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Hydrology of freshwater soaks on the Younghusband Peninsula in a changing climate

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Title page photo credit: Research boats accessing Younghusband Peninsula, Northern Lagoon of the Coorong. Eddie Banks (2025)

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Executive Summary

On the Younghusband Peninsula, soaks are open waterholes with salinity low enough to support human or animal consumption.

This project focused on understanding where we should expect to find low salinity soaks along the Younghusband Peninsula, developing a method to identify where they are from satellite imagery, and carrying out targeted fieldwork at selected soaks to begin to better understand how they function. The specific outcomes from undertaking this research in alignment with land management requirements are:

- Remote sensing mapping and ground-truthing of the freshwater soaks across Younghusband Peninsula,
- Improving cultural connection with research and management of freshwater soaks through on-country activities with FN groups, DEW, and the Landscape Board,
- Understanding of hydrological dynamics of key freshwater soaks,
- Summary of freshwater soak vulnerability to climate change, and
- A graphical representation (infographic) of soak hydrology for broader dissemination and synthesis report suitable for publication in peer-reviewed journal.

Using maps from the early 20th century, we digitised documented soaks along the Younghusband Peninsula. Visual inspection of satellite imagery from the past 15 years indicates that few of these soaks likely exist in the modern landscape. Using multi-spectral imagery, we sought to precisely locate currently existing soaks, which are typically small and often easy to confuse with shadows on satellite imagery. This process was refined following ground-truthing of initially identified, potential soaks. The salinity of the identified soaks ranged from brackish (1,600–16,000 mS/cm) to salty (>16,000 mS/cm; seawater ~55,000 mS/cm).

Most current soaks are located on the Coorong side of the peninsula, at low elevations relative to Coorong water level elevation. The presence of *Phragmites australis* (common reed), a fresh-brackish plant species, was found to be a good indicator of low salinity soak occurrence. While the reed analysis was developed as a proof of concept during the current project, further development of this methodology provides an opportunity to locate and monitor soak distribution throughout the longitudinally expansive and logistically challenging extent of the Younghusband Peninsula.

The soaks exist in a relatively simple but delicate hydrological cycle. Rainfall on Younghusband Peninsula is approximately 500 mm per year. This rainfall percolates through, and gets stored in, the dunes; how much water flows into a given dune each day is dependent on how big the dune is that replenishes the soak, and how much evaporation and plant water use is occurring (e.g., what season it is). This evaporation and transpiration accounts for most of the annual rainfall; evapotranspiration rates were calculated to match or exceed average annual rainfall for the study soaks. Any "leftover" rainfall flows through the soak and into the Coorong.

The soaks exist in an environment that has been heavily impacted by post-colonial development due to vegetation impacts from feral animal species and introduced weeds; however, it has little infrastructure or human water withdrawal. Nevertheless, both Ngarrindjeri and Burrandies communities expressed the wish that vehicle traffic along the Younghusband Peninsula be restricted to protect the delicate dune environment, and this may be a good way to limit future disturbances to the soaks.

Climate change is already affecting South Australia through alterations in the timing and intensity of storm events. While analyses of long-term rainfall records in the Coorong do not show statistically significant changes at an annual scale, previous studies indicate that dune vegetation is sensitive to interannual shifts in rainfall and to sudden storm events. Now that the locations of current soaks in the northern section of the Coorong have been identified, next steps are to:

- Improve the mapping method moving from a mixture of manual and machine learning to more automated deep learning AI methods,
- Extend the mapping to all sections of the Coorong,
- Understand how the hydrology and ecology of the soaks interact,
- Continue longer-term water level and water quality monitoring to understand how they change through time both seasonally and annually, and
- Monitor the impact of sea level rise and periodic flooding events.

Acknowledgements

We acknowledge the cultural connections to the land and connected waters that exist between people of the Ngarrindjeri and Boandik Nations across the Coorong, Lower Lakes, and Murray Mouth region. We recognise that First Nations peoples' spiritual, social, cultural, and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages, and laws which are of ongoing importance. We are committed to fostering and nurturing ongoing relationships with First Nations communities in the CLLMM region as we collectively work toward healthy, resilient and thriving lands, waters, ecosystems and communities across the region.

This project was funded by the Goyder Institute for Water Research's CLLMM Research Centre, which is funded by the Australian Government. We thank the CLLMM Research Centre staff for project initiation, support and management. We thank the Goyder Institute for Water Research, Research Advisory Committee and two anonymous reviewers for constructive feedback on the report.

This project was supported extensively by First Nations involvement. We are grateful to the Ngarrindjeri elders and rangers, who consistently made time to share knowledge with us and who were great to have in the field, and Boandik Uncle Terry, who graciously spent time with us at Wreck Crossing in May 2025 recounting stories of growing up in the Coorong.

We also thank the CLLMM Research Centre staff that facilitated these connections, especially Sue Ellison and Kyla McHughes. Together we have learned more about these invaluable freshwater soaks.

Finally, we thank Flinders University boat skipper Matt Lloyd, who safely navigated us back and forth and up and down the Coorong to find soaks and ferry multiple loads of people to the site, and Flinders University students Juan Lozano Acosta and Jan Schultz for field assistance. Special thanks to Roger Lubbers, who provided data and insights on historical maps and thus provided the foundation for that analysis.

1 Introduction

Coastal wetlands are amongst the most threatened ecosystems in the world; in the 20th century alone, more than 50% of the global area of coastal wetlands was lost (Li et al., 2018). These systems are subject to both regional threats from anthropogenic land alteration and pollution, and global threats such as elevated temperatures, and altered rainfall and inundation due to climate change (He et al., 2025).

