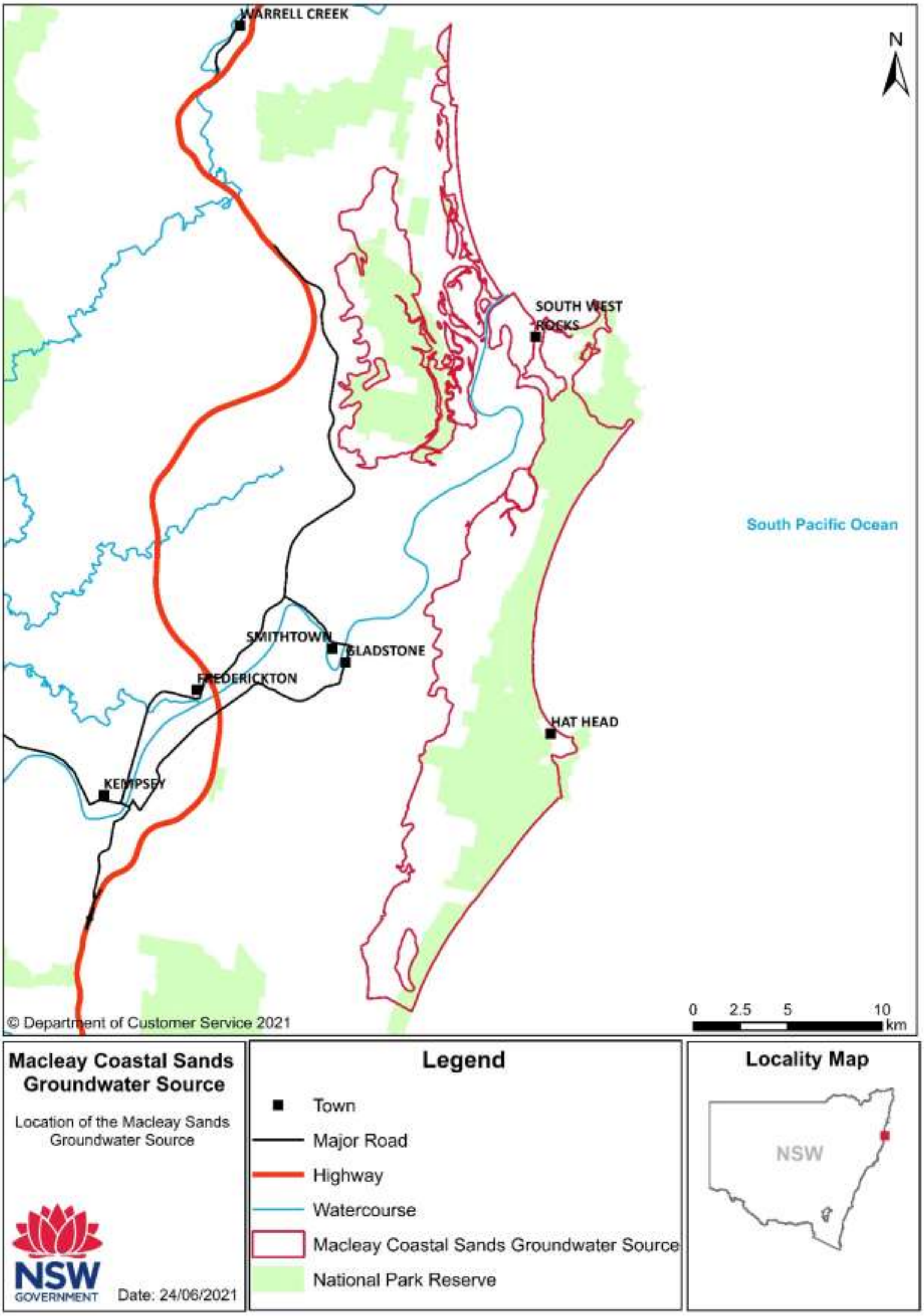


Figure 1. Location of the Macleay coastal sands groundwater source

2. Regional setting

2.1. Topography

The majority of the MCSGS is part of a Pleistocene barrier dunal system (Atkinson, G. 1999). High transgressive dunes can form ridges of up to 70 m in height (usually <30 m), surrounded by low-lying sand sheets, swales, and swamps. Surrounding Holocene units consist of recent beach landscapes and estuarine-influenced swamp landscapes (Atkinson, G. 1999), which have relatively low-lying relief of <5 m.

2.2. Climate

The climate at the MCSGS location is sub-tropical, experiencing warm summers and mild winters influenced by ocean temperatures. The hottest temperatures are between December and February, and the lowest in July. Annual rainfall is around 1,465 millimetres (mm) per year (Bureau of Meteorology - BOM) and the wettest months are February to April (

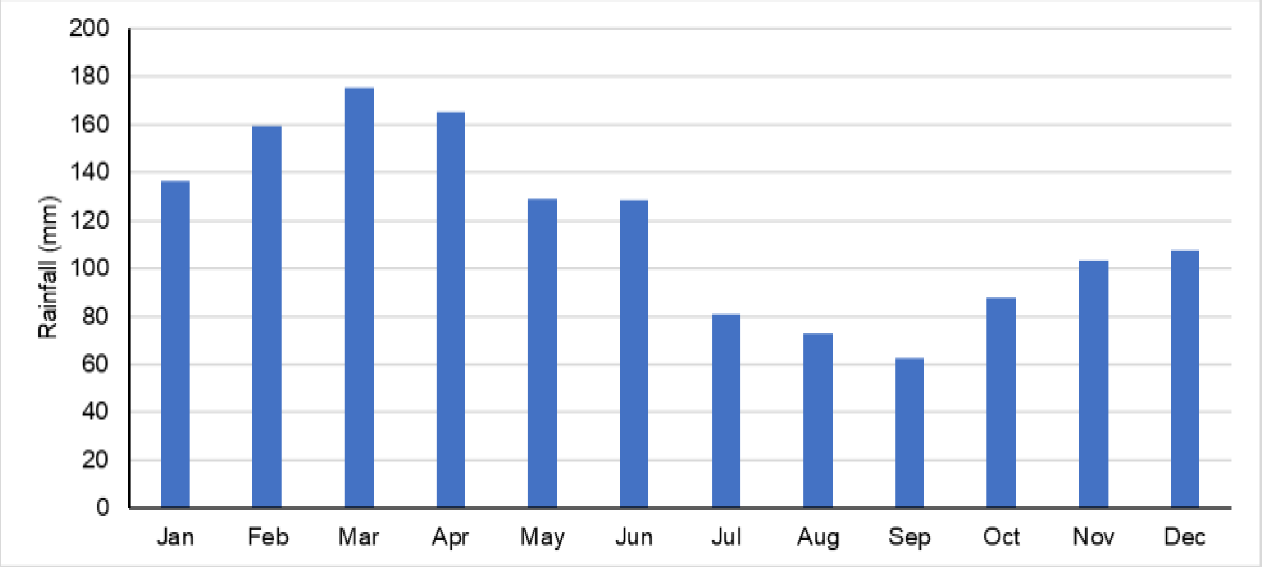


Figure 2).

MCSGS has experienced below average rainfall since 2017. This is observed by the cumulative rainfall departure curve shown in

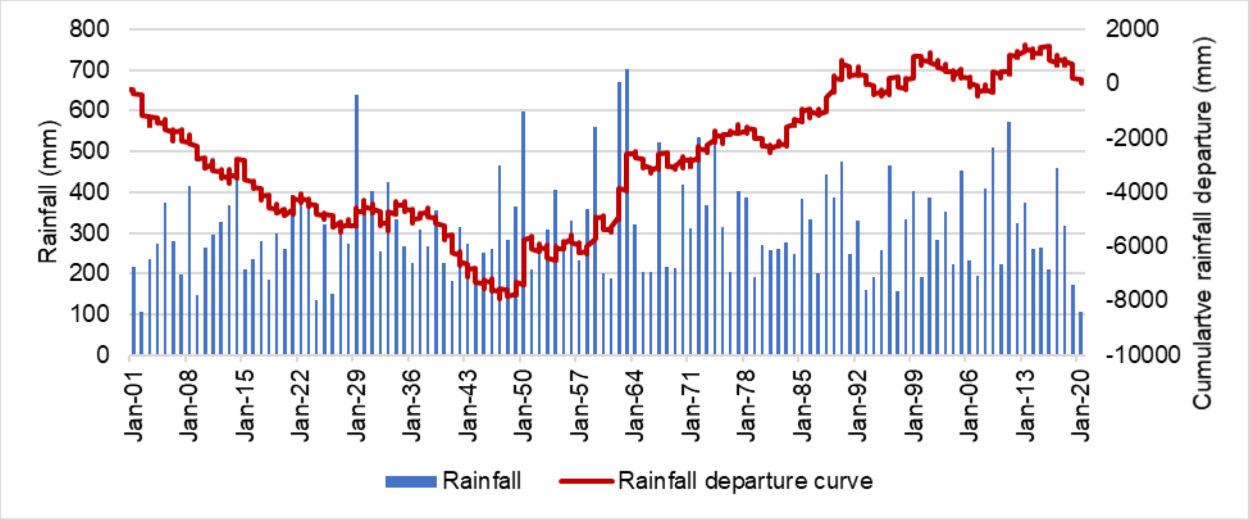


Figure 3. Monthly total rainfall depths since 2017 are shown in

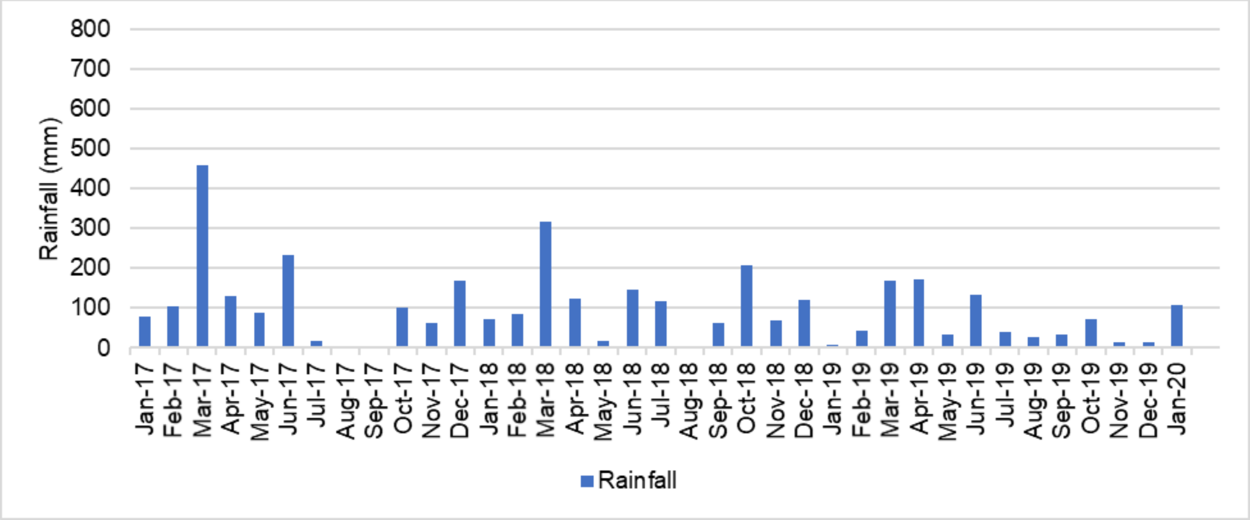


Figure 4.

From July 2017 to December 2019, eight months were recorded having rainfall below 20 mm per month. These significantly low monthly rainfall totals have resulted in low recharge rates occurring, as shown in hydrographs displayed in Section 7 of this report. The highest monthly rainfall depths since January 2017 was 460 mm in March 2017 and 315 mm in March 2018. The highest monthly rainfall in 2019 was 172 mm in April (

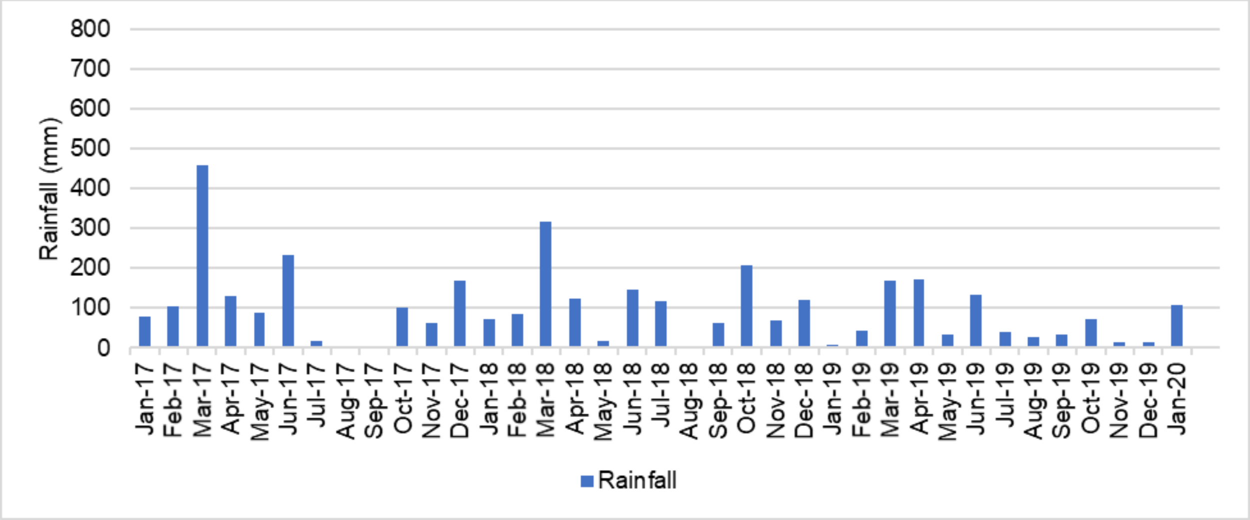


Figure 4).

Rainfall can be influenced by orographic effects associated with prominent land masses such as Smoky Cape. This coastal location is subject to strong winds and storms, as well as salt spray from the nearby ocean.

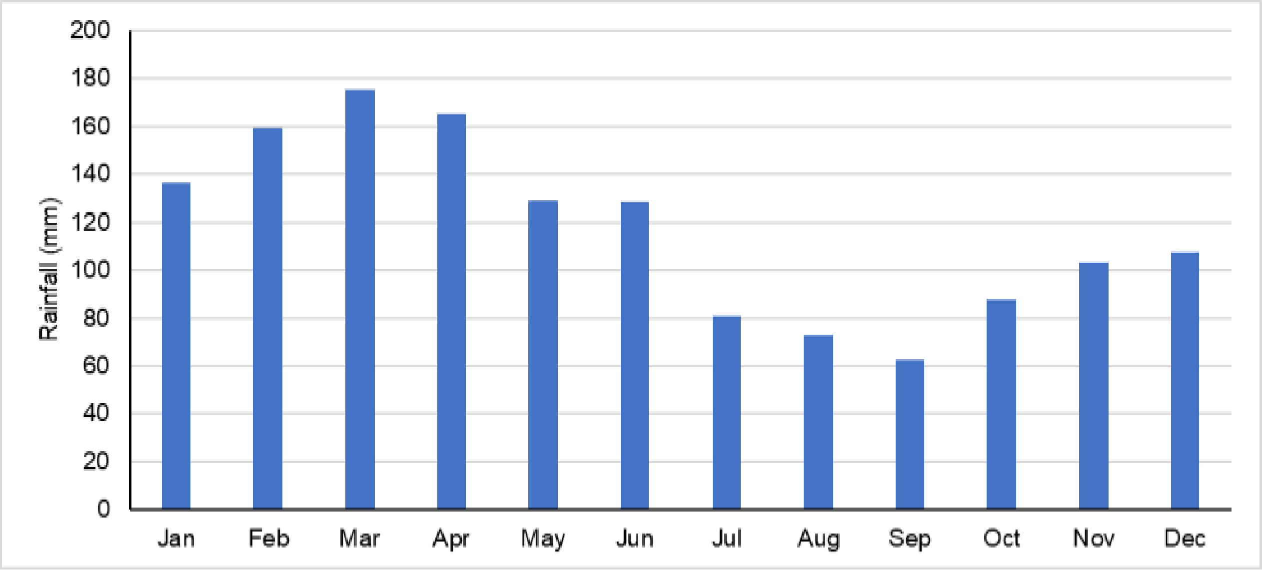


Figure 2. Average total monthly rainfall (BOM) for 1900 to 2020 for Smoky Cape (station 59030)

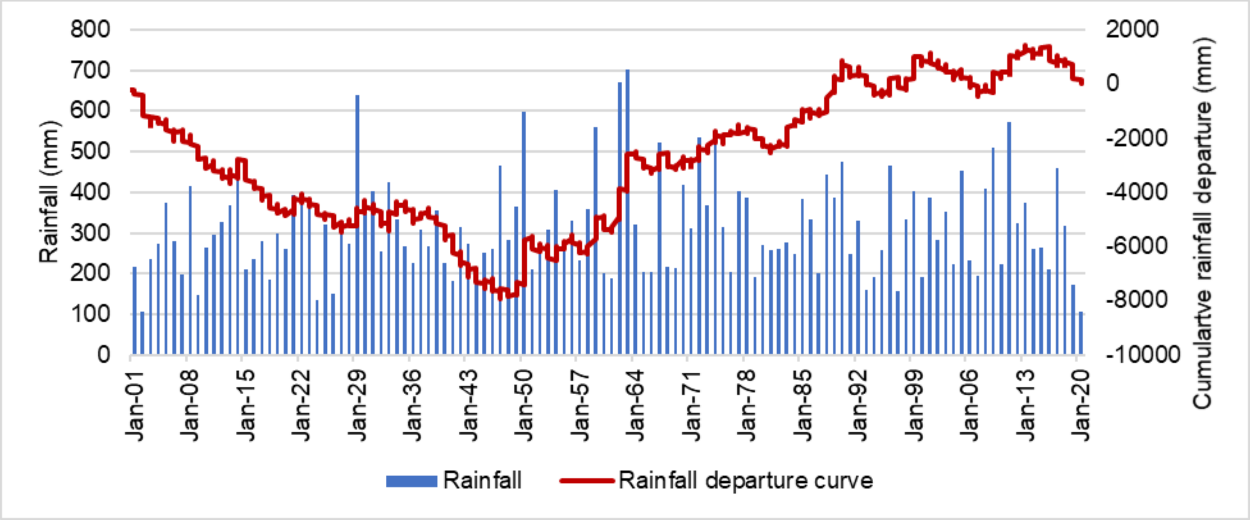


Figure 3. Rainfall cumulative residual mass and total monthly rainfall (BOM) for 1900 to 2020 for Smoky Cape (station 59030)

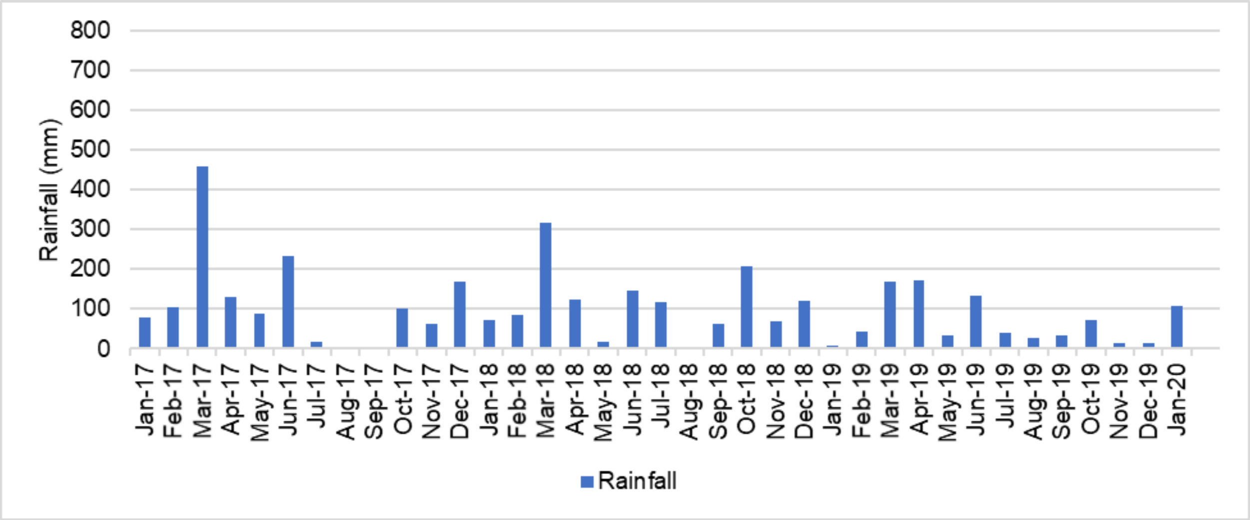


Figure 4. Monthly total rainfall depths (BOM) for 2017 to 2020 for Smoky Cape (station 59030)

2.3. Land use

Prior to European settlement from 1826, the Macleay valley was occupied by the people of the Dunghutti and Ngaku language group (Atkinson, 1999). The European settlers quickly cleared the land, primarily on the floodplains, for agricultural use.

The majority of the MCSGS is now part of the Hat Head National Park. Prior to declaration, the land was mainly poor grazing land or used for sand mining. Land use surrounding the national park consists primarily of grazing for dairy and beef cattle.

Several areas were mined in the 1950s and 1970s for mineral sands. Those are mainly between Hat Head and Crescent Head (Rollason. V. 2013, Kempsey Coastal Processes and Hazards Definition Study). Other areas have been mined for construction purposes.

3. Geology

The Macleay coastal sands are representative of much of the NSW coastal landscape, being characterised by long stretches of coastal sand dunes. These features are the present-day expression of a period of coastal depositional processes that took place during periods of rising, then falling, sea level. As the sea level rose, the dune system transgressed across the pre-existing land. Then, when it fell, another dune system was deposited on the earlier one as the shoreline moved back to the east (Thom et al., 1992).

A geological summary for the Macleay coastal sands is provided by Woolley et al (2011), which draws heavily on work undertaken by Troedson et al (2004), in NSW Coastal Quaternary Geology 2004, and earlier work of Roy (1998).

The coastal geology and geomorphology of NSW is largely the result of sea level fluctuations during the late Quaternary Period. During the latter part of this period, there were two major rapid sea level rises of just over 100 m, separated by a gradual decline of a similar amount. The final period of rise, from about 10,000 years ago to the present, is referred to as the Holocene Period, and the earlier period is the latter part of the Pleistocene Period.

There are numerous geomorphological features along the coast that have resulted from these sea level fluctuations during the late Quaternary Period, but for the present study the dune sands and associated geomorphic features, such as swales and back barrier swamps, are the most relevant. During the late Pleistocene sea level rise, coastal sand deposits were formed along much of the coastline as the sea progressed across the land surface and the shoreline migrated to the west. These deposits are now known as Inner Barriers. A second cycle of sand deposition during the Holocene created dunes that partially overlie the Pleistocene Inner Barriers on the seaward side and are known as Outer Barriers.