Coastal dune wetlands are a special subclass of coastal wetlands. Also called dune slacks, interdunal wetlands, ponds, or soaks, they fill low-lying areas in the dune topography or between dunes. Most of the published literature on dune slacks stems from Europe, where dune slacks line coastal areas (Dwyer, 2022). The EU Habitats Directive lists dozens of coastal dune slack systems, and the ecosystems of these slacks are becoming increasingly studied due to their often degraded state. Nutrient pollution, dune stability issues due to flora and fauna (e.g. loss of vegetation due to addition of rabbits and ungulates on the landscape as explained below), alterations of dune hydrology due to water extraction, and encroachment by human development are amongst the most pressing problems for the European systems (Van Der Hagen et al., 2008). There are several large European restoration projects underway.

Although coastal dune slacks are found around the world, there are only scattered accounts of dune slacks outside of western Europe. In north-eastern Brazil, numerous freshwater ponds are found across the Lençóis Maranhenses National Park. Both seasonal and permanent, freshwater ponds are found in the depressions within the active dune field, caused by seasonal confinement of rainfall or exposed groundwater (Souza dos Santos & dos Santos, 2015). Many of these ponds are tourist attractions. Similarly, the physical environment forming a series of freshwater slacks in southern parts of South Africa is described by Van Der Merwe & McLachlan (1991). The South African environment appears to be similar to the South Australian context, with shallow groundwater tables creating wetlands in an otherwise arid environment receiving a low and winter-dominated annual rainfall 250–400 mm per year.

Semeniuk & Semeniuk (2011) provide a comprehensive review of the history of the term dune slack, and review the usefulness of the European-centric rules for classification as applied to several dune slack systems in Western Australia. This paper is especially useful for its discussion of the defining characteristics of dune slacks. Those characteristics relevant to the current study are;

1. Dune slacks are wet hollows formed in coastal dunes,
2. They are formed by Holocene processes,
3. They can form in both erosional and depositional settings,
4. They are subject to regional geomorphic, hydrologic, and sedimentary processes,
5. They are subject to seasonal inundation,
6. Their hydrology is a balance of rainfall, evapotranspiration and subsequent seasonal groundwater levels; they are not fed by rivers or seawater,

7. They can be any salinity, and
8. They can evolve to other coastal wetland types (such as dune lakes when they remain wet all year).

The Younghusband Peninsula of the Coorong region in South Australia (Figure 1) contains numerous features that conform to these criteria. Locally known as soaks or waterholes (note that these terms are used interchangeably throughout this report in keeping with the common historical vs contemporary terminology), they are of high ecological and cultural significance in the region. Some of these soaks are documented on historical maps of the region, and there has been limited mention of soak occurrence and documentation of soak characteristics in more recent reports. For example, Young (1981) compared avian activity to habitat and weather measurements in three soaks near the Cantara homestead. The study showed that human recreation, temperature, rainfall, food availability, and vegetation cover were the strongest drivers of species-specific activity, highlighting the essential role of fresh surface water and the need for ongoing and informed park management.

Initial location and ground-truthing surveys were undertaken at eight freshwater soaks in the southern Coorong by Bickert & Winter (2001). Photographs, site dimensions, and basic flora and fauna surveys were completed at each site, and monitoring methods were recommended for four of the soaks. Following this study, Winter & Squire (2003) conducted two surveys across seasons and found that soaks in the southern Coorong contained standing water with electrical conductivities of 2–20,000 mS/cm and concluded that several of the soaks were suitable for drinking by native fauna (particularly avian species), but indicated more investigations were required (including groundwater monitoring). To date, each study has investigated a small subset of the existing Coorong soaks; however, there has been no overall survey of the existence and condition of soaks across the full Younghusband Peninsula in several decades, and it is unknown how many of the soaks documented in early maps and reports still exist. Bickert and Winter (2001) note that they were unable to find soaks mentioned by Young (1981). Moreover, with the exception of isolated salinity measurements, there has been no hydrological investigation into the functioning of the soaks.

The goal of this study is to begin addressing the hydrological and current soak location knowledge gaps using Indigenous Knowledge, remote sensing, geophysical, and hydrological techniques. This project adds to our scant knowledge of where soaks occur along the Peninsula, how this compares to historical documented occurrence of soaks, and document basic hydrological characteristics to aid in the determination of vulnerability under climate change.

This report is split into the following sections: **chapter 2** describes the examination of historical and cultural information on the occurrence of soaks along the Younghusband Peninsula in accordance with the aim of understanding where soaks should occur, **chapters 3 and 4** then look at soak occurrence in the present day, describing first the remote sensing investigations to locate present day soaks and then the hydrological and geophysical investigations at a subset of the soaks to better understand how the identified soaks function. **Chapter 5** then brings this information together with projections of future conditions to understand how soaks may be vulnerable under future conditions, and **chapter 6** outlines further research needed to manage these important features under a changing climate. Finally, **chapter 7** summarises the soak hydrology in a simple infographic. This structure is in-line with the story-telling nature of this project, which has benefitted from close collaboration with the Traditional Owners of these lands.

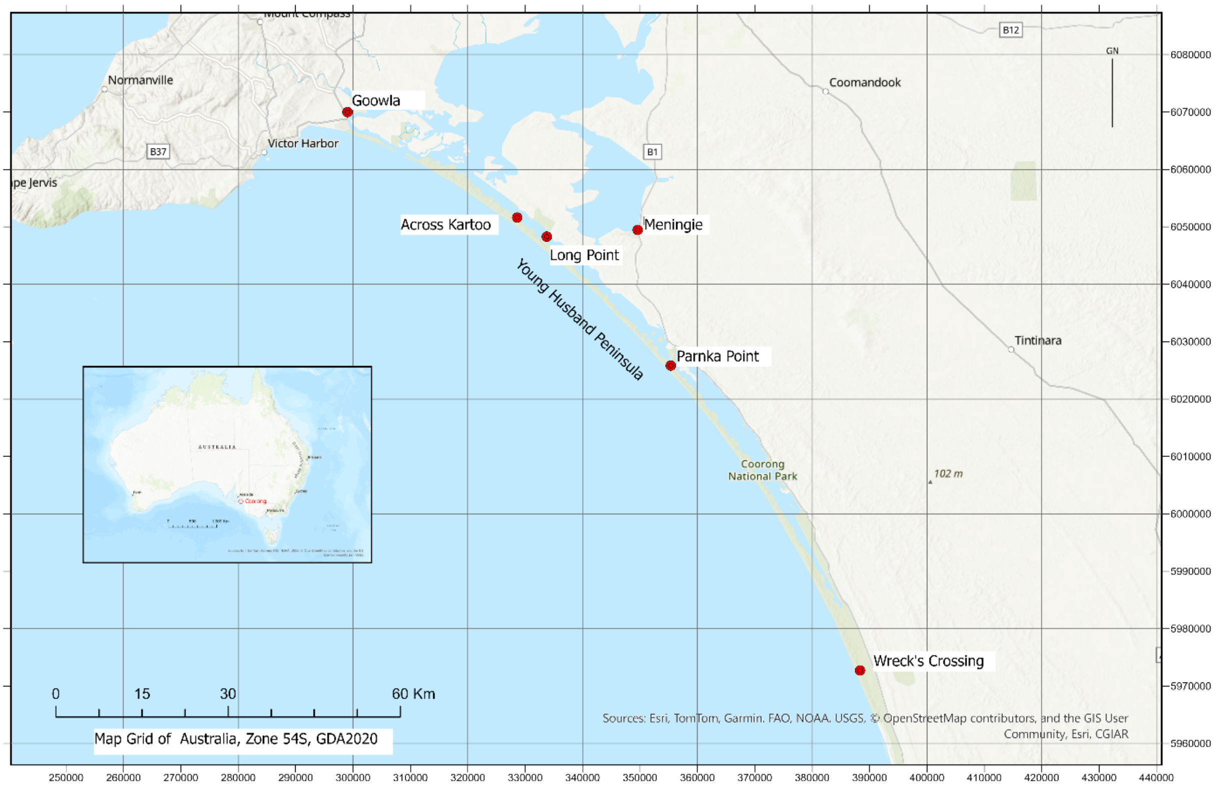


Figure 1. Map of the Coorong region, South Australia, showing the Younghusband Peninsula, which forms the barrier between the Coorong lagoon and the sea. Parnka Point is considered the border between the north and south lagoons of the Coorong; the points denote sampling locations described later. The inset map locates the study region within Australia (red box). Coordinates (m) are shown in MGA zone 54 S, GDA2020.

1.1 The Younghusband Peninsula

The Younghusband Peninsula is a transgressive and parabolic dune field that has evolved over the past 6500–7000 years (Paton, 2010). The Younghusband Peninsula, from the mouth of the Murray River down to the Granites in the Southeast, is made up of Holocene barrier deposits (Dillenburg et al., 2020); south of the Granites, older calcreted inliers related to interstadial sea-level stands of 80–100 ka occur (Moulton et al., 2019; Warner et al., 2022). The dune is composed of medium to fine quartz sand, with 50–90% calcium carbonate due to its origin from marine invertebrates (Bourman et al., 2016). A recent geophysical study in one part of the dune showed that the sands have undergone numerous periods of deposition and erosion, reworking the surface of the dune over time (Warner et al., 2022).

However, the dunes have undergone significant changes in the past 100 years, due to pastoralism, loss of Indigenous activities, introduction of invasive species, and consequent changes in vegetation. In particular, the introduction of rabbits to the region resulted in significant loss of vegetative cover on the dunes. Moulton et al. (2019) estimated approximately 7% vegetative cover at a site in the northern end of the Younghusband Peninsula in 1949 when rabbits were reaching plague densities, increasing more than five-fold into the 21st century after a series of rabbit control measures were undertaken by the government starting in 1952. It is unknown how much the land-use and vegetation changes have impacted the occurrence of waterholes along the Younghusband Peninsula.

1.2 Climate

The Younghusband Peninsula sits with a warm-summer Mediterranean type climate (Csb) (Beck et al., 2018), with rainfall predominantly falling during the winter. Mean annual rainfall in the region varies from 467 mm per year in Meningie at the northern end to 576 mm per year in Kingston at the southern end (Bureau of Meteorology, 2026; sites 024518 and 26012, respectively). An analysis of Meningie rainfall shows moderate inter-annual variations in rainfall (coefficient of variation: 21%) and marked periodic shifts in the cumulative monthly deviation (Figure 2).