Together, these two dune systems can form a very large body of sand in coastal strips, but continuity between them is commonly interrupted by estuarine and/or alluvial material deposited during the late Pleistocene sea level decline. The situation is well illustrated in the cross-section in Figure 5 from Troedson et al (2004), which is a modified version of an illustration in an earlier Roy (1998) publication.

Where the juxtaposition of the Inner and Outer Barrier deposits has resulted in the accumulation of a large body of sand, there is a potential for the presence of a useful aquifer system. Such systems have been identified and are being used for water supply purposes at a number of locations along the NSW coast.

The initial progression of the coastline towards the west as the sea level rose, was across a landscape of estuarine flats. Consequently, the sand beds are commonly underlain by dark grey marine or estuarine clays, which were deposited in the estuaries along the coast prior to the commencement of the sea level rise that led to the earlier dunal deposits. The marine and estuarine clays formed the land surface over which the rising sea advanced and were themselves deposited on an older hard rock floor of essentially impermeable formations.

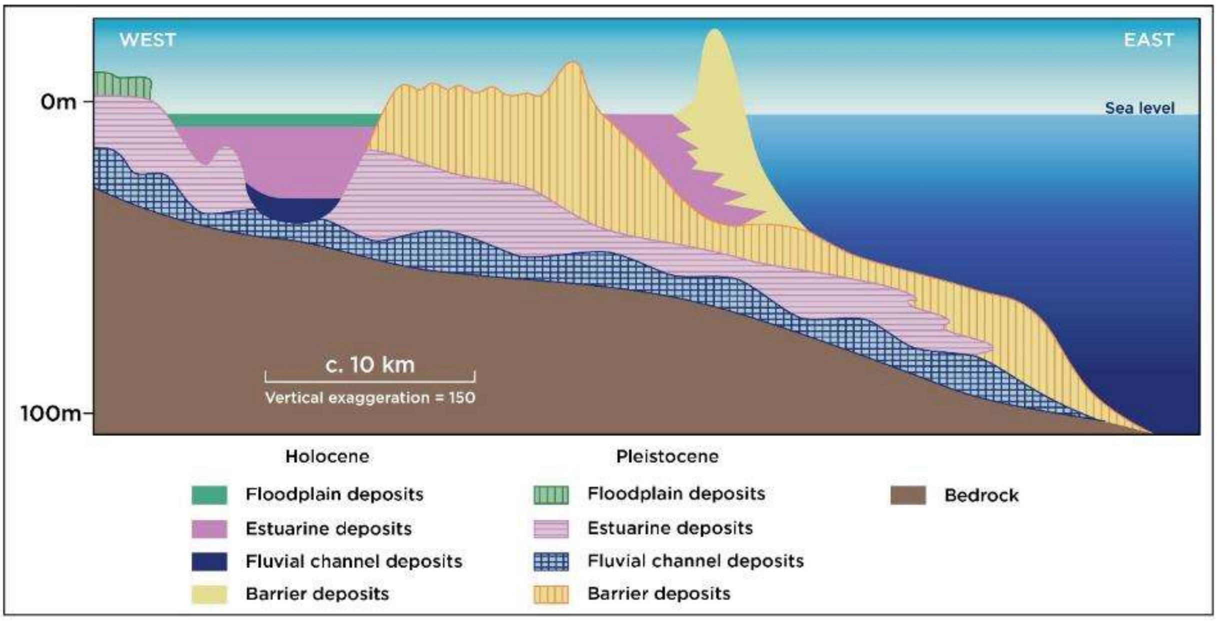


Figure 5. Generalised stratigraphic relationships between Quaternary coastal deposits in NSW, modified after Roy et al (1998) and Troedson et al (2004)

4. Hydrogeology

The coastal sand dune deposits support an aquifer system containing good quality water capable of delivering useful water yield. However, the degree to which groundwater can be used is constrained by the possible impacts on wetlands and local vegetation, and by the potential for landward movement of the saline water interface (seawater intrusion) along the coast that may be initiated by groundwater extractions. The dune sand aquifers are the source of town water supplies for several small towns. These aquifers are recharged only by rainfall. Groundwater from these sand aquifers discharges into local wetland areas and estuarine reaches of the rivers, flowing into the ocean and is lost by evapotranspiration.

The underlying hard rock geology consists of primarily Palaeozoic metamorphic rocks. The permeability and porosity are dependent on the degree of fracturing that has been imposed on the folded and/or metamorphosed sedimentary rocks. These rocks constitute the higher, hilly country and do not constitute aquifers with any significant potential for groundwater supplies suitable for town water or irrigation supply purposes.

A schematic representation of the conceptual hydrogeology of coastal sand aquifer systems is provided in **Figure 6**. There are several features common to all coastal dunal deposits. In NSW, coastal sand aquifer systems all border the Pacific Ocean and include an interface between the saline ocean water in the sand bodies beneath the sea floor and the fresh water in the dunes on the landward side of the shore. Generally, this interface is quite steep and does not move laterally either towards the sea or towards the land under natural circumstances. A high proportion of rainfall infiltrates into the aquifer (Ecoseal 2004). Driven by geomorphology, with linear ridges parallel to the coast, groundwater moves in a direction perpendicular to the coast. Groundwater then flows seaward and discharges on the landward side of the saline water interface (possibly in the intertidal zone or in linear swamps behind the beach). In some circumstances, such as where the dunes are very high, there will be a localised landward movement of groundwater, and swamps may be present near the landward toe of the dune ridges. The landward movement of groundwater is usually impeded or prevented by the underlying clay or rock formation, with much lower permeability than the sand. In some cases, these back-of-dune swamps will be connected to the sea and if these inlets are formed over the dunes, there will be a saline groundwater interface along their shore in the same way that one occurs along the sea beach.

Marine and estuarine deposits underlie a large area of the local coastal plain. The bulk of the shallow subsurface material beneath this plain to the west of the dunal system is composed of marine clay and silt in which there may be thin layers of marine sand in places. In some parts of the plain, a thin veneer of alluvial and aeolian deposits overlies the marine sediments. Along the course of the Macleay River, these alluvial deposits are somewhat thicker. The saline nature of the marine-derived sedimentary deposits in this zone, combined with a hydraulic connection to the tidal Macleay River, has resulted in many of the deposits underlying the coastal plain being likely to contain saline water.

Most of the underlying material is of low permeability and consequently has little potential for the development of useful quantities of groundwater, and any higher permeable zones are likely to contain saline water. Consequently, the prospects for the development of useful groundwater supplies from this zone is low. A minor possible exception is the occurrence of localised areas within the surficial deposits such as levee banks, where the permeability is a little higher than normal or where the deposits are thicker, allowing for an accumulation of low salinity groundwater at shallow depth. The groundwater available from these sources, however, is highly dependent on frequent recharge from rainfall and due to their limited spatial extent, small unreliable yields would be available at best.

With the range of lithologies making up the MCSGS, physical properties can be highly variable. The range extends from highly transmissive, well-graded sands to very low transmissivities within clays, silts and indurated sands. Punthakey (2011) reports previous studies with hydraulic conductivities ranging from 0.5 m/day to 82.3 m/day with transmissivities up to 482 m^2/day. Previous studies are reported to indicate specific yields in the range of 0.0008 to 0.21. Subsequent transient modelling undertaken by Punthakey (2011), resulted in calibrated hydraulic conductivities ranging from 0.4 m/day to 24 m/day and calibrated specific yields ranging from 0.05 to 0.21. It is noted that these figures are attributed to areas of testing which is typically borefield areas only.

The aquifer characteristics of the MCSGS are summarised in **Table 1**.

Table 1. Aquifer characteristics of MCSGS

Water bearing zone	Geological age	Aquifer type	Groundwater flow direction	Physical properties (modelled)	Recharge	Yield	Electrical conductivity
Up to 50 m depth	Holocene – Pleistocene	Unconfined shallow units. Intermittent semi-confined by clay and iron indurated sediments.	West to east, towards the ocean for intermediate flow. Local flow is dependent on topography.	Hydraulic Conductivity 0.4 to 24 m/day Specific Yield: 0.05 to 0.21	70,000 ML/yr	Up to 30 L/s for thick dunal sand deposits	154 to 3,870 µS/cm. Variable depending on proximity to estuarine water sources.

Source: North Coast Coastal Sands Groundwater Sources 2016, Punthakey (2011) Woolley et al (2011), Hydstra groundwater bore database (WaterNSW).

5. Groundwater-dependent ecosystems

Coastal sand groundwater systems often support wetlands, terrestrial vegetation and hypogean ecosystems (Woolley et al, 2011). These communities have developed over thousands of years and have adapted to the natural variation in groundwater levels and quality (**Figure 6**). Whilst not all groundwater-dependent ecosystems (GDEs) are fully groundwater-dependent, groundwater is important to most of them in periods of low rainfall. An important example of this is the coastal Melaleuca communities. The figure below shows an example of a wetland, which in this case is a window to the groundwater, numerous examples of which occur within Hat Head National Park. Many wetlands can include areas of potential acid sulphate soils if composed of Holocene-aged material. High water tables are required to prevent the exposure of iron sulphate minerals to the atmosphere, which can oxidate and become acidic and toxic.

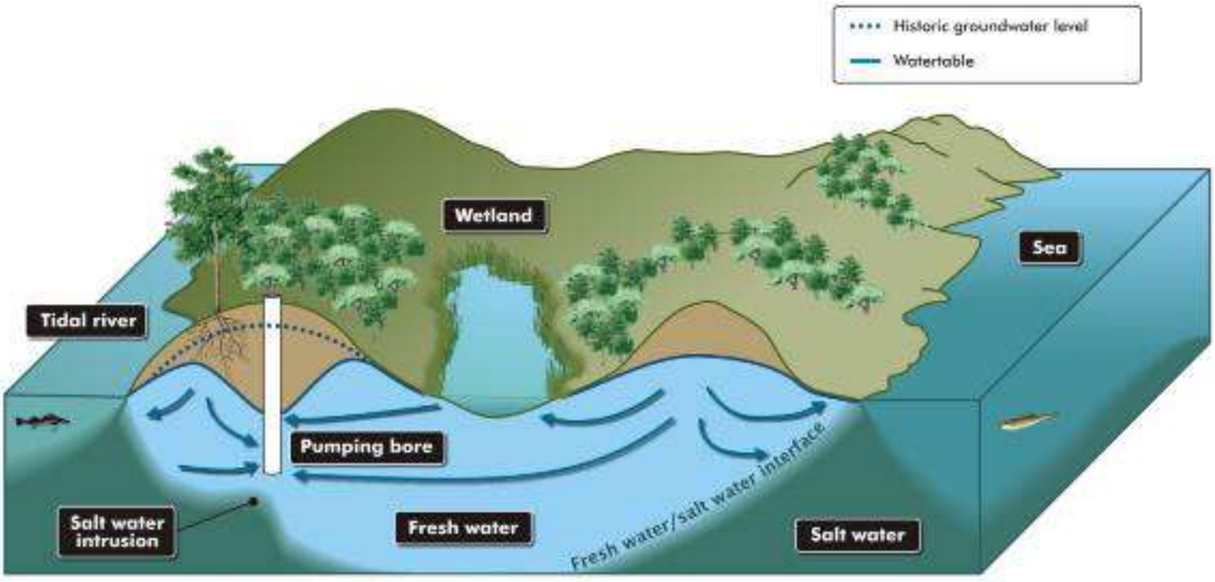


Figure 6. Schematic of coastal sand aquifer with wetland and pumping bore, located close to a saltwater source (DLWC 2002)

Much of the vegetation within the MCSGS area has some degree of groundwater dependence; however, very little appears to be at moderate to high risk from watertable fluctuations (Gow 2011). High-risk areas are those that have either been identified as highly groundwater-dependent vegetation communities (for example, sedgeland) or vegetation communities that have less groundwater dependence, but groundwater level fluctuations would shift the watertable beyond the maximum rooting depth of these species.

Pumping groundwater in such areas could have detrimental effects on vegetation if combined with a general reduction in precipitation and soil moisture. Much of the vegetation within the study area is dependent on groundwater to some degree, thus declining watertable levels could impact on vegetation health.

The water sharing plan covering the MCSGS has identified high-priority GDEs. These are all currently associated with State Environment Planning Policy (SEPP) 14.

6. Groundwater management

6.1. History of groundwater management

Early management of groundwater within the MCSGS was under the *Water Act 1912*. Under this Act, water entitlements were linked to land rights. Licences for bores and wells were granted for a fixed term with no restriction on the volume that could be extracted. During this time, the value of the groundwater source was not recognised due to a lack of demand. The overlying land was considered unsuitable for most primary production opportunities, except for cattle grazing, which was maintained by surface water supplies.

During the late 1960s, Kempsey Shire Council installed several bores within the MCSGS to supply water to the towns of South West Rocks, Hat Head, and Crescent Head.

During the 1970s, all irrigation, commercial and town water supply licences became renewable on a 5-year basis. Town water supplies were issued with a volumetric allocation, whereas irrigation and commercial licences were issued a volume based on area. This was subsequently changed to a policy that determined volume based on need (1990s).

During the drought of the mid 1990s, Macleay Water (Kempsey Shire Council) and the NSW Government installed an emergency borefield at Kinchella along Hat Head Road. This borefield is licensed to supplement the local town water supply when required.

In 1998, the NSW Government released a state-wide Aquifer Risk Assessment for which the Macleay coastal sands (Groundwater Management Area –GWMA – 035) was assessed to be an aquifer at ‘high risk’ from water level and water quality impacts. This high risk was due to several factors, primarily being:

- small groundwater flow system
- potential for existing extraction to draw in high salinity water
- the reliance of groundwater-dependent ecosystems on access to groundwater.

Following on from the aquifer risk assessment, a state-wide amnesty was put in place for a 2-month period to allow unlicensed surface water and groundwater use to be identified and licensed. This process resulted in only a minor increase in licensed access within the MCSGS.

In recognition of the high-risk classification of the MCSGS, between 2007 and 2009 the NSW Government developed a project to install monitoring bores at 38 sites across the MCSGS and undertake water and soil chemistry analysis.

The monitoring bores are owned by WaterNSW and Kempsey Shire Council. Many of these bores are installed with continuous water level loggers and electrical conductivity is monitored in some bores.

6.2. Current management

Groundwater in the MCSGS is managed under the Water Sharing Plan for the North Coast Coastal Sands Groundwater Sources 2016, which commenced on 1 July 2016.

The plan establishes the rules for water sharing between the environment and consumptive users. This is legislated by the *Water Management Act 2000*.

6.3. Groundwater access rights and limits

Groundwater access licence volumes for the MCSGS are shown in **Table 2** below**.**

Table 2. Groundwater access licence volumes

Access licence category	Volume
Local water utility (ML/year)	4,480
Aquifer (unit shares)	22

6.4. Extraction limits

The Water Sharing Plan (WSP) for the North Coast Coastal Sands Groundwater Sources establishes the extraction limit for the groundwater source. The long-term average annual extraction limit for the Macleay coastal sands groundwater source is equal to the estimated long-term average rainfall recharge, minus the amount of recharge reserved as planned environmental water.

The planned environmental water for the MCSGS is equal to 75% of the long-term average annual rainfall recharge in areas that are not high environmental value areas and 95% of the long-term average annual rainfall recharge in high environmental value areas.

At the commencement of this WSP, the long-term average annual rainfall recharge for the MCSGS is estimated to be:

- 39,000 megalitres per year in those areas that are not high environmental value areas
- 31,000 megalitres per year in high environmental value areas.

Extraction in a groundwater source is managed to the long-term average annual extraction limit (LTAAEL) set by the water sharing plan. The long-term average annual extraction limit for the Macleay coastal sands groundwater source is 11,300 ML/year.

6.5 Available water determination and groundwater accounts

An available water determination (AWD) is a volume of water that is made available to access licence holder accounts. An AWD is issued for each licence category within a water source at the commencement of each water year. It is the main tool that is used to ensure that average water extraction does not exceed the long-term average annual extraction limit.

If the average annual extraction in the groundwater source in the preceding three water years has exceeded the long-term average annual extraction limit established in the WSP by 5% or more, then the available water determinations for aquifer access licences are to be reduced for the following water year. This has not occurred for the MCSGS.

Any reduction is to be of an amount that is, in the Minister for Water’s opinion, necessary to return the long-term average annual extractions in the groundwater source to the long-term average annual extraction limit established in the water sharing plan.

Total water availability in a water year is controlled by the available water determinations credited to an access licence account. Carryover of unused account water from one year to the next is not permitted. This means that metered extraction plus transfers out cannot exceed the AWD unless water is transferred in.

6.6 Groundwater take

There are approximately 120 registered bores made of (43 production and 66 Basic Landholder Rights – BLR) in the MCSGS. Most are for stock and domestic supply. BLR bores are typically utilised to supplement existing supplies such as town or rainwater, for gardens or non-potable supplies and for household use. Most production groundwater extraction is for town water supply with less than 1% for irrigation **Figure 7** shows the distribution of water supply bores accessing the groundwater resources. The use is currently not metered.

Nearby seaside towns including South West Rocks in the north, and Hat Head and Crescent Head to the south, extract their town water needs from the MCSGS.

Extraction is through four borefields located 3 km to the south of South West Rocks, 1 km to the west of Hat Head, at Kinchella 4 km to the north-west of Hat Head, and at Maguires Crossing 7 km to the north of Crescent Head (**Figure 7**).

South West Rocks, Hat Head, and Crescent Head have approximate populations of 4,600, 300, and 1,500 respectively (2016 Census), with additional small numbers in outlying localities totalling approximately 7,000 people.

Due to the popularity of these locations with holidays makers, the population approximately doubles during peak holiday periods. These townships are reliant on the MCSGS, which require additional water supply during summer and holiday periods. This increases extraction pressure to the aquifer.

6.7 Groundwater dealings

Under the *Water Management Act 2000*, dealings are permitted in access licences, shares, account water and the nomination of supply works.

Trading may occur within, but not between, individual groundwater sources. There are no trade-restricted areas defined in the MCSGS.

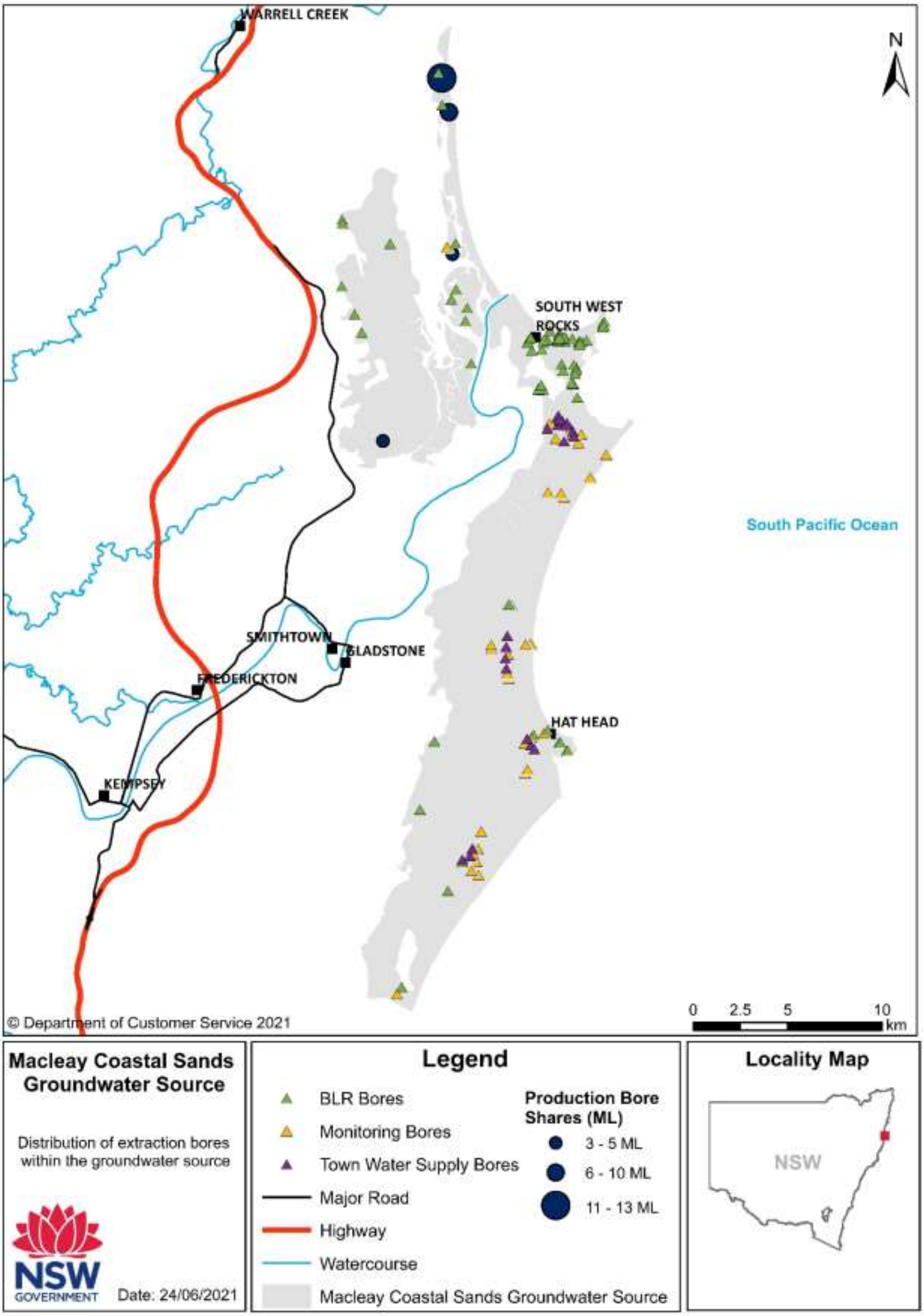


Figure 7. Distribution of bore use within the MCSGS

7. Groundwater behaviour

7.1 Groundwater monitoring network

Limited monitoring bores were installed during the 1980s to assist with the management of the town water supply extraction.

The monitoring network was expanded during the 2000s to monitor the three existing bores fields and the groundwater within the Hat Head National Park. Thirty-eight new monitoring bore sites and the refurbishment (where possible) of the existing monitoring bores occurred between 2007 and 2012.

The monitoring bore network is designed to monitor the impacts of extraction for town water supply on GDEs, saltwater intrusion and water quality. It aims at establishing a long-term record of water level behaviour within the MCSGS. Of the 38 bore sites now existing, 26 sites containing 43 bores are operated by WaterNSW, and 12 sites containing 19 bores are owned by Kempsey Shire Council. A map of the monitoring bores used for this study is shown in **Figure 8**. **Figures 9 to13** show individual borefields.