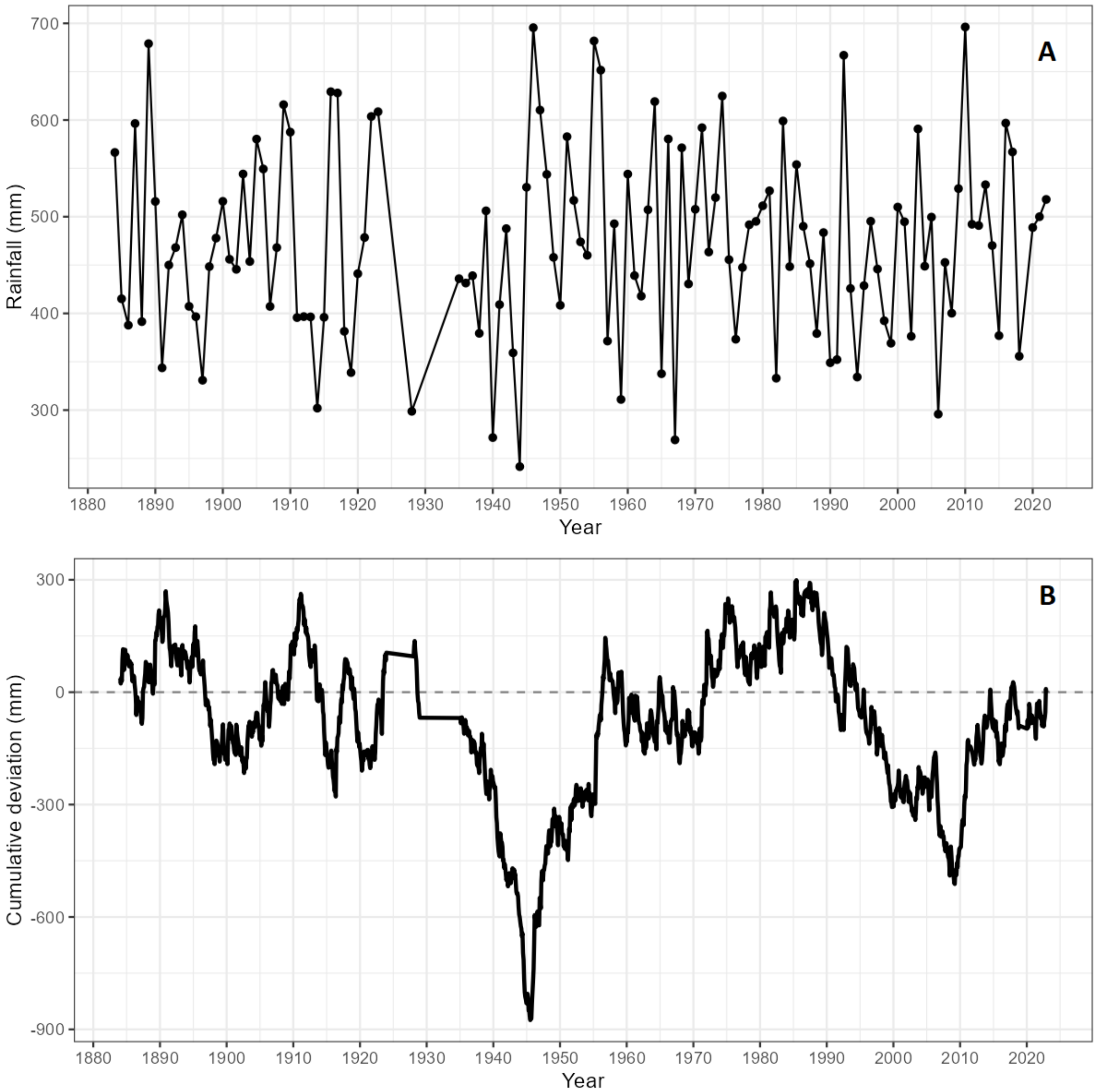


Figure 2. Annual rainfall totals at Meningie (Bureau of Meteorology station 024518) between 1884 and 2026 (A). Years with less than 90% of data were removed. Cumulative monthly rainfall deviation (B).

Temperatures along the Younghusband Peninsula are typically mild, with mean annual minimum and maximum temperatures at Meningie of 10.3°C and 20.9°C (Bureau of Meteorology, accessed 26/3/2026), with strong seasonality (Figure 3). Evapotranspiration rates for the Younghusband Peninsula are estimated herein.

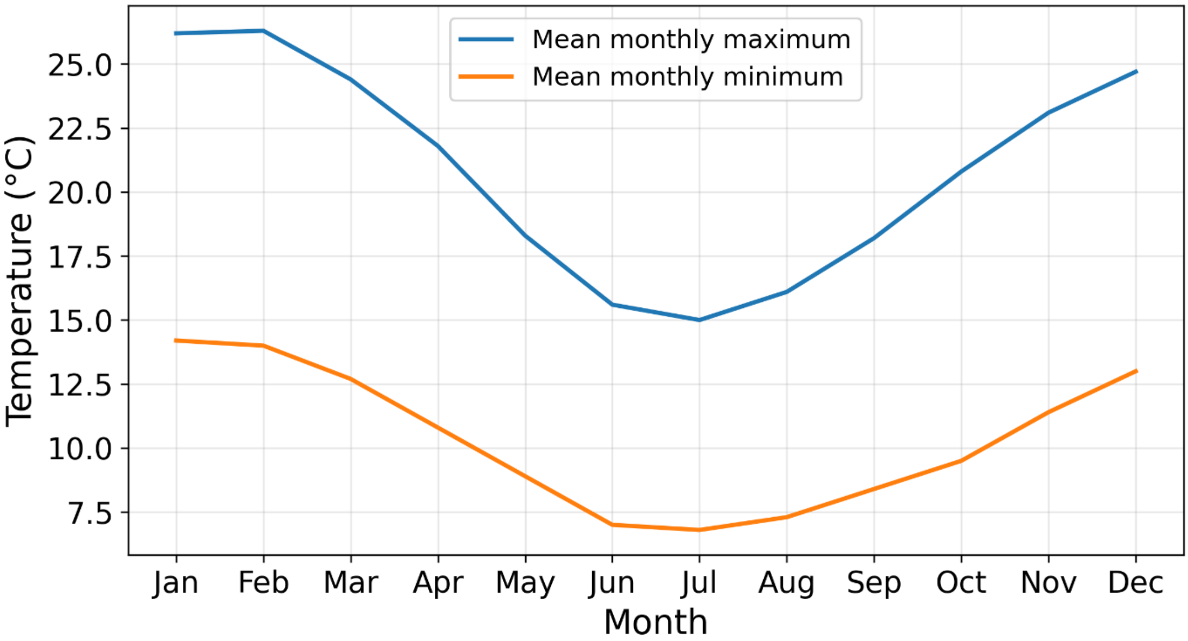


Figure 3. Mean monthly maximum and minimum temperatures at Meningie (Bureau of Meteorology Meningie Station 024518, accessed 8/6/2026).

2 Soaks of the past

2.1 Tindale and Milerum Maps

In the 1930s, anthropologist Norman Barnett Tindale repeatedly travelled the Coorong with Ngarrindjeri colleague Milerum (Clarence Long), recording Milerum's knowledge of Country. Tindale annotated a series of County and Hundred Map Series maps, prepared by the Surveyor-General, to record culturally-important locations (SAM 2026). A hundred is a 100 square mile section of a County (Figure 4). For this project, the Clyde and Santo Hundred and the County Cardwell maps were found to cover the length of the Younghusband Peninsula. In addition to a wealth of culturally important sites such as camps, the hundred maps were found to also demarcate important soaks, likely used for watering stock at the time. The maps denote these features as "waterholes"; therefore, in this section, we refer to soaks as waterholes.

The maps were manually georeferenced in ArcGIS Pro by selecting 4–6 points on the map that corresponded to features on the 2018 Southeast Coast Lidar imagery (Hobbs et al., 2020) and the locations (both colonial and Ngarrindjeri) marked on the maps with points in ESRI ArcGIS Pro software. The likely maximum positional error due to the georeferencing process is approximately 200 m, given that there is almost no development on the Younghusband Peninsula and much of the exact coastline appears to have shifted over the past century.

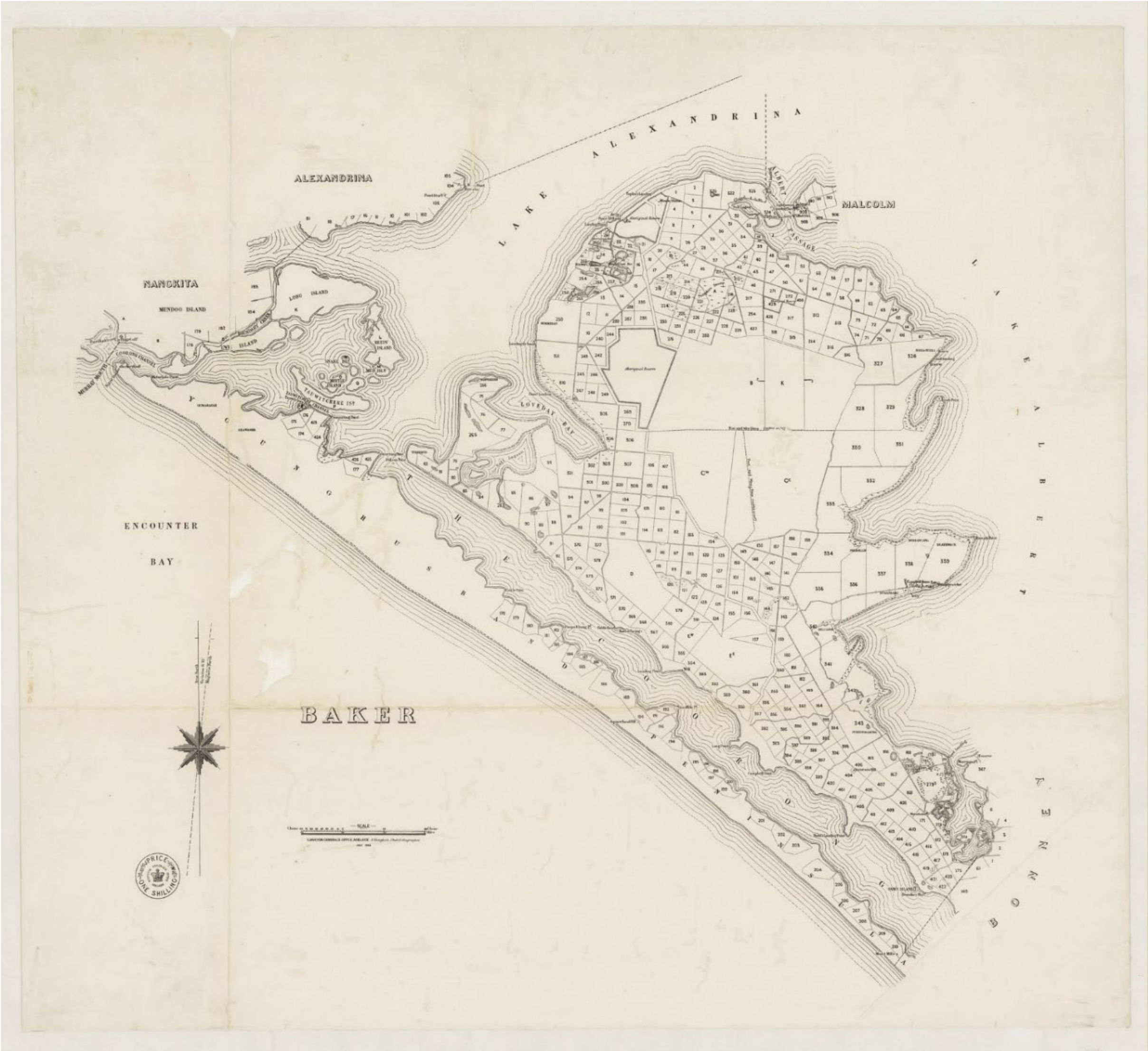


Figure 4. Example of Tindale's basemaps; Hundred of Baker, 1893 (https://www.flickr.com/photos/state_library_south_australia/22472967047). This and other hundreds were annotated by Tindale to reflect culturally-important information told to him in the 1930s. Annotated maps available by request through the South Australian Library.

In total, 81 historic points were digitised, many of which are single Ngarrindjeri words, and likely refer to the family names of camps. However, there are also features specifically annotated as waterholes or lagoons. In total, 53 unidentified Indigenous place names, three lagoons (two with Indigenous names), and 23 waterholes were mapped. Of the waterholes, 12 were marked exclusively on the basemaps, 5 appeared to be on basemaps and have Indigenous names, and six additional waterholes were only identified through the annotations (Figure 5).