7.2 Groundwater levels

Groundwater level variation over time is shown in hydrographs for six sites from across the MCSGS. These are displayed in the figures below. Each hydrograph is displayed on the same interval scale for comparison. In general, the hydrographs show strong positive correlation with rainfall variation.

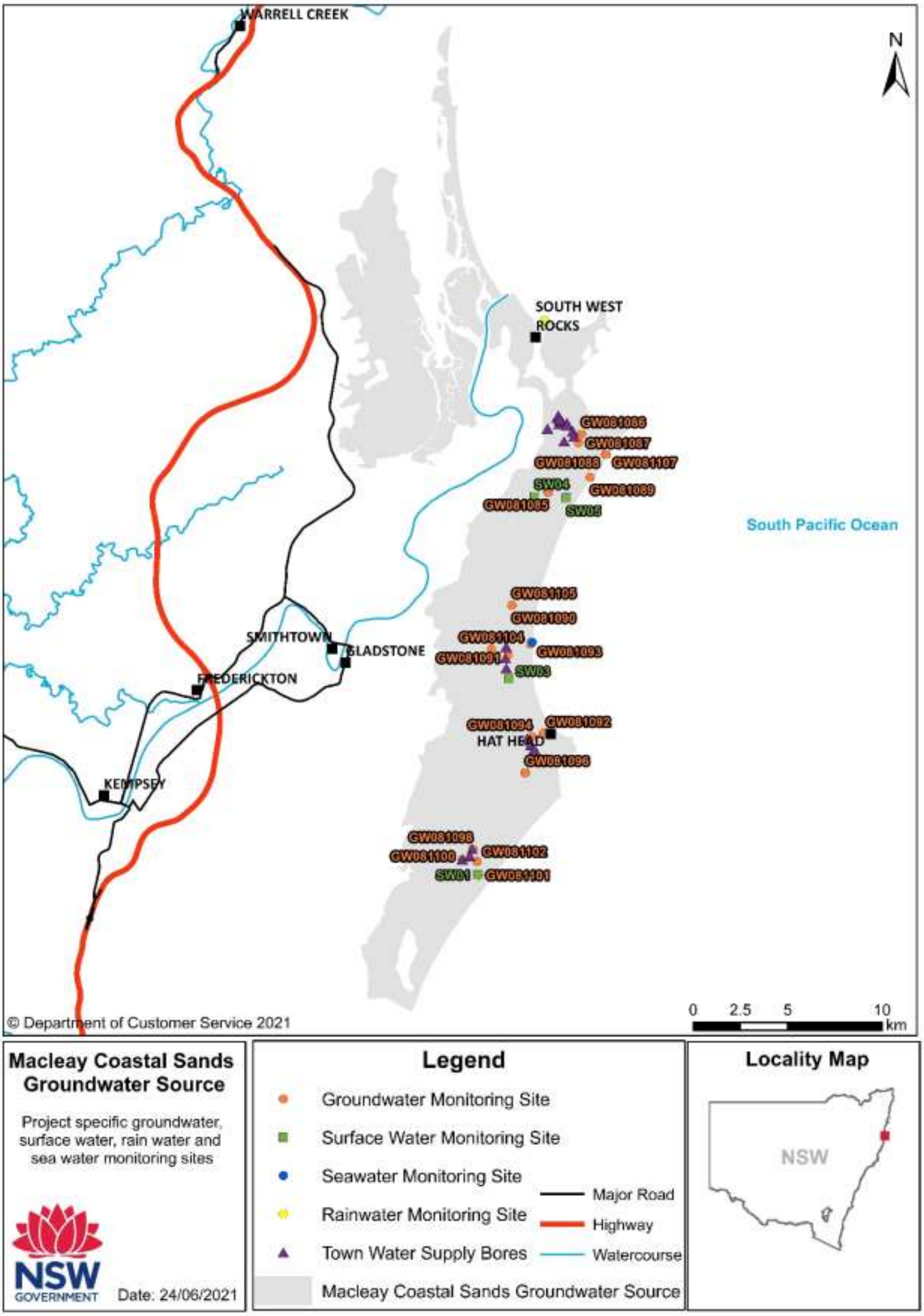


Figure 8. Location of monitoring bores, surface water and seawater sites used for this project

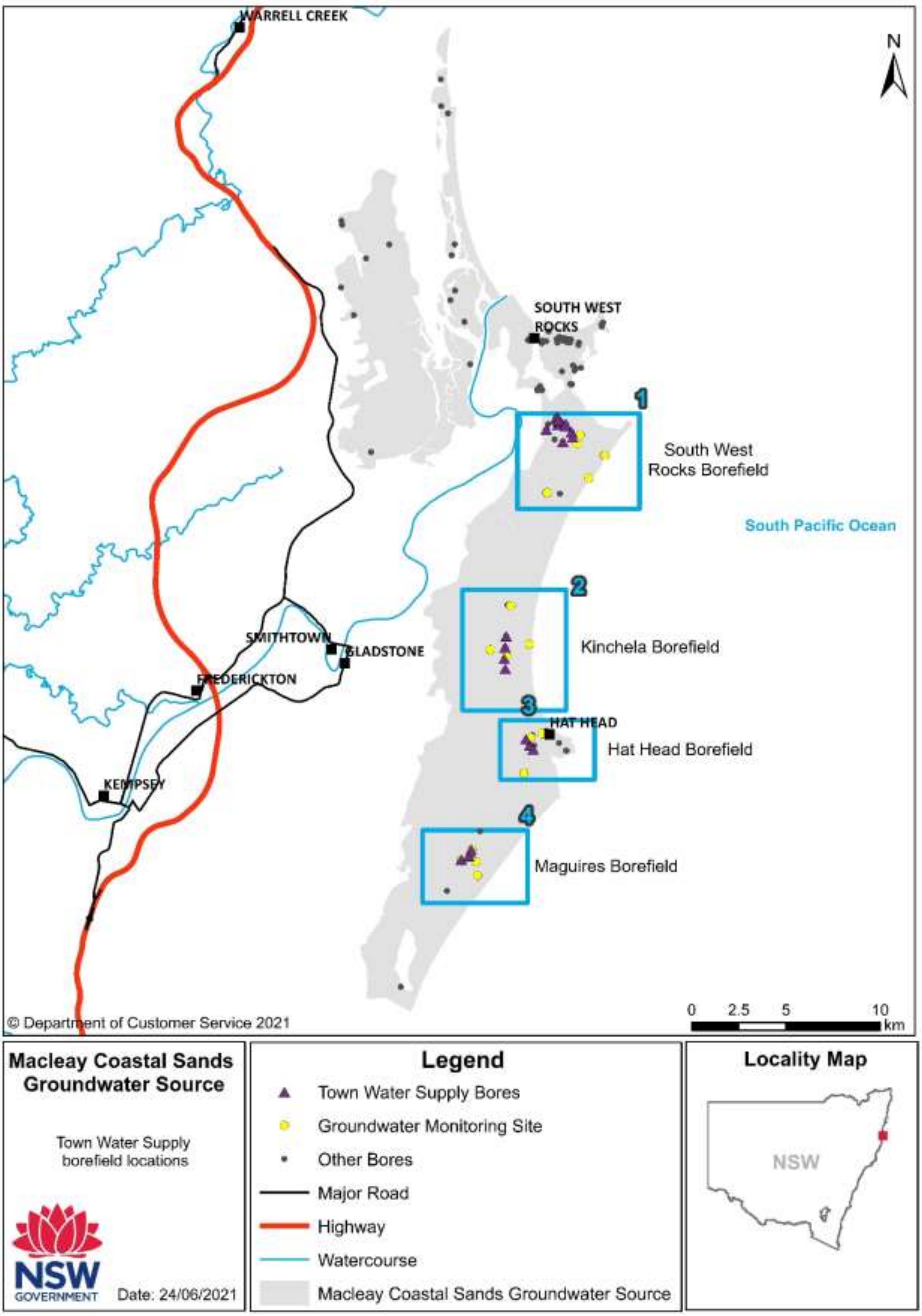


Figure 9. Borefield locations for town water supply

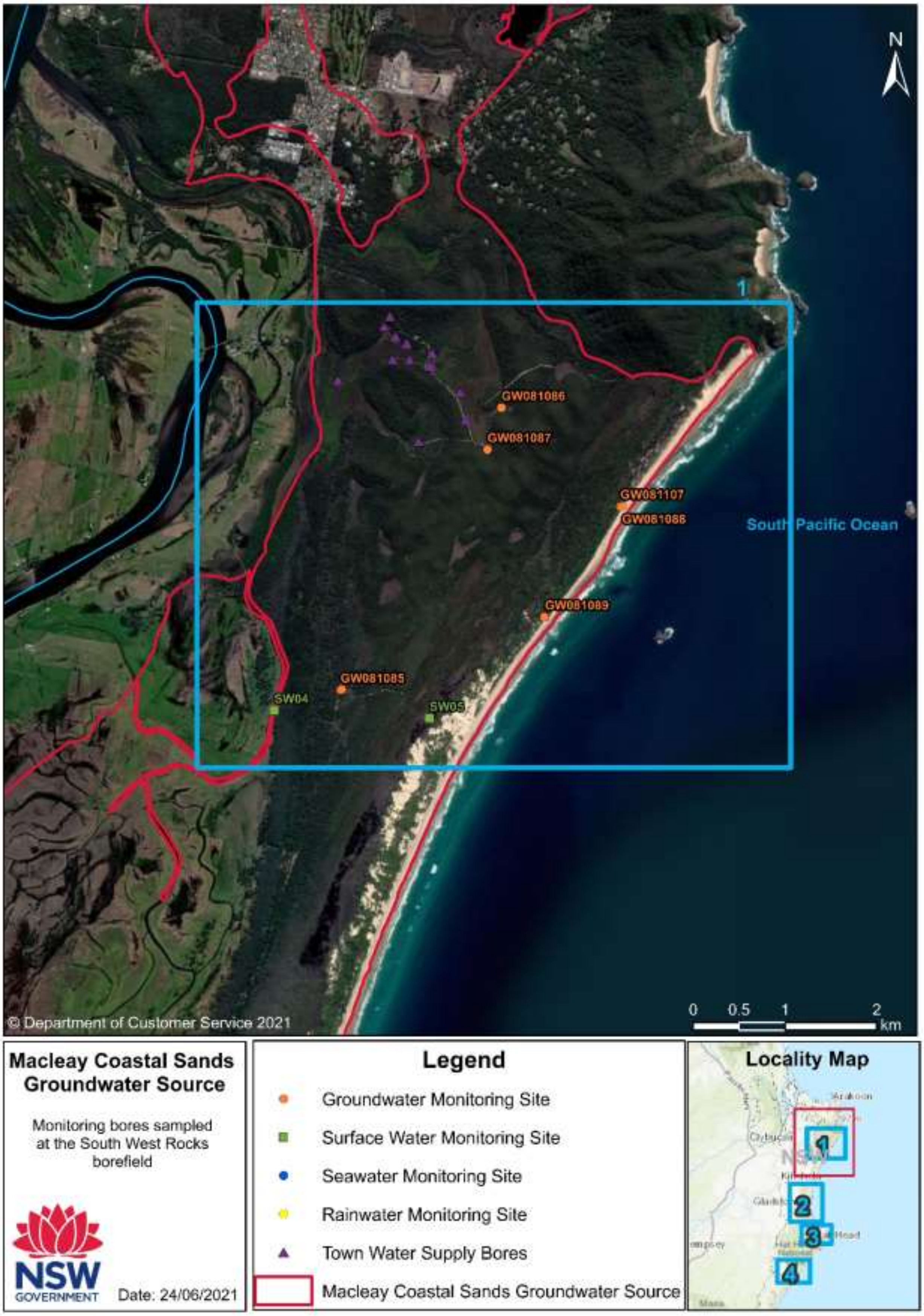


Figure 10. Monitoring bores sampled at the South West Rocks borefield

Figure 11. Monitoring bores sampled at Kinchella borefield

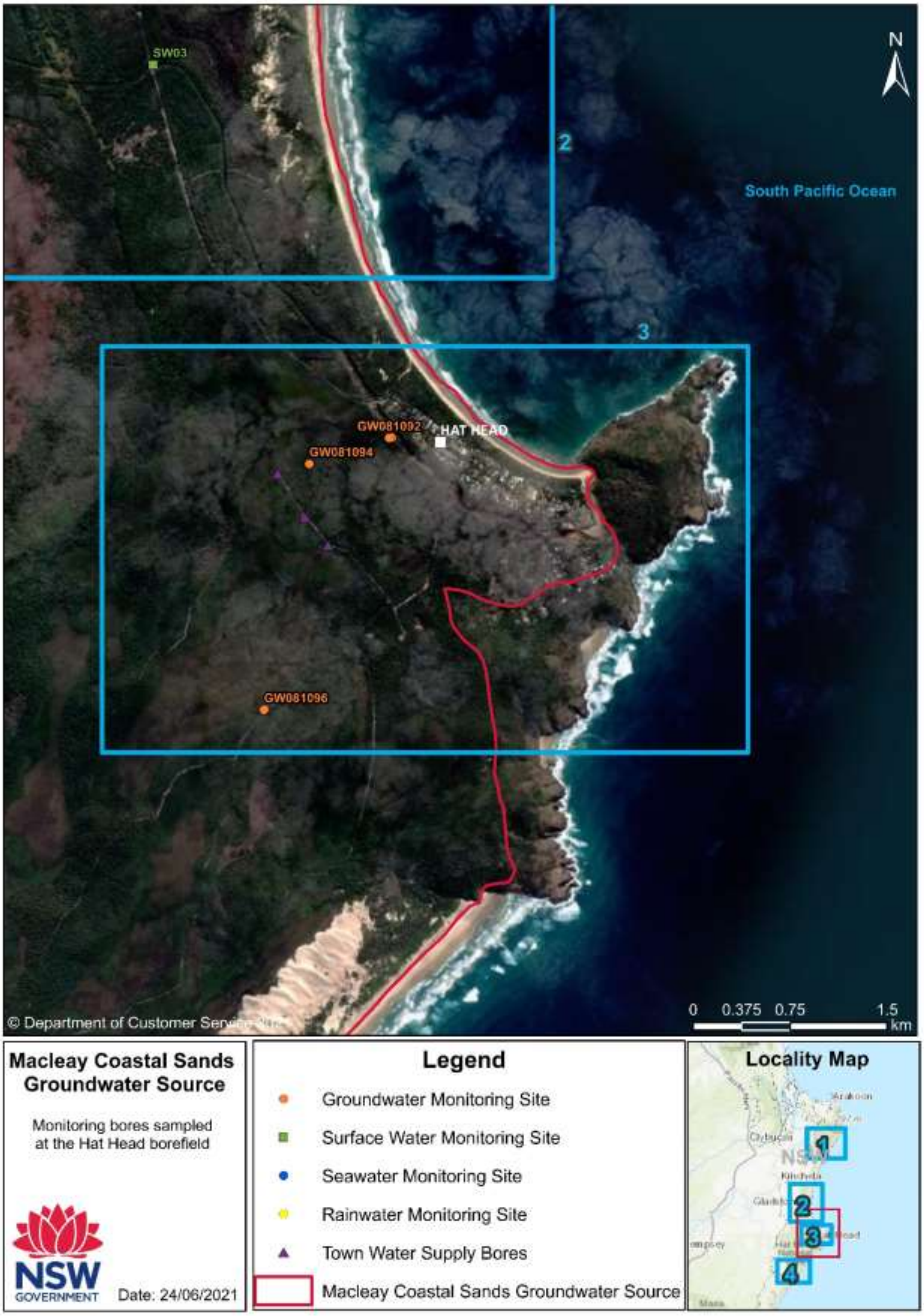
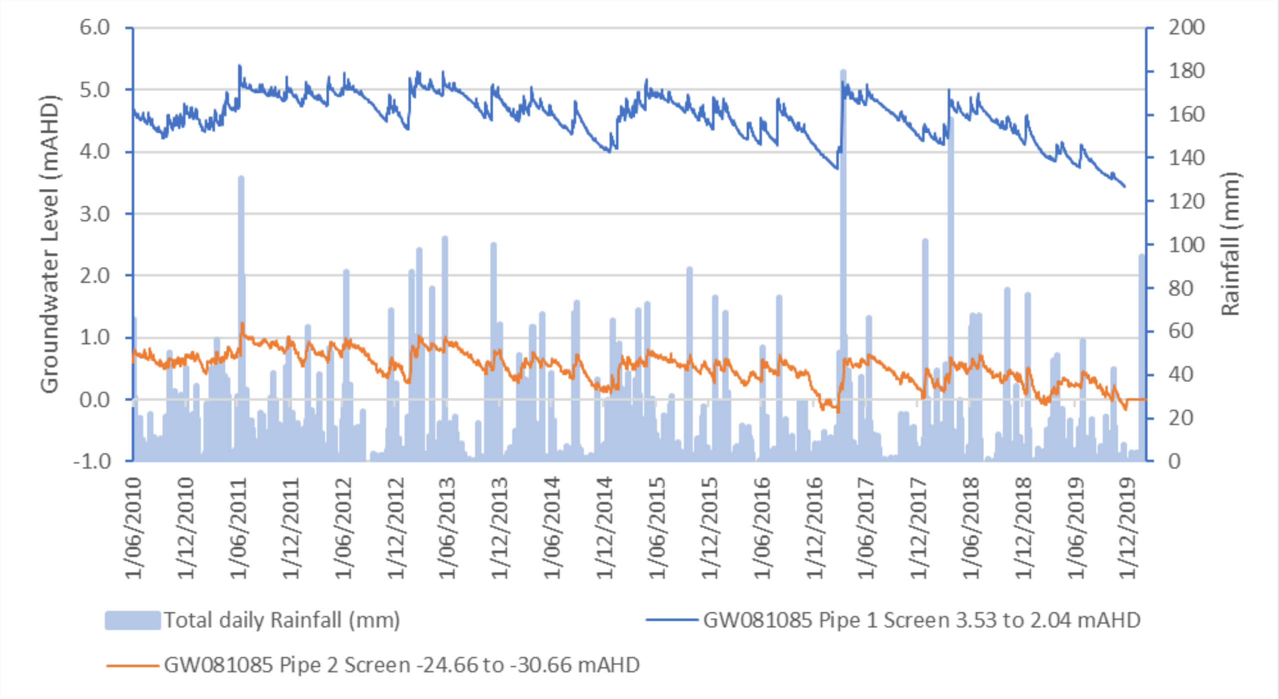


Figure 12. Monitoring bores sampled at Hat Head borefield

Figure 13. Monitoring bores sampled at Maguires (Crescent Head) borefield

The shallow monitoring bores show a direct response to rainfall. When rainfall is high, groundwater levels rise in quick response and decline during periods of no rainfall. There is minor evidence from the influence of pumping bores, however, that this is significantly outweighed by the natural rainfall variation in this area, which has rising water levels typically during summer and early spring and falling water levels during winter and autumn.

Monitoring bore GW081085 is located between South West Rocks and Kinchella borefields. The hydrograph (**Figure** 14) shows the typical seasonal fluctuations due the wet and dry periods. Impacts of pumping from the Kinchella borefield are not observed. The seasonal fluctuation in the deep bore is more subdued than the shallow bore, suggesting that the deep aquifer is semi-confined.



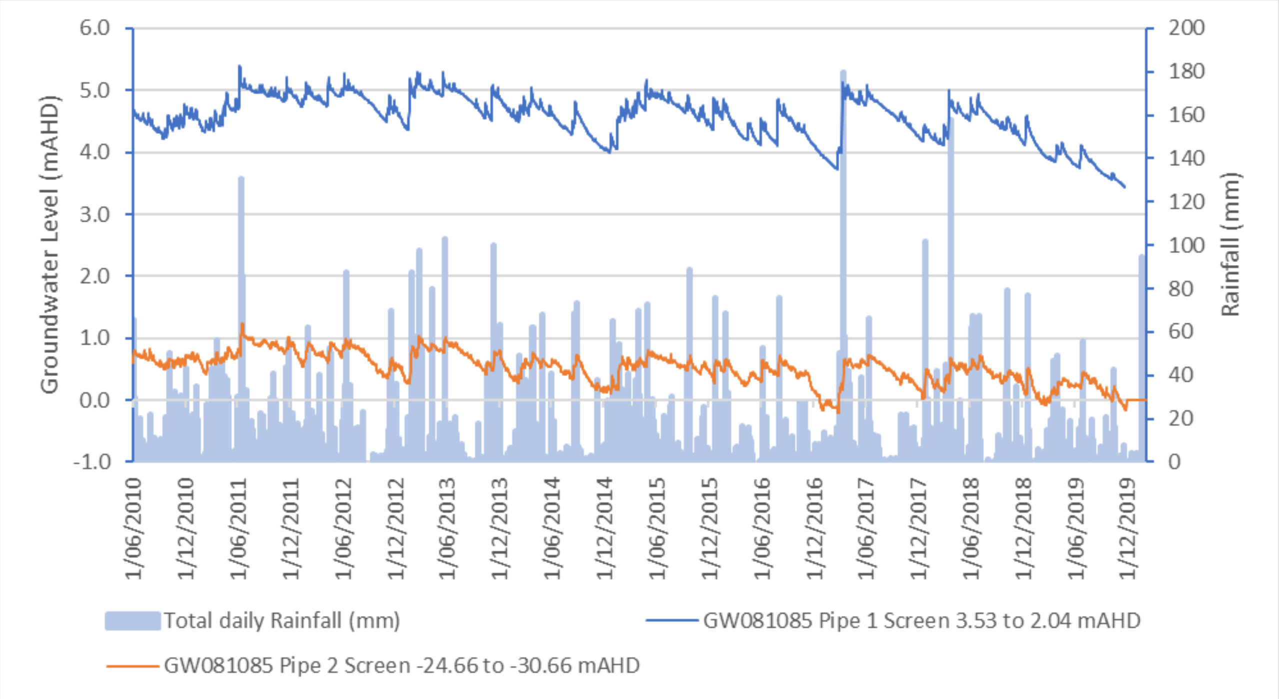
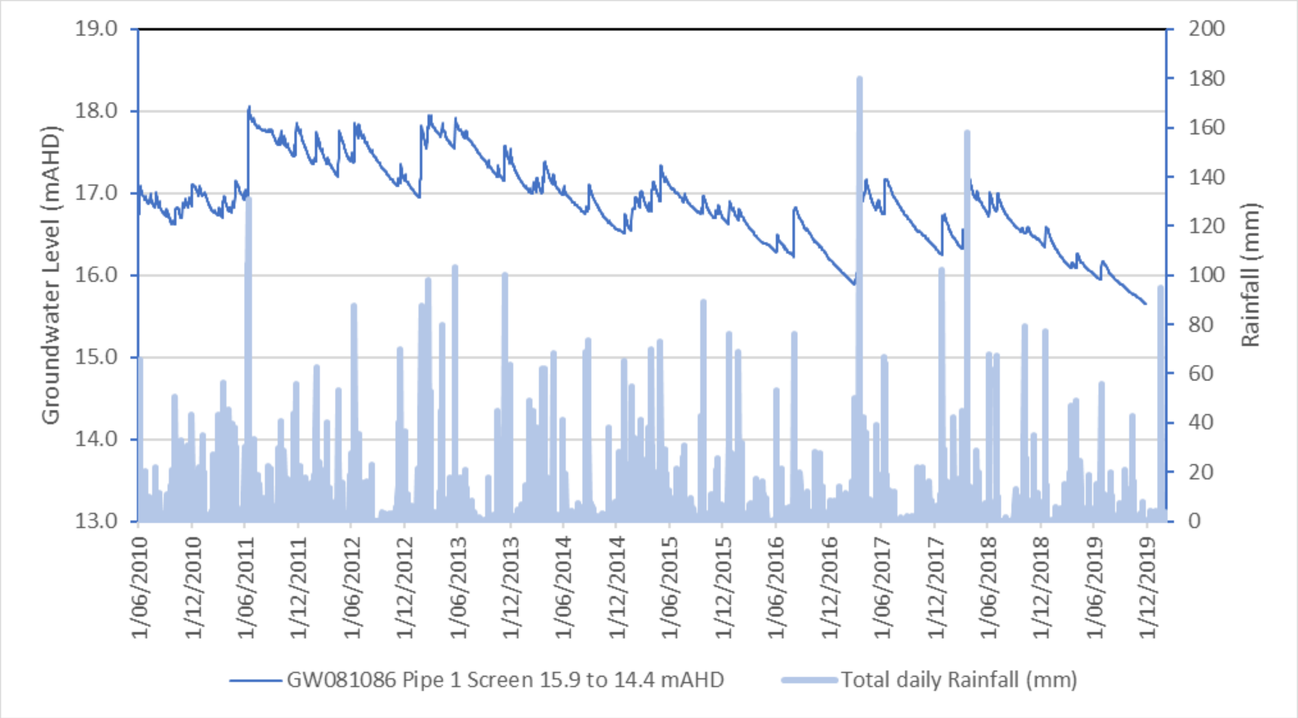


Figure 14. Hydrograph for monitoring bore site GW081085 (South West Rocks)

Monitoring bore GW081086 is located to the south-east of the South West Rocks borefield. The hydrograph (**Figure** 15) for this shallow bore shows the typical seasonal fluctuations of groundwater levels on the north coast. Water levels rise with recharge occurring near the beginning of the year (during the high rainfall season), then decline during the dryer period towards the end of the year.