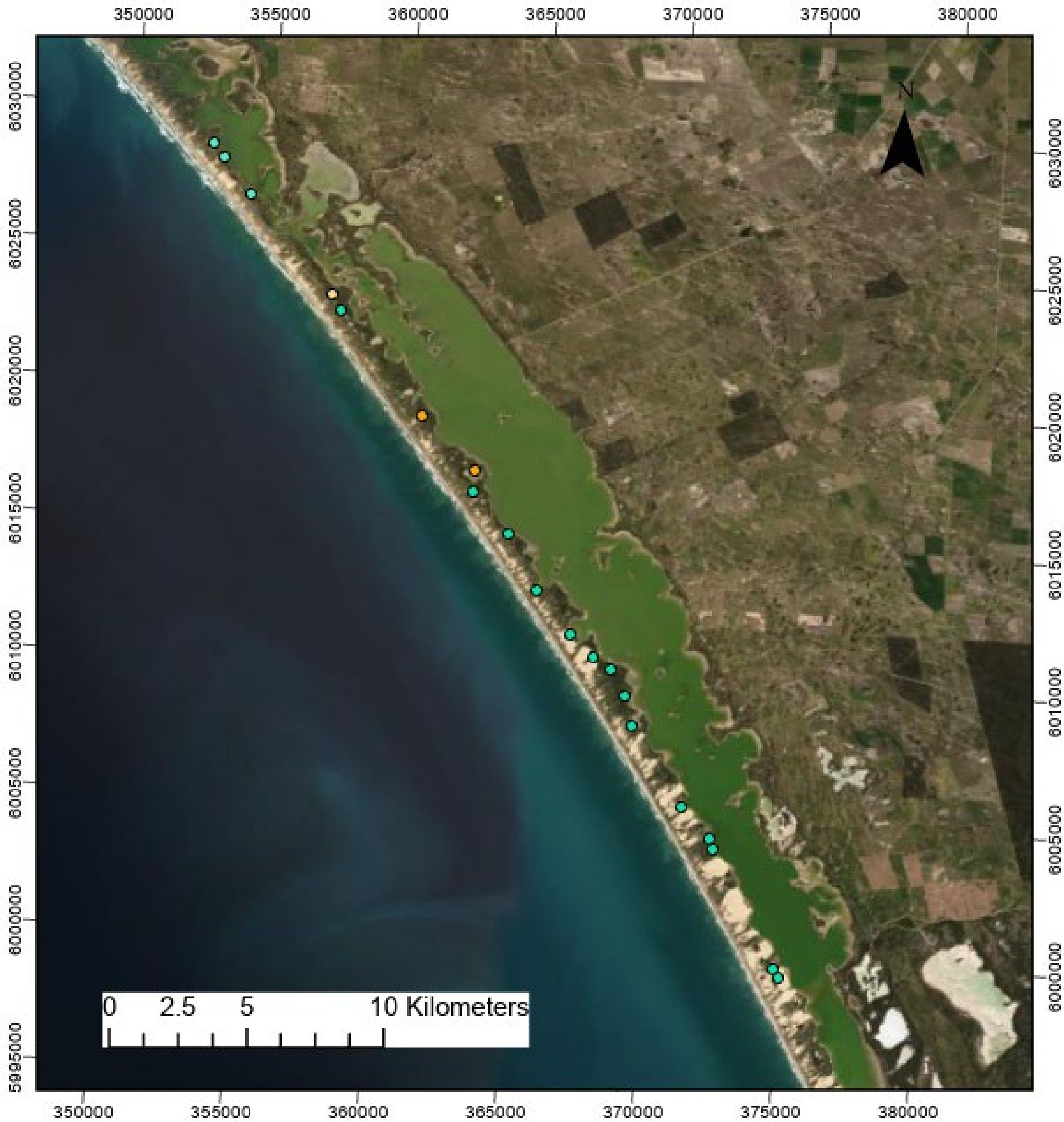


Figure 5. Map of digitised waterholes (blue) and lagoons (orange) from historical hundred maps, plotted over ESRI base imagery. For reference, Pelican Point is near the top of the map. Only the features shown on the basemaps are included here, as the annotated information is culturally sensitive information. Coordinates (m) are shown in MGA zone 54 S, GDA2020.

From the historical maps, it is apparent that waterholes were prevalent along the Coorong coastline, especially in the Southern Lagoon. As an initial investigation of whether these waterholes persist in the modern landscape, Google Earth Pro imagery of the Coorong was scanned. Using the timelapse option, the length of the Younghusband Peninsula was manually scanned for open water bodies in images from 2010 onwards (e.g., when the imagery became clear enough to identify features with high confidence). Of the historical waterhole sites, only two appeared to have (small) surface water expressions within 200 m of the location in Google Earth images, and not consistently throughout the 15 years of imagery. Most of the points did, however, appear to be in or near clumps of green vegetation (Figure 6), prompting further efforts to identify waterholes in satellite imagery using the presence of reeds, as described in the following chapter.