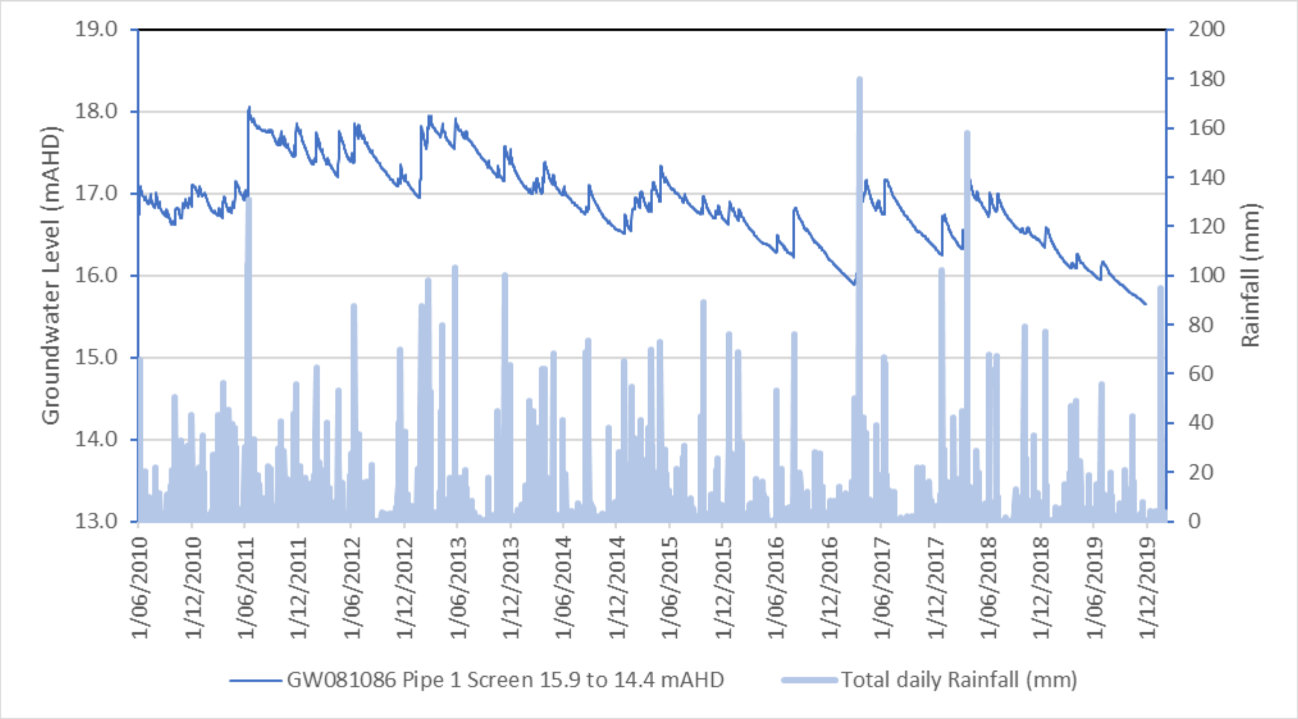
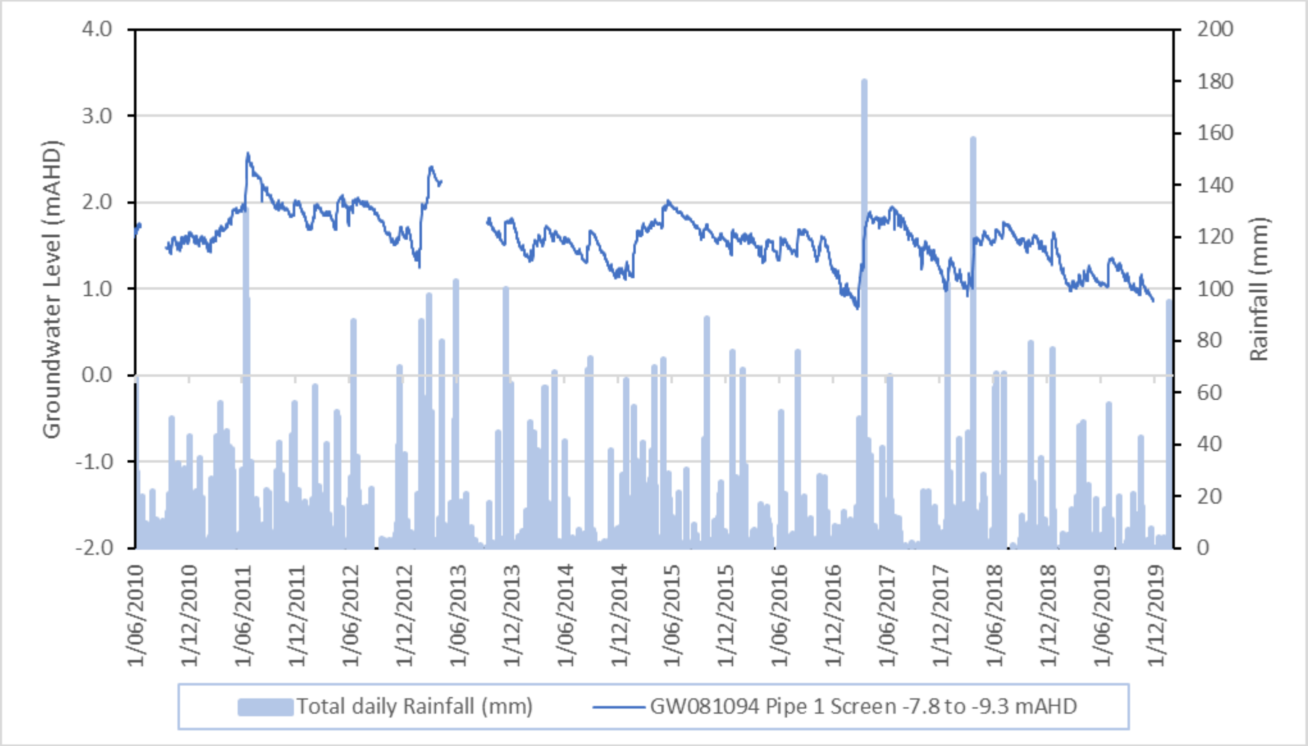


Figure 15. Hydrograph for monitoring bore site GW081086 (SE of South West Rocks borefield)

Monitoring bore GW081094 is located to the immediate east of the Hat Head town borefield. Whilst the hydrograph (**Figure** 16) shows the general seasonal fluctuations, there are very small-scale peaks and troughs. These are believed to be a result of the routine water supply pumping of the Hat Head borefield. This indicated that the shallow location of this monitoring bore is in connection with the deeper aquifer being accessed for the town water supply.



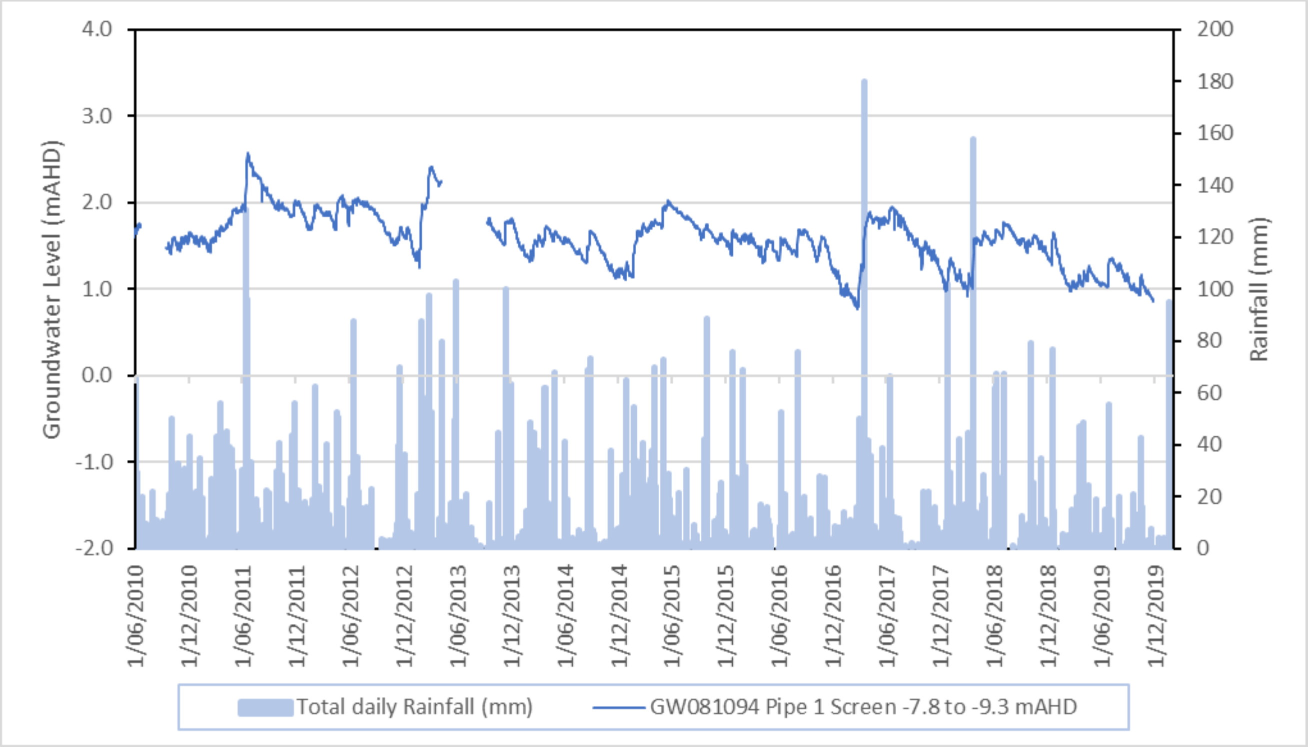
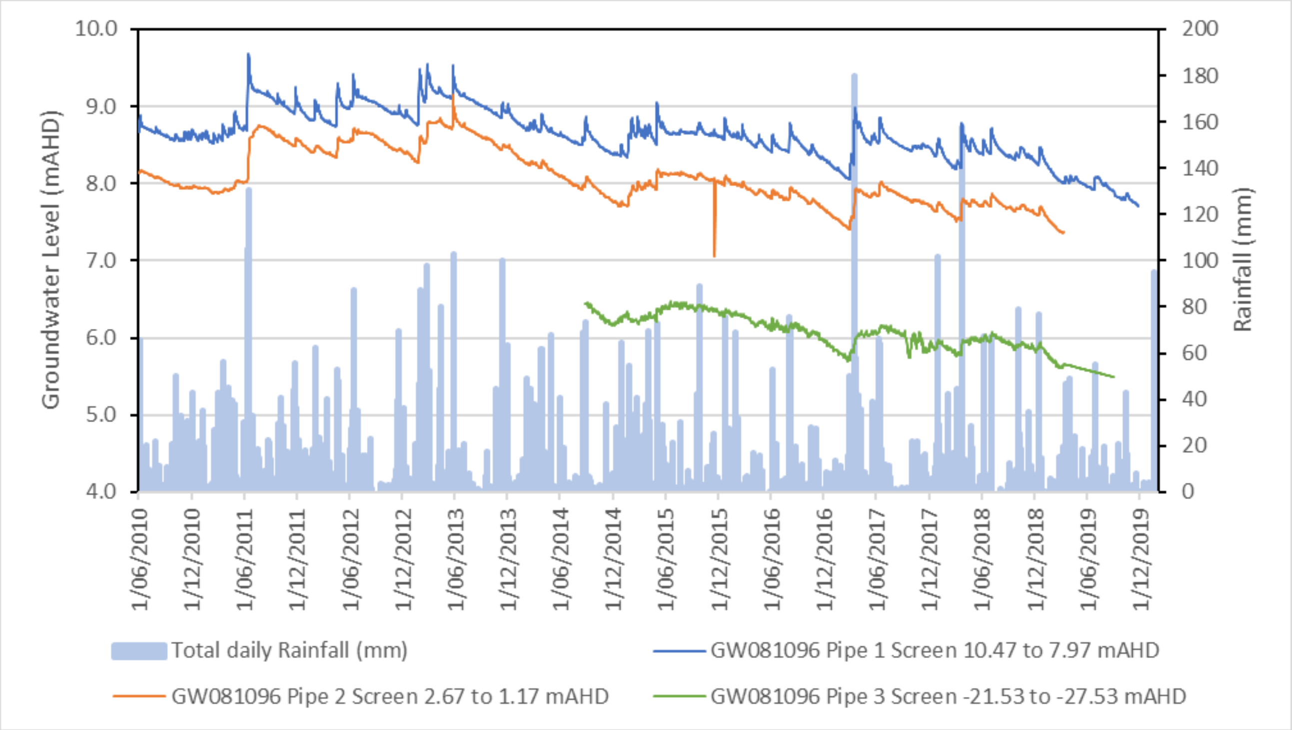


Figure 16. Hydrograph for monitoring bore site GW081094 (East of Hat Head borefield)

Monitoring bore GW081096 is in an area between the Hat Head and Crescent Head borefields. There are three monitoring bores (pipes) at this site. Impacts from pumping are not observed. As can be seen in the hydrograph (**Figure** 17), there are three separate levels with similar patterns, again indicating semi-confined conditions. Water levels in the deepest bore (pipe) do show some seasonal variations, indicating its connectivity with the shallow aquifers at this site. Also evident is the historically low water table of the millennial drought with rapid recovery in late June.



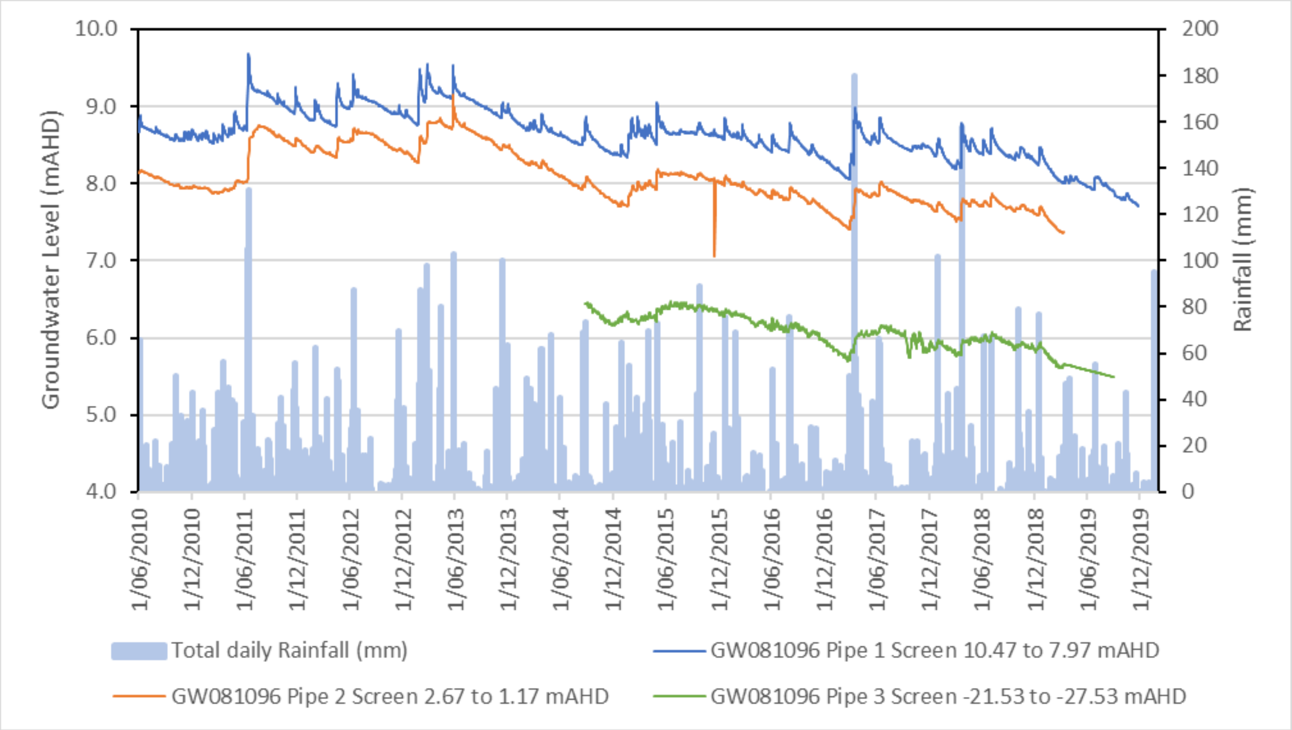
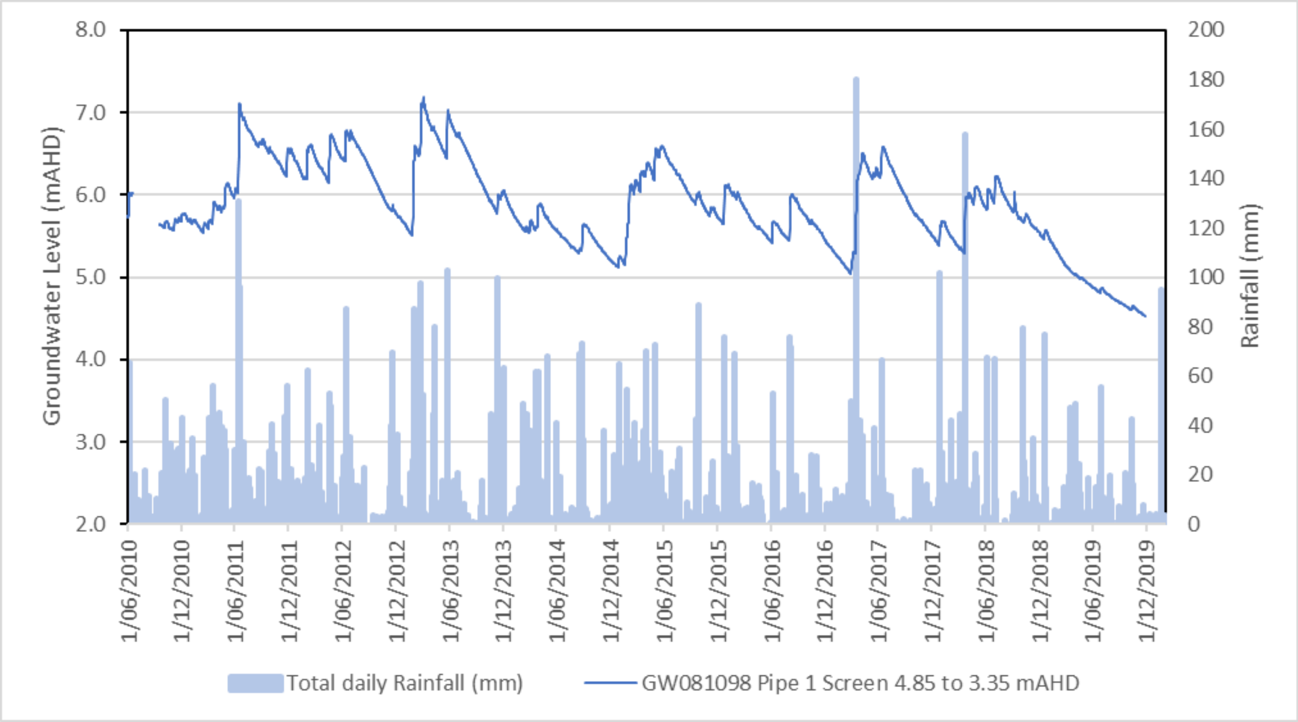


Figure 17. Hydrograph for monitoring bore site GW081096 (Hat Head – Crescent Head)

Monitoring bore GW081098 is near one of the town water pumping bores for Crescent Head. Here we can see the seasonal variations without the peaks and troughs that would be expected from pumping being so close to a pumping bore (**Figure** 18). This indicates that the pumping bore (constructed in the deeper aquifer) is having negligible short-term impact on the shallow groundwater system that supports the groundwater-dependent ecosystems.



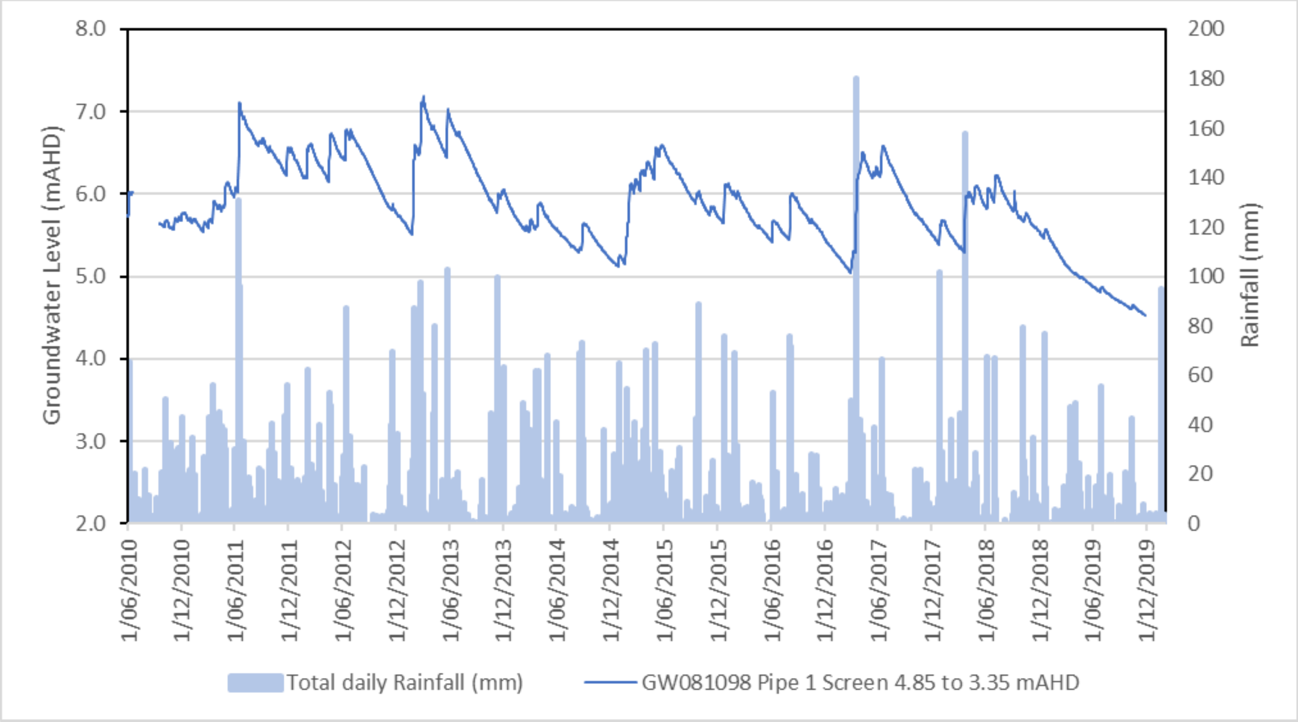
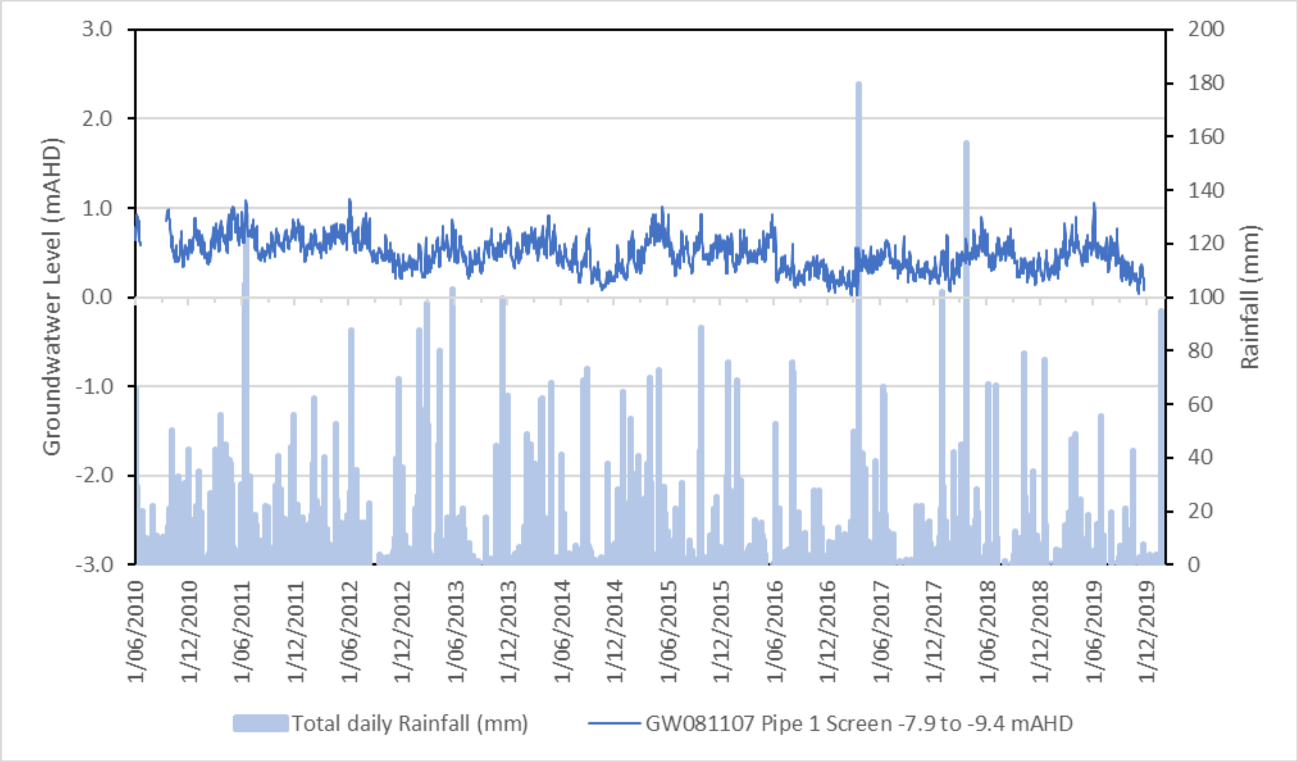


Figure 18. Hydrograph for monitoring bore site GW081098 (Crescent Head)

Monitoring bore GW081107 is located within the dunal system to the south of Smoky Cape. As can be seen in **Figure** 19, there is a very frequent groundwater level oscillation. This is likely to be caused by tidal influences (daily rise and fall). Also worth noting is the very small band of fluctuation, typically between 3 m and 4 m depth. This is due to the regulation of the water level at the saltwater interface where a high water table quickly discharges to the ocean and a low water table is buoyed up by saltwater intrusion.



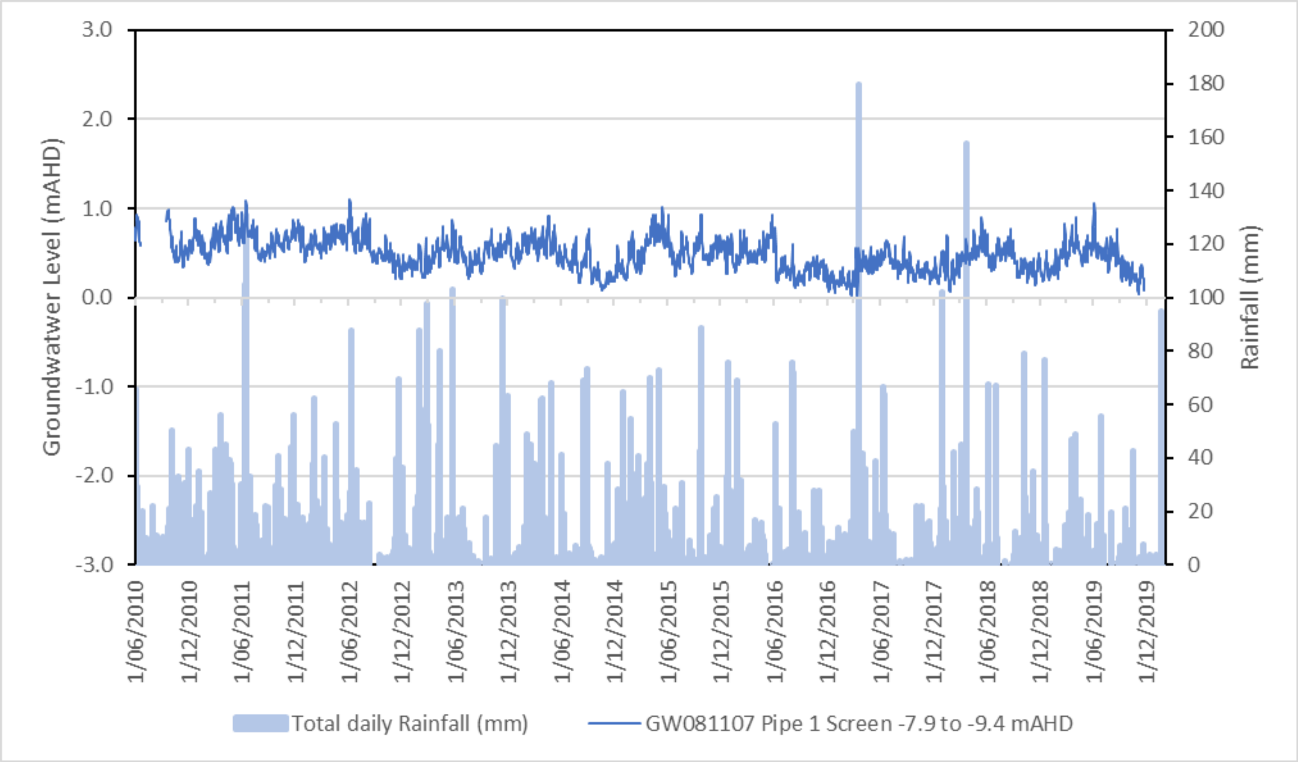


Figure 19. Hydrograph for monitoring bore site GW081107 (South of Smoky Cape)

7.3 Groundwater contours

Groundwater level contour maps are used to display the distribution of groundwater levels or pressures from a specific aquifer and indicate groundwater flow direction, which is perpendicular to the contour lines.

Groundwater levels from 19 government monitoring bores were used to create the contour map provided in **Figure 20** and **Figure 21**. Contours are displayed in metres above the Australian Height Datum (m AHD), which provides a reference level for the measurement of groundwater level or pressure that is independent of topography.

Contours have been prepared for the deep systems for April (end of higher rainfall months) and October (end of drier months) 2019 to demonstrate a possible change in flow direction that could occur. The maps (**Figure 20** and **Figure 21**) show that groundwater flows from west to east, towards the ocean. Groundwater near the Heads (Hat Head and Smoky Cape) have elevated groundwater levels (influenced by higher topographic relief), compared to the groundwater in the middle of the coastal dunes.

An analysis of the contours illustrates that there is minimal change in groundwater flow direction overall between the months of April and October. It confirms that extraction from the town water supply bores had minimal impact on water levels during 2019.

The results of the two potentiometric surface maps show there is a consistent response in water levels across the extent of the water source from April compared with October. The maps do not show any change in groundwater flow direction which, on this local scale, typically shows a subdued representation of the topographic surface, resulting in primarily groundwater flow towards the ocean but with north west and south variations dependent on dune orientations.

Overall, the change in water level and gradient of flow across the MCSGS being generally minimal (less than 0.4 m) between April and October 2019. Extraction from production bore pumping does not appear to change the groundwater pressure in the study area, and therefore the groundwater flow directions do not show impacts from extraction.

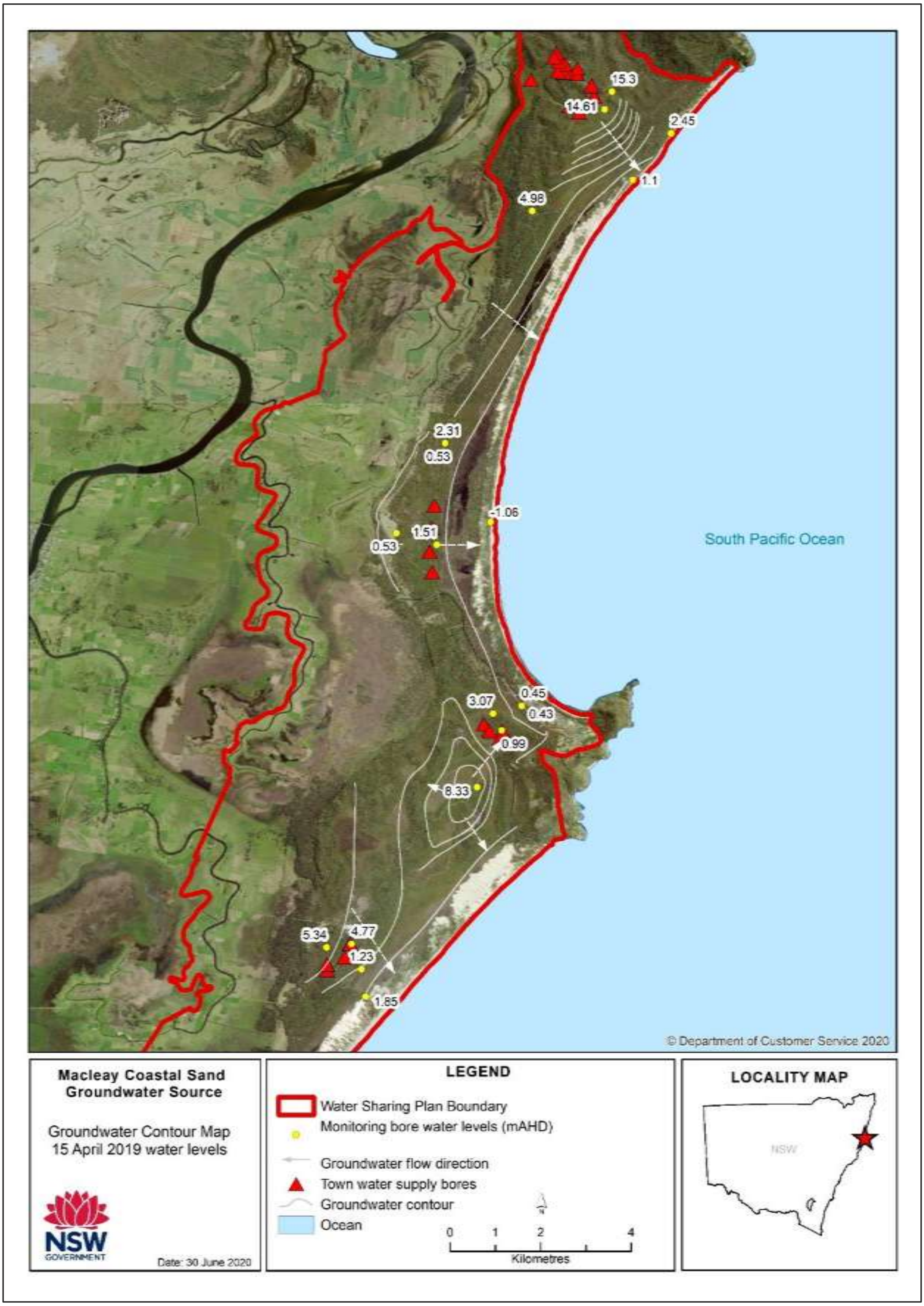


Figure 20. Groundwater level contours for April 2019

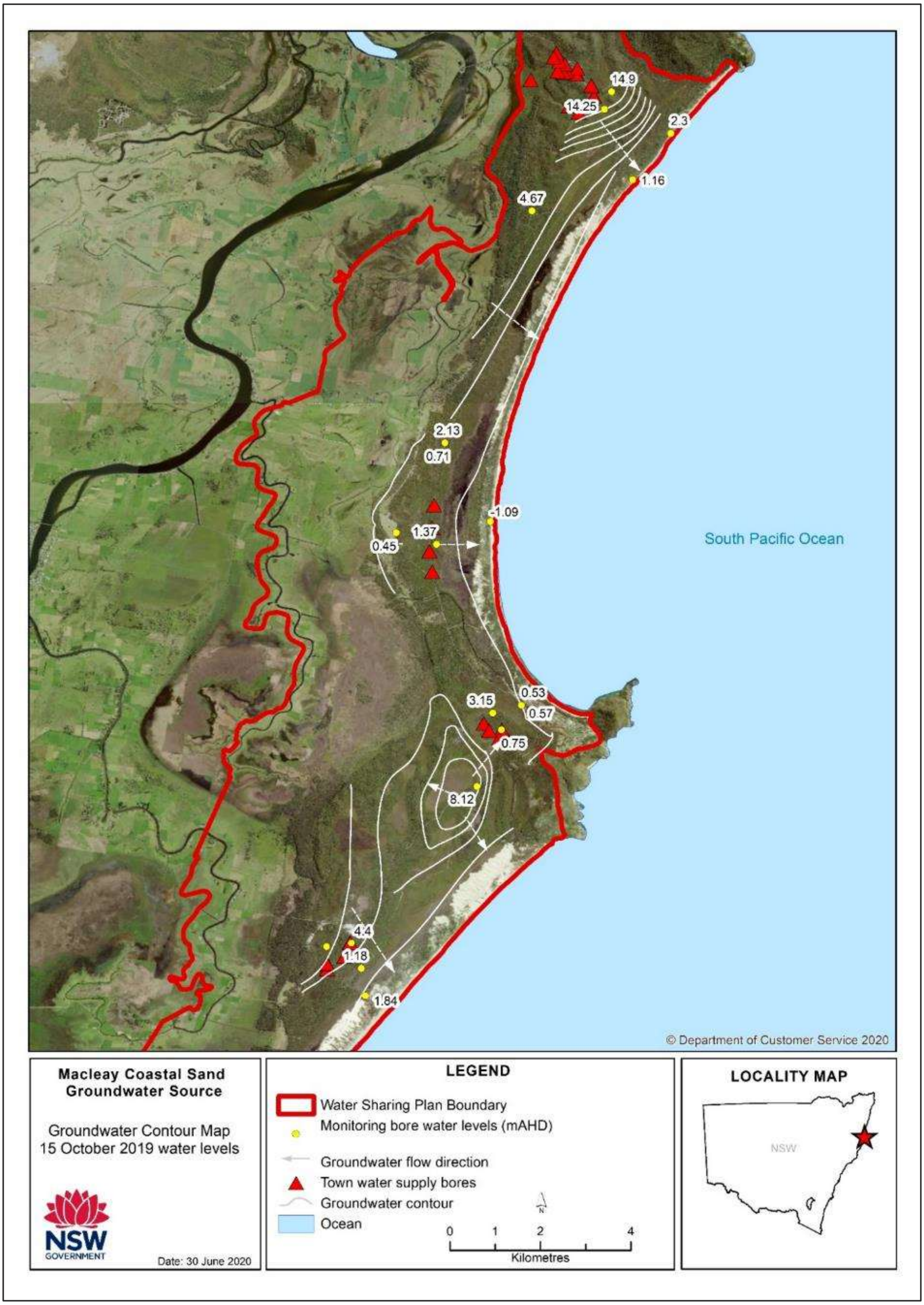


Figure 21. Groundwater level contours for October 2019

8. Groundwater model

A numerical groundwater flow and transport model was developed to assess the impacts on water levels and salinity of various pumping and climate scenarios. The groundwater modelling was undertaken as part of a federally funded National Water Initiative Project in 2011.

The modelling report concludes that it will be possible to increase extraction beyond present levels to meet increasing demand for water in these coastal communities in response to population growth. However, this additional extraction will have to be balanced carefully both spatially and temporally.

Any new production bores will need to be offset by abandoning bores that are not producing enough water and should be located at a sufficient distance from existing high-value production bores to ensure that localised over-pumping does not ensue. In addition, any increase in pumping should consider local drawdown impacts, as well as ensuring that the shallow part of the aquifer does not dry out. The ecosystem functions will then remain intact.

9. Hydrochemistry

Groundwater quality changes from the movement of the oceanic saline water interface is a risk to the town water supply extracting from the near-shore groundwater source. Forewarning of groundwater quality changes can be identified through water quality monitoring over the network of monitoring bores (Kempsey Shire Council 2004).

9.1 Sampling, analysis, and QAQC

9.1.1 Methodology

Water quality sampling was carried out by the NSW Department of Planning, Industry and Environment in April 2019 to assess the conditions of the groundwater source and to identify any emerging risks to water quality. Surface water, sea water and rainwater were included in the sampling program in order to characterise the groundwater chemical make-up and processes. The sampling sites are presented in **Figure 9** to **Figure 13**

The sampling event included:

- 27 groundwater samples (essentially based on access to monitoring sites)
- six surface water monitoring locations of swamps and channels
- one sea water sample (site adjacent to a groundwater monitoring site).

The *in-situ* data and water samples were collected from NSW Government monitoring bores following the guidelines outlined in *Groundwater Sampling and Analysis - A Field Guide* (Sundaram et al., 2010). Groundwater monitoring bores were purged using a high-flow portable groundwater sampling submersible pump (mega monsoon). Groundwater samples were collected after purging three bore volumes from the monitoring bore, with physicochemical parameters monitored throughout the purging process. Collected groundwater samples were filtered where necessary as specified by laboratory requirements using 0.45 µm nylon in-line filters and then stored in 125 mL HDPE bottles with minimal headspace (that is, air bubble in bottle). Samples for cation analysis were acidified to 5% HNO_3. Samples were stored on ice in an esky to reduce the sample temperature to <2°C prior to shipping the samples to the respective analytical laboratories to be stored in refrigerators prior to analysis.

Sea water and surface water grab samples were also collected following the same sample collection, preservation, and storage procedures. Samples were filtered where necessary using luer-lock 0.45 µm nylon filters with compatible syringes. The suite of parameters tested measured during the field program are provided in **Table 3**, along with the relevant analytical laboratory and method.

Table 3. Suite of analytes tested at Macleay coastal sands monitoring sites in April 2019

Suite	Analyte	Method	Laboratory
In-situ data			
Physicochemical parameters	pH Electrical conductivity Redox potential Temperature	Meter and electrodes	NA
Laboratory analysis			
Physicochemical parameters	pH	APHA (4500-H^+): pH meter and electrode	

Suite	Analyte	Method	Laboratory
	Electrical conductivity	APHA (2510): conductivity cell at 25°C	Envirolab Services (Chatswood, NSW)
	Total dissolved solids	Gravimetrically: solids dried at 180 ±10°C	
Major cations	Ca^{2+}, K^+, Mg^{2+}, Na^+	ICP-AES	
Major anions	Cl^-, SO_4^{2-}, Br^-	APHA (4110-B) IC	
	F^-	APHA (4500-F-C): ion selective electrode	
Alkalinity	OH^-, CO_3^{2-}, HCO_3^-, and total (as $CaCO_3$)	APHA (2320-B): Titration	
Hardness	Total hardness (as $CaCO_3$)	Calculation	
Total and dissolved metals	Al, As, Cd, Cr, Cu, Fe, Li, Pb, Mn, Ni, Ag, Sr, Zn	ICP-MS	
	Hg	Cold vapour AAS	
Stable isotopes	$^2H/^1H$ (δ^2H), $^{18}O/^{16}O$ ($\delta^{18}O$)	Picarro Cavity Ring-Down Spectroscopy (CRDS)	ANSTO (Lucas Heights, NSW)

9.1.2 Data QAQC

Quality assurance (QA) and quality control (QC) checks were performed to determine if the geochemistry data is representative of expected conditions for water samples. The QAQC checks utilised in this assessment include the anion-cation balance (APHA *et al.* 2017, Section 1030 pg. 8-9) and duplicate comparisons utilising relative percent difference (RPD) values.