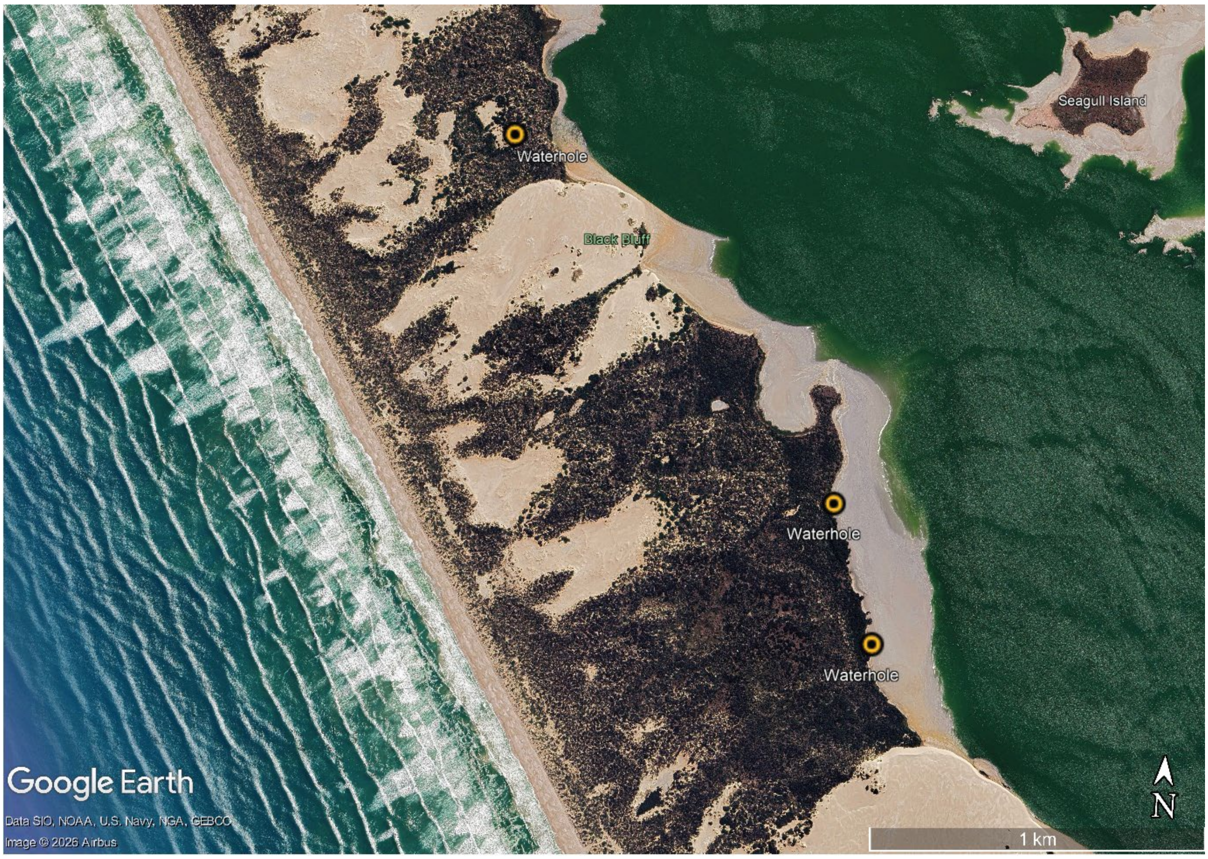


Figure 6. Example of manual examination of Google Earth imagery overlain by several historical points as a first step in "ground-truthing" current soak occurrence. The "waterhole" locations may correspond to the green areas at the margins of the dune where groundwater discharge; however, there is no modern expression of water at the surface at any location in the map section.

2.2 Indigenous Knowledge; consulting the First Nations Elders

The May 2025 field campaign was a time to build relationships with Ngarrindjeri Rangers and First Nations Elders. Each day the project team met elders and rangers, discussed the plans for the day, and listened to the advice of the elders (Figure 7). Although on-Country activities were planned for each day, our plans had to be adjusted on the several days, as weather conditions meant that the group was not comfortable traversing the Coorong. However, this time was used for relationship-building through discussions on-Country on the mainland. In July 2025, digitised data were shared with the Ngarrindjeri community, and Elders spent several hours yarning about soaks with the project team. One particularly interesting comment from the Elders was that the soaks marked as "waterholes" on the historical maps (the government basemaps, not the annotations) would have been natural soaks, not dug out for watering cattle and sheep. These waterholes were critical for the supply of water to both human and animals at the time the maps were produced; one of them is annotated that it is the only fresh water supply in the region. During the July yarning, Uncle Darryl described a memory from 1955, when he experienced Indigenous people still using the soaks as a primary water source. This story confirms that there were Ngarrindjeri camps along the Younghusband Peninsula into the 1950s. Therefore, it was likely that soaks marked on historic maps would have been maintained as water sources at least until this time:

“I travelled with my dad down from 42 mile in an old Ford Model T. We travelled right back to Barkers Knoll, I think. A group of Ngarrindjeri men rushed dad, there was quite a bit of them. There was still people living there then, believe it or not. They looked around for these sticks, probably to try to hit us. But my dad showed them a bottle of water. One of them spoke English, so I think the missionaries must have been over there for them to do that. One of them said, “we all got guts aches, stomach aches”. And my dad asked them what water they were drinking. “Fresh water over there on the Coorong’s edge” And my dad asked “are you boiling your water”. Even though it’s fresh water, still had that bit of salt in it. They said “No. We realised that it’s giving us guts aches”, the man said. “So we went in between the Coorong and the Ocean, and we dug holes there and fresh water come up there, and they had no guts aches.”

Figure 7. May fieldwork was a time to get to know each other. Before each day of fieldwork, the project team met with Ngarrindjeri rangers and elders to plan the day's activities.

3 Current occurrence: Remote Sensing Investigations

Several previous studies including Ji et al. (2022) and Mishra et al. (2013)have used remote sensing techniques to identify small water bodies. Bickerton and Winter (2001) used aerial imagery to identify soak location followed by field verification and positioning with handheld GPS to locate nine soaks in the southern Coorong lagoon. Given the technical challenges in using field methods to manually locate soaks along the largely inaccessible, 180 km long Younghusband Peninsula, the aim of this section was to determine whether remote sensing techniques can be applied to very high resolution (VHR) satellite imagery to detect and map low salinity soaks. The advantage here is that satellite imaging generally covers large areas at a single point in time or within a brief period, potentially allowing remote detection.

The following sub-sections describe first the preparation of the satellite imagery, then the development of a method to identify soaks from the imagery, and conclude by presenting the ground-truthed soaks that were identified by the method.

3.1 Data Sources

Pléiades Neo (PN) is a VHR (Very High Resolution) sensor installed on a constellation of low Earth orbiting satellites. Pléiades Neo products consist of a multi-spectral image with 6 spectral bands (Deep Blue, Blue, Green, Red, Red Edge, Near-infrared) with a 1.2 m spatial resolution, as well as a panchromatic image with a resolution of 30 cm. The two PN images (tiles) used in this research were captured on 5 July and 13 July 2024, respectively.

A subset of the Southeast Coastline LiDAR 2018 dataset was sourced through the ELVIS elevation database (https://elevation.fsdf.org.au). These data were captured using a Trimble AX60 LiDAR sensor between 22 May and 24 August 2018; the dataset includes a Digital Elevation Model (DEM) product which was interpolated from the LiDAR (Hobbs et al., 2020).

At selected soak sites, a DJI Mavic 3 Multispectral drone was used to capture frame imagery and video of the soak. The drone captures imagery in 4 spectral bands (green, red, red-edge, and near-infrared) at 5 megapixels (MP), and a Red, Green, Blue (RGB) image at 20 MP. This high-resolution drone imagery was used to provide detailed imagery to assist in detecting spatial relationships between soak location, vegetation and topography.