9.1.3 Anion-cation balance

The anion and cation sums (expressed as milliequivalents per litre, mEq/L) must balance because all waters are electrically neutral (that is, positively charged ions balance out the negatively charged ions). However, an error between these sums is accepted since multiple analytical methods are used to determine analyte concentrations and there is analytical error associated with each of these determinations. This error, reported as a percentage difference, is calculated as follows:

$$\%\, difference = 100 \times \frac{\sum cations \; - \; \sum anions}{\sum cations \; + \; \sum anions}$$

Equation 1

An acceptable percentage difference is usually determined by the anion sum for most modern laboratory analysis. The acceptable percentage differences are as follows:

Table 4. Acceptable difference for anion-cation balance based on anion sum (mEq/L) (APHA *et al*, 2017).

Anion sum (mEq/L)	Acceptable difference
0 – 3.0	±0.2 mEq/L
3.0 – 10.0	±2%
≥10.0	±5%

A total of 20 samples (of 33 samples) did not have an anion-cation balance that was within the acceptable percentage difference ranges. However, this could be due to nitrate (NO_3^-) not being analysed in the collected samples rather than an issue with the laboratory analysis. Considering that these samples were collected from coastal and estuarine environments, it could be expected for NO_3^- to be present in significant concentrations in the water samples. Therefore, all analytical results will be utilised in this investigation to describe broad trends in the water geochemistry.

9.1.4 Duplicate comparisons

The collection, storage, and analysis of duplicate samples assists in determining how field and laboratory methods influence the repeatability of the analytical results. The reported concentrations between a sample and its duplicate is compared using a relative percent difference (RPD) value. This is calculated utilising the below equation:

$$RPD\ (\%) = \frac{(sample\ result - duplicate\ result)}{(sample\ result + duplicate\ result)/2} \times 100$$

Equation 2

Considering that the relative percent difference (RPD) values can vary considerable due to sample matrix and concentration, along with slight differences in sample collection and storage conditions, a graded acceptance criterion is applied based on the difference between the reported concentrations and the method detection limit (MDL). The MDL is the lowest concentration of an analyte that an analytical laboratory can detect, given the particular method and instrumentation they are utilising. This criterion is outlined in **Table 5**:

Table 5. Acceptable difference for RPD based on the method detection limit (MDL)

Reported concentration vs. MDL	Acceptable difference
Reported concentration < 10 times MDL	No limit
Reported concentration 10 – 20 times MDL	±50%
Reported concentration > 20 times MDL	±20%

Of the two duplicate comparisons performed, there were two instances (of 86 calculation) where the RPD was not within the acceptable difference ranges. These are outlined in **Table 6**. Considering that these exceedances are limited (that is, they occur in 2.4% of RPD calculations) and the analytes involved are not being utilised in future interpretation at this point in time, it can be determined that the repeatability of the reported results is high and the analytical results can be confidently utilised in further investigations. Care will need to be taken in determining the repeatability and representativeness of reported results if analytes involved in the RPD exceedances are to be utilised in further investigations.

Table 6. Instances where duplicate RPD not within acceptable difference limits.

Analyte	Sample	Reported concentration (mg/L)	RPD (%)	Acceptable difference (%)
Bromide	Seawater	<0.5	184%	±50%
	DUP2	6.1		
Iron (total)	Seawater	0.1	123%	±50%
	DUP2	0.024		

9.2 Stable isotopes of hydrogen and oxygen

9.2.1 Use and local meteoric water lines (LMWL)

Stable isotopes of hydrogen and oxygen are useful for determining the source of the water sampled and to aid in the identification of water mixing. Groundwater sample results were compared to meteoric (rainfall) and marine (seawater) origin endmember samples. Physical processes that dictate the stable water isotope changes of water sampled include mixing of water sources, diffusion, condensation, evaporation and seasonal and rain-source changes (Kendall & Doctor, 2003).

Other chemical reasons for stable isotopes changes (mineral hydration; exchange with minerals, gases (CO_2, H_2S), aqueous SO_4^{2-}, bore cement; methane production.) are not considered here.

The water sample analysis is expressed as isotope ratios, δ, of $^2H/^1H$ and $^{18}O/^{16}O$. Values are reported as parts per thousand (‰) compared to an internationally agreed standard (called the Vienna Standard Mean Ocean Water, or VSMOW). Water signatures that have more ‘heavier’ isotopes (that is, that have a higher composition of ^2H and ^{18}O) are referred to as ‘enriched’. Alternatively, the water signatures that have more ‘lighter’ isotopes (that is, that have a higher composition of ^1H and ^{16}O) are referred to as ‘depleted’.

The benchmark for comparing the stable water isotope results is against a local meteoric water line (LMWL). The source of the data for monthly rainfall isotopic composition used to calculate the LMWL was from the International Atomic Energy Agency’s (INAE) Global Network of Isotope in Precipitation (GNIP) station located at Sydney Airport. The Sydney GNIP station (number 9476700) is the closest to the Macleay coastal sand groundwater source sharing similar climatic conditions. The climate condition classification for Sydney and Macleay coastal sands groundwater source extent is temperate, warm and dry (Kottek et al 2006). The Sydney station is located near to the coast of NSW, which is likely to have sea spray in the local rainwater, akin to the Macleay coastal sands study area.

The Sydney Airport LMWL has previously been determined by Hollins *et al*. (2018) utilising a precipitation-amount weighted reduced major axis (PWRMA) regression. A precipitation-amount weighted method was utilised to reduce the influence of small rainfall events, that have potentially been influenced by evaporative enrichment, in the calculation of the slope of the LMWL (Hughes and Crawford, 2012; Crawford *et al*., 2014). This is more applicable in hydrological studies since low rainfall events do not significantly contribute to runoff and recharge events. In addition, a reduced major axis (RMA) regression was utilised since it is more appropriate to optimise the fit in both the x-axis and y-axis directions when the two variables are related by underlying physical processes, as both δ^2H and $\delta^{18}O$ are (IAEA, 1992; Crawford *et al*, 2014).

The equation for the PWRMA LMWL for the Sydney Airport GNIP station utilised in this description is:

$$\delta^2 H = 7.77 \bullet \delta^{18} O + 15.19$$

Equation 3

9.2.2 Results

The δ2H and δ18O composition of groundwater, swamp, estuarine, and seawater is shown in **Figure 22**. The Sydney Airport PWRMA LMWL is also shown.

The δ2H and δ18O composition of groundwater samples within the South-West Rocks, Hat Head, and Kinchela borefields plot close to the Sydney Airport PWRMA LMWL, indicating that local rainfall is the dominant recharge source and that minimal evaporation is occurring during infiltration (**Figure 22)**.

The $\delta^{2}H$ and $\delta^{18}O$ composition of groundwater samples within the Maguires borefield is more variable than the other borefields, with some samples plotting close to the Sydney Airport PWRMA LMWL and others plotting along an evaporation trend line. The $\delta^{2}H$ and $\delta^{18}O$ composition of these groundwater samples varies with both distance from the coast (GW081098.1.1, GW081102.1.1, GW081101.1.1) and depth down the profile (GW081101.1.1, GW081101.1.2, GW081101.1.3), with samples closer to the coast and to the ground surface generally having an enriched (that is, more positive values) $\delta^{2}H$ and $\delta^{18}O$ composition. This suggests that evaporative processes are influencing groundwater down a flow path and close to the ground surface. These same trends occur in the other borefields, but to a lesser extent (**Figure 22**).

The $\delta^{2}H$ and $\delta^{18}O$ composition of swamp water collected within the South-West Rocks borefield (SW05) plots close to the Sydney Airport LMWL, with the composition more enriched that that of local groundwater (**Figure 22**). This suggests that the swamp water source could be slightly evaporated rainfall, evaporated local groundwater, or a mixture of the two. The $\delta^{2}H$ and $\delta^{18}O$ composition of swamp water collected within the Maguires borefield (SW01) plots along an evaporation line coming from the Sydney Airport LMWL, with the composition being similar to groundwater sampled from monitoring site GW081101.1.1 and being more enriched than seawater (**Figure 22**). This suggests that the swamp water source at this site could be highly evaporated rainfall, evaporated local groundwater, or a mixture of the two.

The $\delta^{2}H$ and $\delta^{18}O$ composition of most estuarine water samples either plot between the groundwater and seawater compositions (SW03 and SW04 in the Kinchela and South-West Rocks borefields, respectively) or near seawater (SW06 in the Hat Head borefield) (**Figure 22**). This shows that estuarine water at these sites is either a potential mixture between groundwater and seawater (SW03 and SW04) or that seawater is the dominant water source (SW06). Another estuarine water sample taken near the Kinchela borefield (SW02) has a similar $\delta^{2}H$ and $\delta^{18}O$ composition to that of the local groundwater (**Figure 22**), suggesting that groundwater may be the dominant water source with some evaporation occurring to enrich the $\delta^{2}H$ and $\delta^{18}O$ compositions.

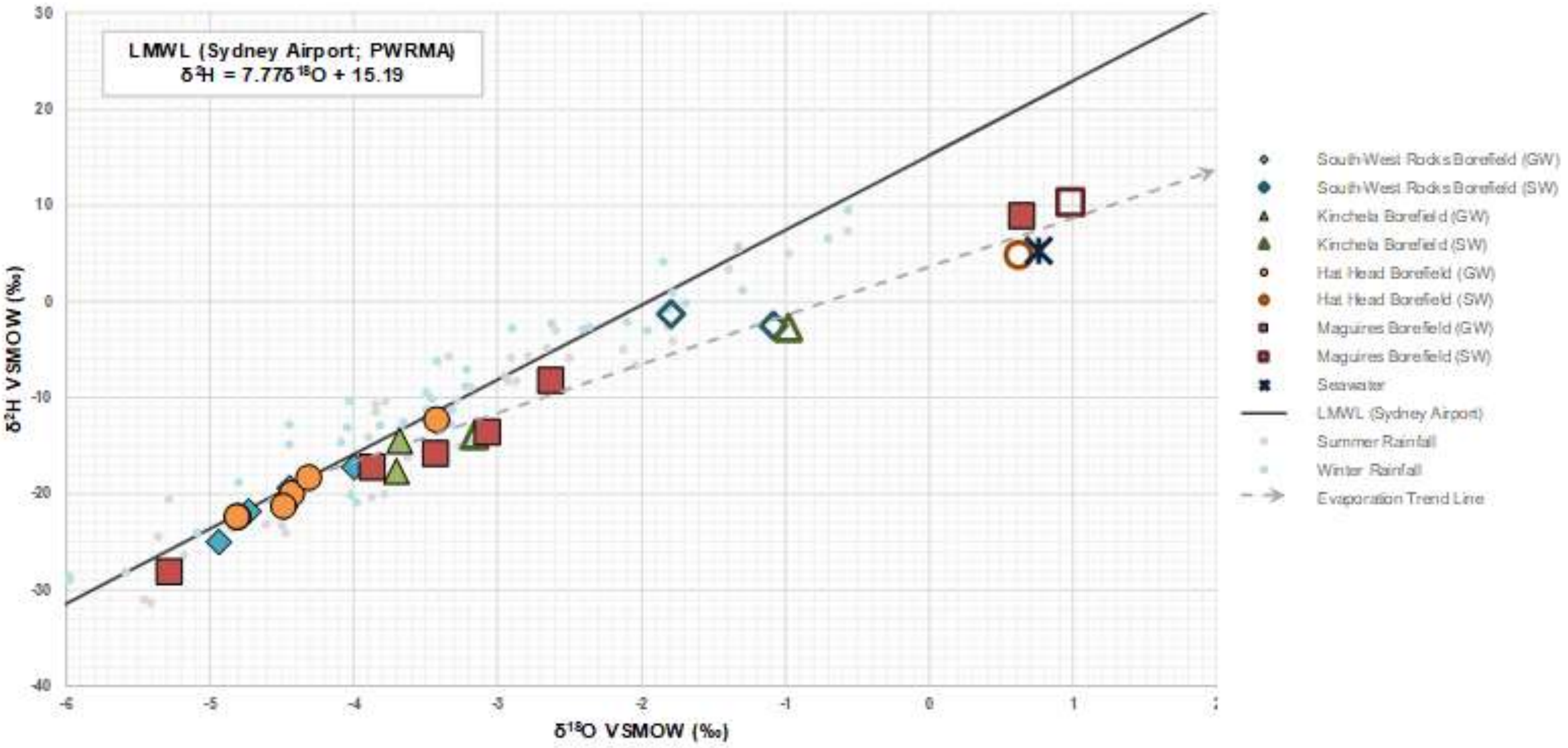


Figure 22. Stable isotope composition of groundwater, swamps, estuaries, and seawater of the Macleay coastal sands groundwater source. The Sydney Airport PWRMA LMWL and rainfall composition is also shown (uncertainty: δ^2H ±1‰, $\delta^{18}O$ ±0.15‰).

9.3 Physicochemical and major ion chemistry – results

The full dataset of the groundwater quality monitoring program is tabled in **Appendix A**, this includes site details and chemistry analysis results. Summary statistics for physicochemical parameters for groundwaters and surface waters are presented in **Table 7**. The major ion composition for each of the water samples is also displayed in a Piper Diagram (**Figure 23**) to assist in determining the water type of each sample, water sources, and potential mixing that may be occurring.

Groundwater in the Macleay coastal sands groundwater source tends to be acidic (that is, $pH < 7$) to circum-neutral (that is, $pH \approx 7$), with groundwater being most acidic in the Maguires borefield and being least acidic in the Hat Head borefield. Groundwater salinity is ‘fresh’ (that is, total dissolved solids or TDS < 1,000 mg/L), with some occurrences of ‘brackish’ (that is, TDS 1,000 – 3,000 mg/L) groundwater in the Kinchela (sites GW081092.1.1 and GW081104.1.1) and Hat Head borefields (GW081092.1.3) (**Appendix A, Table 2**). Groundwater tends to be dominated by Na^+-Cl^- type waters (**Figure 23**). There are some occurrences of (Na^+-Ca^{2+}-Mg^{2+})-HCO_3^- and Ca^{2+}- HCO_3^- water types in the Kinchela borefield (GW081093.1.1 and GW081093.2.2 respectively; **Figure 23**). There are also some occurrences of (Na^+-Ca^{2+})- Cl^-, (Na^+-Ca^{2+}-Mg^{2+})-HCO_3^-, and Na^+-HCO_3^- water types in the Maguires borefield (GW081101.1.1, GW081101.1.2, and GW081101.1.3 respectively; **Figure 23**).

Surface water in swamps also tends to be acidic (that is, $pH < 7$) to circum-neutral (that is, $pH \approx 7$), with water salinity classified as ‘fresh’. Surface water from estuaries tends to be circum-neutral (that is, $pH \approx 7$) and saline (that is, TDS 5,000 – 35,000 mg/L). There are some occurrences of hyper-saline (that is, TDS >35,000 mg/L) estuarine water (SW03 and SW06; **Table 7**). These surface waters are dominated Na^+-Cl^- type waters (**Figure 23**).

The seawater sample is a circum-neutral (that is, $pH \approx 7$), hyper-saline (**Table 7**), Na^+-Cl^- type water (**Table 7**; **Figure 23**).

Table 7. Summary statistics for physicochemical parameters

Site	Parameter	No. points	No. non-detects	Min	Median	Max
South-West Rocks borefield	pH	8	0	4.1	5.1	6.4
	Electrical conductivity (µS/cm)	8	0	122	184	474
	Total dissolved solids (mg/L)	8	0	78.0	165	280
Kinchela borefield	pH	7	0	4.1	5.2	6.5
	Electrical conductivity (µS/cm)	7	0	165	620	1,900
	Total dissolved solids (mg/L)	7	0	140	350	1,300
Hat Head borefield	pH	5	0	4.8	5.1	7.0
	Electrical conductivity (µS/cm)	5	0	150	233	3,870
	Total dissolved solids (mg/L)	5	0	110	150	2,200
Maguires borefield	pH	6	0	3.7	5.1	6.1
	Electrical conductivity (µS/cm)	6	0	149	245	347
	Total dissolved solids (mg/L)	6	0	150	195	260
Swamps	pH	2	0	4.0	---	6.2
	Electrical conductivity (µS/cm)	2	0	277	---	410

Site	Parameter	No. points	No. non-detects	Min	Median	Max
	Total dissolved solids (mg/L)	2	0	180	---	360
Estuaries	pH	4	0	5.3	6.6	7.9
	Electrical conductivity (µS/cm)	4	0	9,020	27,805	52,440
	Total dissolved solids (mg/L)	4	0	4,400	18,500	41,000
Seawater	pH	1	0	---	7.8	---
	Electrical conductivity (µS/cm)	1	0	---	52,295	---
	Total dissolved solids (mg/L)	1	0	---	45,000	---

Each borefield has distinct major ion geochemical groupings on a Piper Diagram (**Figure 23**). Groundwater relatively enriched in Ca^{2+}, Mg^{2+}, and HCO_3^- was identified in monitoring sites to the south of the South-West Rocks borefield (GW081085.2.2, GW081089.1.1, and GW081089.2.2) and in monitoring sites closest to the coast in the Kinchela (GW081093.1.1 and GW081083.2.2) and Maguires (GW081101.1.1, GW081101.1.2, and GW081101.1.3) borefields (**Figure 23 a,b,d**). In addition, the relative composition of Ca^{2+} decreases down the profile whilst the relative composition of Mg^{2+} and HCO_3^- increases down the profile at these monitoring sites. All other groundwater monitoring sites have a major ion geochemical composition similar to seawater (**Figure 23**).

Considering that most of the groundwater samples were more acidic (that is, lower pH) and less saline that seawater, the similar major ion geochemistry between groundwater and seawater in the MCSGS could be due to the influence of sea spray introducing Na^+ and Cl^- salts into the landscape rather than mixing with seawater. This is also supported by the δ^2H and $\delta^{18}O$ composition of these waters being more similar to the LMWL (**Figure 22**). The relatively acidic groundwater can also be attributed to rainfall quickly infiltrating the aquifers, interactions with acid sulphate soils, and/or interactions with organics within the lithological profile. One monitoring site in the Hat Head borefield (GW081092.1.3) did have elevated salinity and pH relative to all other sampling sites in the borefield (**Appendix A, Table 2**). This could either indicate some seawater/estuary water mixing is occurring and/or localised lithology interactions are changing the geochemistry at this site. Considering that the δ^2H and $\delta^{18}O$ composition at this monitoring site plots near the LMWL, and that the geochemical composition plots away from the seawater and surface water points on the Piper Diagram, it is possible that the elevated salinity and pH is due to either localised lithology interactions or mixing between groundwater and estuarine water, with the groundwater being the dominant mixing component, rather than seawater intrusions (**Figure 22; Figure 23**). Geochemical mixing models will need to be utilised to confirm the process(es) leading to the elevated salinity and pH at site GW081092.1.3.

The major ion geochemical composition of the swamp water samples collected within the South-West Rocks borefield (SW05) and the Maguires borefield (SW01) are more similar to groundwater major ion geochemistry than seawater major ion geochemistry (**Figure 23**). The swap water sample collected within the South-West Rocks borefield has a major ion geochemistry most like that of groundwater monitoring site GW081085.1.1., whilst the swamp water sample collected within the Maguires borefield has a major ion geochemistry most like that of groundwater monitoring site GW081098.1.1. Given the δ^2H and $\delta^{18}O$ composition of SW05, along with the low pH and salinity, it is likely that this swamp water is a mixture of local rainfall and groundwater (**Appendix A, Table 2**). The geochemical composition of swamp water at site SW01 indicates that is a highly evaporated water that is a potential mixture of local rainfall and groundwater. The similar pH, electrical conductivity, and δ^2H and $\delta^{18}O$ composition to shallow groundwater at site GW081101.1.1 also supports this contention (**Appendix A, Table 2**).

The major ion geochemical composition of estuarine water samples is very similar to seawater (**Figure 23)**. In general, estuarine water becomes less acidic (that is, pH increases) as the salinity increases (**Appendix A**, **Table 2**). These trends reflect the mixing contributions that seawater can have in these environments. Therefore, seawater mixing contributions in estuarine waters could be highest at site SW06 (Hat Head borefield) and lowest at site SW02 (Kinchela borefield). This is also supported by the δ^2H and δ^{18}O composition of SW06 being similar to seawater and the δ^2H and δ^{18}O composition of SW02 being more similar to local groundwater (**Figure 22**).

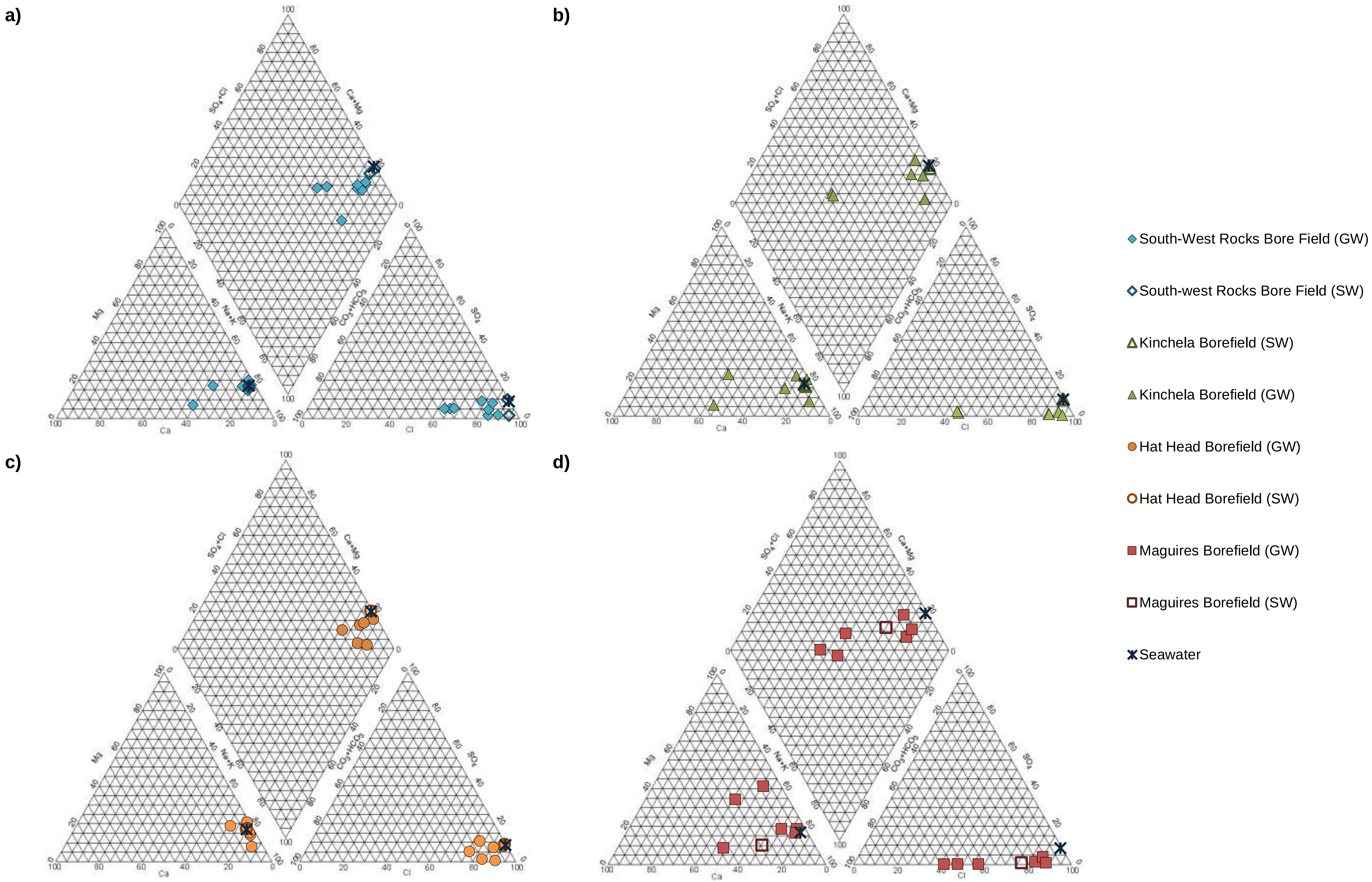


Figure 23. Piper Plots for the a) South-West Rocks, b) Kinchela, c) Hat Head, and d) Maguires borefields

9.4 Metal and metalloid chemistry – results

The full dataset of the groundwater quality monitoring program is tabled in **Appendix A**; this includes site details and chemistry analysis results. Summary statistics for dissolve and total metals and metalloids for groundwaters and surface waters are presented in **Appendix A**.

The metal and metalloid concentrations in groundwater, swamp, estuary, and seawater samples were compared to the following water quality guidelines to assess beneficial use of the MCSGS:

- National Health and Medical Research Council (NHMRC) (2011) *Australian Drinking Water Guidelines 6 (version 3.6)*
- Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC and ARMCANZ) (2018) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*

The relevant guideline values are summarised in **Appendix B, Table 3**.

There were occasions where analyte limit of reporting (LOR) values were higher than water quality guideline values. These are summarised in (**Table 8**). Comparisons with water quality guidelines could not occur in these instances.

Table 8. Occurrences where analyte LORs were higher than water quality guideline values

Analyte	LOR (mg/L)	Water Quality Guideline	Value (mg/L)
Arsenic	0.001	99% species protection (freshwater)	0.0005
Cadmium	0.0001	99% species protection (freshwater)	0.00006
Chromium	0.001	99% species protection (freshwater)	0.0001
		99% species protection (marine)	0.00014
Copper	0.001	99% species protection (freshwater)	0.0001
Silver	0.001	95% species protection (freshwater)	0.00005
		99% species protection (freshwater)	0.00002
		99% species protection (marine)	0.0008

There were no comparable metal or metalloid (both dissolved and total) concentrations that exceeded livestock drinking water quality guidelines (**Appendix B, Table 3**). There were also no detected concentrations of the following metals and metalloids that were higher than comparable guidelines:

- Cadmium (dissolved and total);
- Lead (dissolved);
- Mercury (dissolved);
- Nickel (dissolved and total); and
- Silver (dissolved).

There were sporadic occurrences (that is, occurring in $\geq$5 (of 33) sites) where detected concentrations of metals and metalloids were higher than comparable water quality guidelines. (**Appendix B, Table 3**). These are summarised in **Table 9**. There were occurrences where detected concentrations of metals and metalloids were often (that is, occurring in $\geq$15 (of 33) sites) higher than comparable water quality guidelines. These are summarised in **Table 10**. Further investigations should occur to confirm: (1) if these values are true occurrences; (2) processes that may produce these concentrations, and (3) if these concentrations are within ‘natural variability; or if they are ‘once-off’ detections.

Further investigations should occur to confirm these values, processes that may produce these concentrations, and if these concentrations are within ‘natural variability; or if they are ‘once-off’ detections.

Table 9. Occurrences where detected metal/metalloid concentrations were higher than comparable water quality guideline values

Site	Analyte	Concentration (mg/L)	Guideline	Value (mg/L)
GW081085.1.1	Chromium (total)	0.002	95% Species Protection (freshwater)	0.001
	Copper (dissolved and total)	0.012(d); 0.067(t)	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.0013
	Lead (total)	0.004	95% Species Protection (freshwater)	0.0034
			99% Species Protection (freshwater)	0.001
			99% Species Protection (marine)	0.0022
	Mercury (total)	0.0001	99% Species Protection (freshwater)	0.00006
	Zinc (dissolved and total)	0.11(d); 0.4(t)	95% Species Protection (freshwater)	0.008
			99% Species Protection (freshwater)	0.0024
			95% Species Protection (marine)	0.015
			99% Species Protection (marine)	0.007
GW081085.2.2	Chromium (total)	0.002	95% Species Protection (freshwater)	0.001
GW0081088.1.1	Arsenic (dissolved and total)	0.037(d); 0.042 (t)	Drinking Water	0.01
			95% Species Protection (freshwater)	0.013
	Chromium (dissolved and total)	0.002	95% Species Protection (freshwater)	0.001
	Copper (dissolved and total)	0.012(d); 0.02(t)	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.0013
	Zinc (dissolved)	0.008	99% Species Protection (marine)	0.007
GW081089.1.1	Zinc (total)	0.008	99% Species Protection (marine)	0.007
GW081082.1.3	Copper (total)	0.002	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.0013

Site	Analyte	Concentration (mg/L)	Guideline	Value (mg/L)
GW081091.1.1	Zinc (dissolved)	0.008	99% Species Protection (marine)	0.007
GW081092.1.3	Zinc (total)	0.01	95% Species Protection (freshwater)	0.008
			99% Species Protection (marine)	0.007
GW081093.2.2	Copper (total)	0.002	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.0013
	Silver (total)	0.005	95% Species Protection (marine)	0.0014
GW081094.1.1	Copper (total)	0.089	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.001
	Zinc (dissolved and total)	0.06(d); 0.054(t)	95% Species Protection (freshwater)	0.008
			99% Species Protection (freshwater)	0.0024
			95% Species Protection (marine)	0.015
			99% Species Protection (marine)	0.007
SW01	Copper (dissolved)	0.005	95% Species Protection (freshwater)	0.0014
			95% Species Protection (marine)	0.0013
	Zinc (dissolved)	0.017	95% Species Protection (freshwater)	0.008
			99% Species Protection (freshwater)	0.0024
			95% Species Protection (marine)	0.015
			99% Species Protection (marine)	0.007
SW04	Manganese (dissolved and total)	0.34(d); 0.32(t)	Drinking Water	0.1[a]; 0.5

NOTE: a: aesthetic guideline; (d) dissolved concentration; (t) total concentration

Table 10. Summary of occurrences where detected metal/metalloid concentrations for dissolved (d) and total (t) were higher than comparable water quality guideline values.

Analyte	Guideline	Value (mg/L)	No. Exceedances
Aluminium (dissolved and total)	Drinking Water[a]	0.2	17(d); 23(t)
	95% Species Protection (freshwater)	0.055	26(d); 29(t)
	99% Species Protection (freshwater)	0.027	30(d); 33(t)
Iron (dissolved and total)	Drinking Water[a]	0.3	13(d); 16(t)
Zinc (dissolved and total)	99% Species Protection (freshwater)	0.0024	20(d); 21(t)

NOTE: a: aesthetic guideline; (d) dissolved concentrations; (t) total concentrations

10. Conclusion

The majority of the MCSGS is contained within the Hat Head National Park. Land use surrounding the National Park consists primarily of grazing for dairy and beef cattle.

March to June are the wettest months when most recharge occurs to the groundwater source. Groundwater contours prepared for the months of April and October show minimal change in flow direction, indicating that extractions from town water supply bores had minimal impact on water levels during 2019. The seasonal fluctuations in groundwater levels observed are largely caused by rainfall variation. Increased rainfall recharging MCSGS increases the groundwater flow gradients, which occurs following the wetter months earlier in the year.

Groundwater elevation and flow respond to rainfall variation and show little response to groundwater pumping under the current pumping regime. The monitoring bore data for groundwater level and chemistry (EC, TDS and major ions) around the town water supply bores and throughout the MCSGS do not immediately indicate seawater intrusion impacts.

Groundwater is used predominantly for town water supply with less than 1% used for irrigation and other commercial purposes. Groundwater use at present is not metered. Yields within this groundwater source are typically moderate to high, with yields of up to 30 L/s.

In the future, however, the system could be vulnerable to potential increases in demand for water due to population growth and tourism. There are other potential risks such as aquifer contamination and increased sea levels, which would impact the availability of water. It is critical that extraction in the MCSGS be managed properly to prevent adverse impacts through processes such as:

- the installation of flow meters on each extraction bore
- regular review and updates of the groundwater model when new information becomes available
- inclusion of investigations targeting saltwater intrusion
- regular updates to groundwater-dependent ecosystems.

11. References

APHA, AWWA, and WEF (2017) ‘Section 1030 E. Checking Analyses’ Correctness’ in *Standard Methods for the Examination of Water and Wastewater 23rd Edition*; prepared and published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation; American Public Health Association, Washington, Section 1030 pp 8-9.

Atkinson. G. 1999 Soil Landscapes of the Kempsey - Korogoro Point 1:100 000 Sheet. Department of Land and Water Conservation.

Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australian and New Zealand (ARMCANZ) (2018) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. www.waterquality.gov.au/anz-guidelines

Bureau of Meterology. (2020). *Climate Data Online,* Monthly Rainfall South West Rocks (Smoky Cape Lighthouse), website accessed 3 July 2020

Crawford, J., Hughes, C.E., & Lykoudis, S. (2014) Alternative least squares methods for determining the meteoric water line, demonstrated using GNIP data. *Journal of Hydrology*, *519*, 2331-2340.

Department of Land and Water Conservation (2002). The NSW state groundwater dependent ecosystem policy: A component of the NSW state groundwater policy framework document. Prepared by Department of Land and Water Conservation, NSW Government, April 2002.

Ecoseal. (2004). Groundwater Monitoring & Assessment for Coastal Borefields - Kempsey Local Government Area. Extended C.

Gow, L.J. 2011. Report for the National Water Commission: Sustainable management of coastal groundwater resources – Final Groundwater Dependent Ecosystems report. Geoscience Australia, Canberra.

Hollins, S.E., Hughes, C.E., Crawford, J., Cendón, D.I., & Meredith, K.T. (2018) Rainfall isotope variations over the Australian continent – Implications for hydrology and isoscape applications. *Science of the Total Environment*, *645*, 630-645

Hughes, C.E., and Crawford, J. (2012) A new precipitation weighted method for determining the meteoric water line for hydrological applications demonstrated using Australian and global GNIP data. *Journal of Hydrology*, *464*, 344-351.

International Atomic Energy Agency (IAEA) (1992) *Statistical Treatment of Data on Environmental Isotopes in Precipitation: Technical Reports Series No. 3311*. International Atomic Energy Agency, Vienna, p.781

International Atomic Energy Agency. (2018). Australian Global Network of Isotope in Precipitation (GNIP) database 1960-2014 (p. MS Excel dataset).

Kendall, C., & Doctor, D. H. (2003). Stable Isotope Applications in Hydrologic Studies. Treatise on Geochemistry, 5.11, 319–364. https://doi.org/10.1016/B0-08-043751-6/05081-7

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). Meteorologische Zeitschrift, World map of the Köppen-Geiger climate classification updated. 15(3), 259–263.

National Health and Medical Research Council (NHMRC) & Natural Resource Management Ministerial Council (NRMMC) (2011) *Australian Drinking Water Guidelines 6 (version 3.4)*. Commonwealth of Australia, Canberra.

Punthakey JF., Woolley D. (2011). Sustainable Management of Coastal Groundwater Resources & Opportunities for Further Development: Development of a Flow & Transport Model for the Macleay Sands Aquifer.

Rollason. V. 2013. Kempsey Coastal Processes and Hazards Definition Study. BTM WMB Pty Ltd prepared for Kempsey Shire Council.

Roy, P.S. 1998. Cainozoic geology of the coast and shelf. *In*: Scheibner E. & Basden H. eds. *Geology of the New South Wales – Synthesis, Volume 2: Geological Evolution*, pp. 361-385. Geological Survey of New South Wales, Memoir Geology13(2).

Sundaram, B., Feitz, J. A., Caritat, D. P., Plazinska, A., Brodie, S. R., Coram, J., Ransley, T., & Geoscience Australia. (2010). Groundwater Sampling and Analysis - A Field Guide.

Thom et al. 1992. Coastal Geomorphology and Quaternary Geology of the Port Stephens – Myall Lakes Area. ANU Canberra, Dept of Biogeography and Geomorphology, Monograph #6, 1992.

Troedson, A., Hashimoto, T. R., Jaworska, J., Malloch, K. & Cain, L. 2004. New South Wales coastal Quaternary geology. In: NSW coastal Quaternary geology data package (on CD-ROM) (Ed. by Troedson, A. & Hashimoto, T. R.). Maitland: New South Wales Department of Primary Industries, Mineral Resources, Geological Survey of New South Wales.

Woolley D., Punthakey JF., Brodie, R., Gow L, Green R. and Rumpf C. 2011. Sustainable Management of Coastal Groundwater Resources & Opportunities for Further Development: Hydrogeology, Monitoring and Hydrochemistry for the Macleay Sands Aquifer. National Water Commission. Ecoseal Consulting Report CR 11-1116. Pp 143.

12. Appendix A

12.1. Geochemical results

12.1.1. Sample site details

Table 1. Details of the sites visited in the April 2019 field program

Site name	Longitude	Latitude	Screen bottom (m bgl)	Type of water sample
SW01	153.0116	-31.10968	N/A	Fresh swamp
SW02	153.02606	-32.03021	N/A	Estuarine
SW03	153.02625	-31.03967	N/A	Estuarine
SW04	153.03838	-30.95543	N/A	Estuarine
SW05	153.0536	-30.95609	N/A	Fresh swamp
SW06	153.04311	-30.0518	N/A	Estuarine
Seawater 81093	153.03727	-31.01482	N/A	Marine
Rainwater	153.04322	-30.88360	N/A	Meteoric water
GW081086.1.1	153.06064	-30.92997	3.1-4.6	Groundwater
GW081087.1.1	153.05927	-30.93349	4-5.5.0	Groundwater
GW081102.1.1	153.01107	-31.10424	5.0-6.5	Groundwater
GW081100.2.2	153.0041	-31.10346	2.2-4.0	Groundwater
GW081101.1.1	153.01181	-31.10979	1.0-2.5	Groundwater
GW081101.1.2	153.01181	-31.10979	5.0-6.5	Groundwater
GW081101.1.3	153.01181	-31.10979	15.0-30.0	Groundwater
GW081104.1.1	153.017912	-31.01766	30.0-33.0	Groundwater
GW081085.1.1	153.04487	-30.95368	2.89-4.34	Groundwater
GW081085.2.2	153.04499	-30.95364	31.0-37.0	Groundwater
GW081096.3.3	153.03395	-31.0681	33.0-39.0	Groundwater
GW081096.2.2	153.03392	-31.06814	8.79-10.25	Groundwater
GW081096.1.1	153.03392	-31.06815	1.04-3.5	Groundwater
GW081094.1.1	153.03706	-31.05351	12.0-13.5	Groundwater
GW081092.1.3	153.04279	-31.05194	40.0-49.0	Groundwater
GW081092.1.2	153.04261	-31.05196	2.6-8.5	Groundwater
GW081092.1.1	153.04261	-31.05196	0.57-3.5	Groundwater
GW081105.1.1	153.02759	-30.99981	9.0-15.0	Groundwater
GW081090.1.1	153.02760	-30.99983	2.0-3.5	Groundwater
GW081091.1.1	153.02572	-31.02021	2.1-3.55	Groundwater

Site name	Longitude	Latitude	Screen bottom (m bgl)	Type of water sample
GW081107.1.1	153.07229	-30.93826	17.0-30.0	Groundwater
GW081088.1.1	153.07246	-30.93825	6.5-8.0	Groundwater
GW081089.1.1	153.06489	-30.94756	7.0-8.5	Groundwater
GW081098.1.1	153.00899	-31.09925	4.04-5.5	Groundwater
GW081089.2.2	153.06484	-30.94755	9.0-33.0	Groundwater - coastal dune
GW081093.1.1	153.03659	-31.01550	3.5-5.0	Groundwater - coastal dune
GW081093.2.2	153.03659	-31.01550	0.4-8.76	Groundwater

screen bottom unable to be identified.

12.1.2. General chemistry

Table 2. General chemistry in-situ field results for samples collected in April 2019

Site name	EC	pH	Redox (measured)	TDS (measured)
Units	µS/cm	pH units	mV	mg/L
SW01	277	6.15	-159.6	180
SW02	9,020	5.33	-183	4,400
SW03	34,610	6.22	94.1	23,000
SW04	21,000	6.9	-	14,000
SW05	410	4	-	360
SW06	52,440	7.94	9.7	41,000
Seawater 81093	52,295	7.83	95	45,000
Rainwater	0.5*	-	-	-
GW081086.1.1	125	4.47	-42.6	170
GW081087.1.1	122	4.74	-94	78
GW081102.1.1	168	4.07	-48	180
GW081100.2.2	149	4.36	-37.6	150
GW081101.1.1	321	6.01	-176	220
GW081101.1.2	327	5.9	-196	200
GW081101.1.3	347	6.08	-253	260
GW081104.1.1	1,050	5.77	-208	610
GW081085.1.1	202	4.08	-92.2	280
GW081085.2.2	140	5.5	-175	83
GW081096.3.3	233	4.75	-108	110
GW081096.2.2**	161	5.98	219.5	-
GW081096.1.1	150	5.23	-202	150

Site name	EC	pH	Redox (measured)	TDS (measured)
GW081094.1.1	264	4.97	-172	140
GW081092.1.3	3,870	6.98	-168	2,200
GW081092.1.2	222	5.09	-173	180
GW081092.1.1	1,900	5.2	-	1,300
GW081105.1.1	490	4.96	-175	360
GW081090.1.1	259	4.42	-114	260
GW081091.1.1	165	4.1	-1148	140
GW081107.1.1	166	4.72	-12.9	99
GW081088.1.1	379	5.56	89.2	160
GW081089.1.1	474	6.37	-143	190
GW081098.1.1	154	3.74	-44.5	190
GW081098.2.2	455	6	-265	190
GW081093.1.1	720	6.5	-275	350
GW081093.2.2	620	6.51	-277	240

Notes: EC recorded is specific conductance corrected to 25 degrees Celsius. Alkalinity, TDS and hardness are laboratory results. EC, pH and redox are *in-situ* measurements.

- Indicates no data available.

* Indicates data patched using half the limit of reporting laboratory value where there is not data available.

** Indicates site unable to be sampled.

Table 3. Major ion chemistry for samples collected in April 2019 (lab results)

Site name	Calcium	Potassium	Sodium	Magnesium	Chloride	Sulphate	Hardness CaCO3	Hydroxide alkalinity (CaCO3)	Bicarbonate Alkalinity (CaCO3)	Carbonate Alkalinity	Total Alkalinity (CaCO3)
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
SW01	11	1.5	34	2.9	54	1	39	<5	19	<5	19
SW02	54	55	1,500	170	2,200	290	820	<5	<5	<5	<5
SW03	230	240	7,000	740	9,500	1,300	3,600	<5	76	<5	76
SW04	170	150	4,600	490	6,300	930	2,500	<5	66	<5	66
SW05	2.2	0.8	62	7	89	2	34	<5	<5	<5	<5
SW06	390	430	12,000	1,400	16,000	2,200	6,600	<5	120	<5	120
Seawater 81093	390	440	12,000	1,400	19,000	2,500	6,700	<5	120	<5	120
Rainwater	<0.5	<0.5	2.5	<0.5	-	-	<3	-	-	-	-
GW081086.1.1	<0.5	<0.5	16	2.2	24	<1	9	<5	<5	<5	<5
GW081087.1.1	<0.5	<0.5	17	2	27	2	8.3	<5	<5	<5	<5
GW081102.1.1	2.5	<0.5	19	2.7	32	<1	18	<5	<5	<5	<5
GW081100.2.2	1.1	0.7	19	2.2	31	2	12	<5	<5	<5	<5
GW081101.1.1	25	0.5	33	3.2	54	<1	75	<5	53	<5	53
GW081101.1.2	15	1.4	29	13	44	<1	91	<5	84	<5	84
GW081101.1.3	5.9	4.4	42	19	59	1	94	<5	87	<5	87
GW081104.1.1	11	10	200	10	240	5	70	<5	40	<5	40
GW081085.1.1	1.3	<0.5	26	2.5	39	1	14	<5	<5	<5	<5
GW081085.2.2	1	0.8	17	1.8	28	3	9.9	<5	15	<5	15
GW081096.3.3	0.8	1.2	33	4	51	6	19	<5	<5	<5	<5

Site name	Calcium	Potassium	Sodium	Magnesium	Chloride	Sulphate	Hardness CaCO3	Hydroxide alkalinity (CaCO3)	Bicarbonate Alkalinity (CaCO3)	Carbonate Alkalinity	Total Alkalinity (CaCO3)
GW081096.1.1	2.2	0.6	19	2.7	31	3	17	<5	8	<5	8
GW081094.1.1	<0.5	1.7	37	5.3	61	<1	22	<5	6	<5	6
GW081092.1.3	37	26	720	36	910	170	240	<5	180	<5	180
GW081092.1.2	0.8	2.4	31	3.2	51	1	15	<5	10	<5	10
GW081092.1.1	11	14	400	37	530	64	180	<5	9	<5	9
GW081105.1.1	13	3.3	81	9.1	140	1	70	<5	8	<5	8
GW081090.1.1	<0.5	1.2	37	4.9	61	2	20	<5	<5	<5	<5
GW081091.1.1	0.9	0.9	17	2.7	32	<1	13	<5	<5	<5	<5
GW081107.1.1	0.6	0.9	22	2.6	39	5	12	<5	<5	<5	<5
GW081088.1.1	3.6	2.5	53	6.3	82	13	35	<5	16	<5	16
GW081089.1.1	29	2	58	3.7	92	10	89	<5	63	<5	63
GW081098.1.1	0.5	<0.5	13	1.7	21	<1	8.4	<5	<5	<5	<5
GW081098.2.2	16	1.9	59	8.6	94	10	76	<5	51	<5	51
GW081093.1.1	50	3.5	67	19	120	6	200	<5	190	<5	190
GW081093.2.2	60	1.5	59	4.5	99	8	170	<5	160	<5	160

Table 4. Dissolved metal results for samples collected in April 2019

Site name	Aluminium	Arsenic	Cadmium	Chromium	Copper	Iron	Lithium	Lead	Manganese	Mercury	Nickel	Silver	Strontium	Zinc
Units	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
LOR	10	1	0.1	1	1	10	1	1	5	0.05	1	1	1	1
SW01	30	1	<0.1	<1	5	260	2	<1	7	<0.05	<1	<1	58	17
SW02	330	<1	<0.1	<1	<1	360	22	<1	11	<0.05	<1	<1	920	2
SW03	110	<1	<0.1	<1	<1	280	91	<1	10	<0.05	<1	<1	4,100	2
SW04	30	<1	<0.1	<1	<1	360	84	<1	340	<0.05	<1	<1	2,900	6
SW05	410	<1	<0.1	<1	<1	420	2	<1	<5	<0.05	<1	<1	23	2
SW06	10	2	<0.1	<1	<1	<10	180	<1	<5	<0.05	<1	<1	6,900	2
Seawater	10	2	<0.1	<1	<1	<10	200	<1	<5	<0.05	<1	<1	7,400	<1
Rainwater	100	<1	<0.1	<1	<1	<10	<1	<1	<5	<0.05	<1	<1	2.5	46
GW081086.1.1	540	<1	0.1	<1	<1	130	1	<1	<5	<0.05	<1	<1	10	7
GW081087.1.1	620	<1	0.1	<1	<1	150	1	<1	<5	<0.05	<1	<1	2.4	3
GW081102.1.1	370	<1	0.1	<1	<1	380	<1	<1	<5	<0.05	<1	<1	23	3
GW081100.2.2	380	<1	0.1	<1	<1	79	4	<1	<5	<0.05	<1	<1	13	4
GW081101.1.1	220	3	0.1	<1	<1	2,500	<1	<1	19	<0.05	<1	<1	120	1
GW081101.1.2	120	<1	0.1	<1	<1	16	4	<1	14	<0.05	<1	<1	130	2
GW081101.1.3	290	<1	0.1	1	<1	63	2	<1	<5	<0.05	<1	<1	72	3
GW081104.1.1	30	2	0.1	<1	<1	6,600	5	<1	84	<0.05	<1	<1	130	3
GW081085.1.1	290	<1	0.1	<1	12	260	1	<1	<5	<0.05	2	<1	11	110
GW081085.2.2	130	5	0.1	<1	<1	4,600	2	<1	25	<0.05	<1	<1	11	6
GW081096.3.3	170	<1	0.1	<1	<1	15	2	<1	<5	<0.05	<1	<1	15	3

Site name	Aluminium	Arsenic	Cadmium	Chromium	Copper	Iron	Lithium	Lead	Manganese	Mercury	Nickel	Silver	Strontium	Zinc
GW081096.1.1	580	<1	0.1	<1	<1	170	5	<1	<5	<0.05	<1	<1	16	2
GW081094.1.1	110	<1	0.1	<1	<1	1,300	<1	<1	<5	<0.05	2	<1	10	60
GW081092.1.3	<10	2	0.1	<1	<1	610	11	<1	43	<0.05	<1	<1	390	3
GW081092.1.2	1300	<1	0.1	<1	<1	250	4	<1	<5	<0.05	<1	<1	15	2
GW081092.1.1	1600	<1	0.1	1	<1	150	9	<1	<5	<0.05	<1	<1	160	3
GW081105.1.1	450	<1	0.1	<1	<1	8,400	3	<1	74	<0.05	<1	<1	100	6
GW081090.1.1	790	<1	0.1	<1	<1	1,500	3	<1	7	<0.05	<1	<1	11	5
GW081091.1.1	370	<1	0.1	<1	<1	180	<1	<1	<5	0.06	<1	<1	9.7	8
GW081107.1.1	100	<1	0.1	<1	<1	32	2	<1	<5	<0.05	<1	<1	8.9	3
GW081088.1.1	200	37	0.1	2	15	3,100	2	<1	9	<0.05	<1	<1	49	8
GW081089.1.1	170	3	0.1	<1	<1	220	1	<1	8	<0.05	<1	<1	160	4
GW081098.1.1	230	1	0.1	<1	<1	140	1	<1	<5	<0.05	<1	<1	15	2
GW081098.2.2	230	<1	0.1	<1	<1	660	1	<1	<5	<0.05	<1	<1	93	2
GW081093.1.1	30	<1	0.1	<1	<1	130	<1	<1	<5	<0.05	<1	<1	310	2
GW081093.2.2	190	<1	0.1	<1	<1	65	<1	<1	<5	<0.05	<1	<1	440	2

Table 5. Total metal results for samples collected in April 2019

Site name	Aluminium	Arsenic	Cadmium	Chromium	Copper	Iron	Lithium	Lead	Manganese	Mercury	Nickel	Silver	Strontium	Zinc
Units	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
LOR	10	1	0.1	1	1	10	1	1	5	0.05	1	1	1	1
SW01	50	2	<0.1	<1	<1	510	4	<1	10	<0.05	<1	<1	61	3
SW02	360	<1	<0.1	<1	<1	430	23	<1	11	<0.05	<1	<1	940	2
SW03	240	<1	<0.1	<1	<1	580	93	<1	11	<0.05	<1	<1	4,200	2
SW04	80	<1	<0.1	<1	<1	830	82	<1	320	<0.05	5	<1	2,800	6
SW05	410	<1	<0.1	<1	<1	480	4	<1	<5	<0.05	<1	<1	25	2
SW06	30	1	<0.1	<1	<1	25	190	<1	<5	<0.05	<1	<1	7,300	3
Seawater	60	2	<0.1	<1	<1	100	200	<1	<5	<0.05	<1	<1	7,700	2
Rainwater*	140	<1	<0.1	<1	<1	20	<1	<1	<5	<0.05	<1	<1	2.8	60
GW081086.1.1	580	<1	<0.1	<1	<1	180	4	<1	<5	<0.05	<1	<1	10	3
GW081087.1.1	600	<1	<0.1	<1	<1	150	4	<1	<5	<0.05	<1	<1	2.2	2
GW081102.1.1	380	<1	<0.1	<1	<1	380	3	<1	<5	<0.05	<1	<1	22	4
GW081100.2.2	530	<1	<0.1	1	<1	97	5	<1	<5	0.06	<1	<1	17	6
GW081101.1.1	240	3	<0.1	<1	<1	2,600	2	<1	19	<0.05	<1	<1	120	2
GW081101.1.2	140	<1	<0.1	<1	<1	20	6	<1	12.5	<0.05	<1	<1	140	3
GW081101.1.3	310	<1	<0.1	<1	<1	68	3	<1	<5	<0.05	<1	<1	70	2
GW081104.1.1	50	3	<0.1	<1	<1	7,000	6	<1	86	<0.05	<1	<1	130	3
GW081085.1.1	660	<1	<0.1	2	67	440	2	4	8	0.1	1	<1	17	400
GW081085.2.2	140	5	<0.1	2	<1	4,700	3	<1	26	<0.05	1	<1	10	5
GW081096.3.3	210	<1	<0.1	<1	<1	21	4	<1	<5	<0.05	<1	<1	17	2

Site name	Aluminium	Arsenic	Cadmium	Chromium	Copper	Iron	Lithium	Lead	Manganese	Mercury	Nickel	Silver	Strontium	Zinc
GW081096.1.1	700	<1	<0.1	<1	1	160	8	<1	<5	<0.05	<1	<1	17	0
GW081094.1.1	120	<1	<0.1	<1	89	1,300	2	<1	<5	<0.05	3	<1	10	2
GW081092.1.3	600	2	<0.1	1	2	770	11	<1	44	<0.05	<1	<1	390	54
GW081092.1.2	1,400	<1	<0.1	<1	<1	250	4	<1	<5	<0.05	<1	<1	14	10
GW081092.1.1	1,700	<1	<0.1	<1	<1	120	7	<1	<5	<0.05	<1	<1	130	2
GW081105.1.1	770	1	<0.1	<1	1	8,100	4	<1	68	<0.05	<1	<1	92	4
GW081090.1.1	900	<1	<0.1	<1	<1	1,600	3	<1	7	<0.05	1	<1	11	4
GW081091.1.1	450	<1	<0.1	<1	<1	200	2	<1	<5	0.06	<1	<1	11	4
GW081107.1.1	100	<1	<0.1	<1	<1	38	2	<1	<5	<0.05	<1	<1	9.3	4
GW081088.1.1	220	42	<0.1	2	20	3,400	2	<1	9	<0.05	<1	<1	49	3
GW081089.1.1	220	4	<0.1	<1	1	250	<1	<1	8	<0.05	<1	<1	170	6
GW081098.1.1	300	<1	<0.1	<1	<1	140	3	<1	<5	0.06	<1	<1	15	8
GW081098.2.2	230	1	<0.1	<1	<1	640	1	<1	<5	<0.05	<1	<1	92	3
GW081093.1.1	30	<1	<0.1	<1	<1	150	<1	<1	<5	<0.05	<1	<1	320	2
GW081093.2.2	210	<1	<0.1	<1	2	70	<1	<1	<5	<0.05	<1	5	440	1

Notes: Where the concentration is the same as the LOR, the LOR has been reported in the table. The exception to this is for rainwater, where half the LOR was adopted where no data was available.

Seawater corresponds to sample “Seawater 81093” laboratory identification.

- Rainwater taken opportunistically from a Colourbond roof during a heavy rainfall event

13. Appendix B

13.1. Geochemical results

Table 1. Summary statistics for dissolved metals and metalloids

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
South-West Rocks borefield	Aluminium	8	0	0.10	0.22	0.62
	Arsenic	8	4	<0.001	0.001	0.037
	Cadmium	8	8	<0.0001	<0.0001	<0.0001
	Chromium	8	7	<0.001	<0.001	0.002
	Copper	8	6	<0.001	<0.001	0.015
	Iron	8	0	0.03	0.24	4.6
	Lead	8	8	<0.001	<0.001	<0.001
	Lithium	8	1	<0.001	0.001	0.002
	Manganese	8	5	<0.005	<0.005	0.025
	Mercury	8	8	<0.00005	<0.00005	<0.00005
	Nickel	8	7	<0.001	<0.001	0.002
	Silver	8	8	<0.001	<0.001	<0.001
	Strontium	8	0	0.0024	0.011	0.16
	Zinc	8	0	0.002	0.005	0.11
Kinchela borefield	Aluminium	7	0	0.03	0.37	1.60
	Arsenic	7	6	<0.001	<0.001	0.002
	Cadmium	7	7	<0.0001	<0.0001	<0.0001
	Chromium	7	6	<0.001	<0.001	0.001
	Copper	7	7	<0.001	<0.001	<0.001
	Iron	7	0	0.07	0.18	8.4
	Lead	7	7	<0.001	<0.001	<0.001
	Lithium	7	3	<0.001	0.003	0.009
	Manganese	7	4	<0.005	<0.005	0.084
	Mercury	7	6	<0.00005	<0.00005	<0.00005
	Nickel	7	7	<0.001	<0.001	<0.001
	Silver	7	7	<0.001	<0.001	<0.001
	Strontium	7	0	0.0097	0.13	0.44
	Zinc	7	0	0.002	0.003	0.008
	Aluminium	5	1	<0.01	0.17	1.30

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
Hat Head borefield	Arsenic	5	4	<0.001	<0.001	0.002
	Cadmium	5	5	<0.0001	<0.0001	<0.0001
	Chromium	5	5	<0.001	<0.001	<0.001
	Copper	5	5	<0.001	<0.001	<0.001
	Iron	5	0	0.02	0.25	1.3
	Lead	5	5	<0.001	<0.001	<0.001
	Lithium	5	1	<0.001	0.004	0.011
	Manganese	5	4	<0.005	<0.005	0.043
	Mercury	5	5	<0.00005	<0.00005	<0.00005
	Nickel	5	4	<0.001	<0.001	0.002
	Silver	5	5	<0.001	<0.001	<0.001
	Strontium	5	0	0.01	0.015	0.39
	Zinc	5	0	0.002	0.003	0.06
Maguires borefield	Aluminium	6	0	0.12	0.26	0.38
	Arsenic	6	5	<0.001	<0.001	0.003
	Cadmium	6	6	<0.0001	<0.0001	<0.0001
	Chromium	6	6	<0.001	<0.001	<0.001
	Copper	6	6	<0.001	<0.001	<0.001
	Iron	6	0	0.02	0.11	2.5
	Lead	6	6	<0.001	<0.001	<0.001
	Lithium	6	2	<0.001	0.002	0.004
	Manganese	6	4	<0.005	<0.005	0.019
	Mercury	6	6	<0.00005	<0.00005	<0.00005
	Nickel	6	6	<0.001	<0.001	<0.001
	Silver	6	6	<0.001	<0.001	<0.001
	Strontium	6	0	0.013	0.048	0.13
	Zinc	6	0	0.001	0.003	0.004
Swamps	Aluminium	2	0	0.03	---	0.41
	Arsenic	2	1	<0.001	---	0.001
	Cadmium	2	2	<0.0001	---	<0.0001
	Chromium	2	2	<0.001	---	<0.001
	Copper	2	1	<0.001	---	0.005
	Iron	2	0	0.26	---	0.42
	Lead	2	2	<0.001	---	<0.001

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
	Lithium	2	0	0.002	---	0.002
	Manganese	2	1	<0.005	---	0.007
	Mercury	2	2	<0.00005	---	<0.00005
	Nickel	2	2	<0.001	---	<0.001
	Silver	2	2	<0.001	---	<0.001
	Strontium	2	0	0.023	---	0.058
	Zinc	2	0	0.002	---	0.017
Estuaries	Aluminium	4	0	0.01	0.07	0.33
	Arsenic	4	3	<0.001	<0.001	0.002
	Cadmium	4	4	<0.0001	<0.0001	<0.0001
	Chromium	4	4	<0.001	<0.001	<0.001
	Copper	4	4	<0.001	<0.001	<0.001
	Iron	4	1	<0.01	0.32	0.36
	Lead	4	4	<0.001	<0.001	<0.001
	Lithium	4	0	0.022	0.088	0.18
	Manganese	4	1	<0.005	0.011	0.340
	Mercury	4	4	<0.00005	<0.00005	<0.00005
	Nickel	4	3	<0.001	<0.001	0.006
	Silver	4	4	<0.001	<0.001	<0.001
	Strontium	4	0	0.92	3.5	6.9
	Zinc	4	0	0.002	0.002	0.006
Seawater	Aluminium	1	1	---	<0.01	---
	Arsenic	1	0	---	0.002	---
	Cadmium	1	1	---	<0.0001	---
	Chromium	1	1	---	<0.001	---
	Copper	1	1	---	<0.001	---
	Iron	1	1	---	<0.01	---
	Lead	1	1	---	<0.001	---
	Lithium	1	0	---	0.2	---
	Manganese	1	1	---	<0.005	---
	Mercury	1	1	---	<0.00005	---
	Nickel	1	1	---	<0.001	---
	Silver	1	1	---	<0.001	---
	Strontium	1	0	---	7.4	---

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
	Zinc	1	1	---	<0.001	---

Table 2. Summary statistics for total metals and metalloids

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
South-West Rocks borefield	Aluminium	8	0	0.10	0.23	0.66
	Arsenic	8	4	<0.001	<0.001	0.042
	Cadmium	8	8	<0.0001	<0.0001	<0.0001
	Chromium	8	5	<0.001	<0.001	0.002
	Copper	8	5	<0.001	<0.001	0.067
	Iron	8	0	0.04	0.35	4.7
	Lead	8	7	<0.001	<0.001	0.004
	Lithium	8	2	<0.001	0.002	0.004
	Manganese	8	4	<0.005	<0.005	0.026
	Mercury	8	7	<0.00005	<0.00005	0.00010
	Nickel	8	6	<0.001	<0.001	0.001
	Silver	8	8	<0.001	<0.001	<0.001
	Strontium	8	0	0.002	0.014	0.17
	Zinc	8	0	0.002	0.004	0.4
Kinchela borefield	Aluminium	7	0	0.03	0.45	1.7
	Arsenic	7	5	<0.001	<0.001	0.003
	Cadmium	7	7	<0.0001	<0.0001	<0.0001
	Chromium	7	6	<0.001	<0.001	0.001
	Copper	7	5	<0.001	<0.001	0.002
	Iron	7	0	0.07	0.2	8.1
	Lead	7	7	<0.001	<0.001	<0.001
	Lithium	7	2	<0.001	0.003	0.007
	Manganese	7	4	<0.005	<0.005	0.086
	Mercury	7	6	<0.00005	<0.00005	0.00006
	Nickel	7	6	<0.001	<0.001	0.001
	Silver	7	6	<0.001	<0.001	0.005
	Strontium	7	0	0.011	0.13	0.44
	Zinc	7	0	0.001	0.004	0.004
	Aluminium	5	0	0.12	0.6	1.4

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
Hat Head borefield	Arsenic	5	4	<0.001	<0.001	0.002
	Cadmium	5	5	<0.0001	<0.0001	<0.0001
	Chromium	5	5	<0.001	<0.001	<0.001
	Copper	5	2	<0.001	0.001	0.089
	Iron	5	0	0.02	0.25	1.3
	Lead	5	5	<0.001	<0.001	<0.001
	Lithium	5	0	0.002	0.004	0.011
	Manganese	5	4	<0.005	<0.005	0.044
	Mercury	5	5	<0.00005	<0.00005	<0.00005
	Nickel	5	4	<0.001	<0.001	0.003
	Silver	5	5	<0.001	<0.001	<0.001
	Strontium	5	0	0.01	0.017	0.39
	Zinc	5	0	0.002	0.002	0.054
Maguires borefield	Aluminium	6	0	0.14	0.31	0.53
	Arsenic	6	5	<0.001	<0.001	0.003
	Cadmium	6	6	<0.0001	<0.0001	<0.0001
	Chromium	6	5	<0.001	<0.001	0.001
	Copper	6	6	<0.001	<0.001	<0.001
	Iron	6	0	0.02	0.12	2.6
	Lead	6	6	<0.001	<0.001	<0.001
	Lithium	6	0	0.002	0.003	0.006
	Manganese	6	4	<0.005	<0.005	0.019
	Mercury	6	3	<0.00005	<0.00005	0.00006
	Nickel	6	6	<0.001	<0.001	<0.001
	Silver	6	6	<0.001	<0.001	<0.001
	Strontium	6	0	0.015	0.046	0.14
	Zinc	6	0	0.002	0.003	0.006
Swamps	Aluminium	2	0	0.05	---	0.41
	Arsenic	2	1	<0.001	---	0.002
	Cadmium	2	2	<0.0001	---	<0.0001
	Chromium	2	2	<0.001	---	<0.001
	Copper	2	2	<0.001	---	<0.001
	Iron	2	0	0.48	---	0.51
	Lead	2	2	<0.001	---	<0.001

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
	Lithium	2	0	0.004	---	0.004
	Manganese	2	1	<0.005	---	0.01
	Mercury	2	1	<0.00005	---	0.00006
	Nickel	2	2	<0.001	---	<0.001
	Silver	2	2	<0.001	---	<0.001
	Strontium	2	0	0.025	---	0.061
	Zinc	2	0	0.002	---	0.003
Estuaries	Aluminium	4	0	0.03	0.16	0.36
	Arsenic	4	3	<0.001	<0.001	0.001
	Cadmium	4	4	<0.0001	<0.0001	<0.0001
	Chromium	4	4	<0.001	<0.001	<0.001
	Copper	4	4	<0.001	<0.001	<0.001
	Iron	4	0	0.03	0.51	0.83
	Lead	4	4	<0.001	<0.001	<0.001
	Lithium	4	0	0.023	0.088	0.19
	Manganese	4	1	<0.005	0.011	0.320
	Mercury	4	4	<0.00005	<0.00005	<0.00005
	Nickel	4	3	<0.001	<0.001	<0.001
	Silver	4	4	<0.001	<0.001	<0.001
	Strontium	4	0	0.940	3.5	7.3
	Zinc	4	0	0.002	0.0025	0.006
Seawater	Aluminium	1	0	---	0.06	---
	Arsenic	1	0	---	0.002	---
	Cadmium	1	1	---	<0.0001	---
	Chromium	1	1	---	<0.001	---
	Copper	1	1	---	<0.001	---
	Iron	1	0	---	0.1	---
	Lead	1	1	---	<0.001	---
	Lithium	1	0	---	0.2	---
	Manganese	1	1	---	<0.005	---
	Mercury	1	1	---	<0.00005	---
	Nickel	1	1	---	<0.001	---
	Silver	1	1	---	<0.001	---
	Strontium	1	0	---	7.7	---

Site	Parameter (mg/L)	No. points	No. non-detects	Min	Median	Max
	Zinc	1	0	---	0.002	---

Table 3. Summary statistics for water quality guidelines

Analyte	Water quality criteria (mg/L)					
	Drinking water	Livestock drinking	Freshwater		Marine	
			95% species protection	99% species protection	95% species protection	99% species protection
Aluminium (Al)	0.2[a]	5	0.055	0.027	---	---
Arsenic (As)	0.01	0.5	0.013[AsV]	0.0008 [AsV]	---	---
Cadmium (Cd)	0.002	0.01	0.0002	0.00006	0.0055	0.0007
Chromium (Cr)	0.05[CrVI]	1	0.001[CrVI]	0.0001[CrVI]	0.0044[CrVI]	0.00014[CrVI]
Copper (Cu)	2; 1[a]	0.4[sheep]–5[pigs]	0.0014	0.0001	0.0013	0.0003
Iron (Fe)	0.3[a]	---	---	---	---	---
Lead (Pb)	0.01	0.1	0.0034	0.001	0.0044	0.0022
Lithium (Li)	---	---	---	---	---	---
Manganese (Mn)	0.5; 0.1[a]	---	1.9	1.2	---	---
Mercury (Hg)	0.001	0.002	0.0006	0.00006	0.0004	0.0001
Nickel (Ni)	0.02	1	0.011	0.008	0.07	0.007
Silver (Ag)	0.1	---	0.00005	0.00002	0.0014	0.0008
Strontium (Sr)	---	---	---	---	---	---
Zinc (Zn)	3[a]	20	0.008	0.0024	0.015	0.007

NOTE: a: aesthetic guideline; AsV: as Arsenic(V); CrV: as Chromium(V). Value displayed is the upper limit.