Spatial locations of sites were recorded in the field using a differential GNSS RTK device (Trimble DA2 Catalyst), which provided a spatial horizontal accuracy of 5 cm and a vertical spatial accuracy of 10 cm.

3.2 Typical Soak Site

Initially, the characteristics of a "typical" soak were defined in order to assist the identification of soak sites across the two PN tiles (Figure 8 and Figure 9). From initial fieldwork and human observation of satellite imagery, a low salinity soak site was observed likely to exhibit the following:

- Specific topography consisting of relatively steep dunes around the edges of a concave Coorong shoreline, Soaks are likely to occur in flat terrain between the base of the dunes and edge of hypersaline water in the Coorong and be slightly elevated in respect to mean water heights in the Coorong, and
- Gradation of vegetation species spread along the dune edge edged by *Phragmites australis* (common reed) and finishing with samphire species surrounding the soak. The spatial relationship between *Phragmites australis* and low salinity soaks appears strong with this being supported by Jason Nicol (pers. comm Jan 2026; Chambers et al (2003) and https://revegetation.org.au/?project=phragmites-australis). Figure 8 and Figure 13 clearly show *Phragmites australis* adjacent to soaks. Bickerton and Winter (2001) also note this relationship.

Figure 8. Drone imagery of two adjacent soak sites (outlined in red) found during fieldwork in October 2025. Photo credit: Eddie Banks.

Figure 9. 3D perspective view from a northerly direction of a known soak site with the imagery draped over the DEM from LiDAR. Soak outlined in red and surrounded on the eastern, southern and northern sides by *Phragmites australis.*

3.3 *Image processing*

Satellite image processing was undertaken using ArcGIS Pro v3.6 (ESRI, Redlands, California) with QGIS version 3.40 used for additional processing (QGIS Development Team, 2026). All raster and vector layers imported and created were projected or reprojected to the MGA Zone 54S GDA2020 coordinate system.

3.3.1 Pan-sharpening

Initial processing included pan-sharpening each PN tile, using the GDAL algorithm built-into QGIS version 3.40. Pan-sharpening is the product of sharpening lower-resolution multi-spectral imagery by fusing it to high-resolution panchromatic imagery (Alcaras et al., 2021). Pan-sharpening enabled a higher spatial resolution to be utilised than if just multi-spectral imager was used.

3.3.2 Image Rectification and Mosaicking

AirBus states the geometric accuracy of its PN orthoimage product as 3.5 m CE90 (3 pixels) (https://space-solutions.airbus.com/imagery/our-optical-and-radar-satellite-imagery/pleiades-neo/). Thus, it was expected that there may be minor spatial disagreement between field based GNSS – RTK measurements and locations of potential soaks established from PN image processing. It was also likely that differing tiles / images from PN image captures and subsequent pan-sharpening were likely to differ in position. In this latter case, the relative position of the two images used in this research did not agree, as illustrated in the overlap area shown in Figure 10. Because training for the machine learning algorithms explained in Section 3.5 required that imagery be in one file, these images needed to be mosaicked.

Figure 10. Enlarged view of the overlap / junction of two PN images, with the red line symbolizing the boundary of the junction area and illustrating the spatial mis-alignment (yellow ellipse). This view was established after removal of edge pixels by image masking.

Eight manual image control points (ICP) were selected in the overlap area to the two PN tiles; these were used with an image matching algorithm to locate a further 306 ICPs. Using a first order similarity geometric transform, coefficients and least squares residuals were computed for the 314 ICPs and, after inspection, the transform was applied to the north-westerly image. After image geometric transformation the two images were mosaicked using a "blend" of image pixels from one side of the overlap area to the other.

3.3.3 Final Mosaicked Imagery

Statistics for the 314 ICPs used in image transformation showed a total Root Mean Square (RMS) of 0.459m with a minimum and maximum of 0.009m and 1.586m respectively. This was within the tolerance quoted by AirBus. Figure 11 provides a view of a section of the mosaiced imagery and Figure 12 illustrates the result of the mosaicking to the same area shown in Figure 10.

Figure 11. Mosaicked imagery with mask boundaries for each image shown in red (Southeastern image) and black (Northwestern image). The image overlap area corresponds to the intersection of the red and black polygons.

Figure 12. Result of image mosaicking to same area illustrated in Figure 10.

3.4 Human Identification of Potential Soaks – creation of vector polygons

Potential soaks along the eastern edge of Younghusband Peninsula in the two PN tiles were manually identified and digitised as polygons. This involved visually scanning the tiles, starting at the south-east corner of the tile and working up along the Coorong / dune boundary, to identify potential soaks based on size, shape, location, and colour.

The polygons were identified by an inexperienced operator, directed by staff who have multiple years of experience in the Coorong (Banks and Shanafield). At this point in the process, the result was provisional, requiring additional digital filtering and field assessment to confirm or deny soak presence. Once this area had been assessed, scanning was applied to dunes areas. This process was reiterated across both tiles multiple times to include as many potential soaks as possible, while minimizing uncertainty for sites that may not be soaks. To uniquely identify each potential soak that was digitized, a unique ID was created for each vector. This followed the rule of S - (Tile Number) - (Soak Number), where 'SoakNo' incremented after each soak. An example is S-02-04, which is the 4th soak from the second tile. In a few cases, after ground truthing, multiple samples were taken in larger soaks. To account for this, an additional number was added to the end of the Soak Number (e.g. If Tile 2 Soak 4 had two soak locations, it would be written as: S-02-04-1 and S-02-04-2).

A validation process occurred after digitizing the potential soak locations, which included a review of each polygon against historical Google Earth Imagery. This was undertaken to determine if there was evidence of a water body at the location of the potential soak historically.

A total of 29 potential sites were digitized across the first PN tile and a further 15 sites were digitized across the second PN tile. An example of three digitized potential soaks is shown in Figure 13.

Figure 13. Digitisation in red of 3 potential soak vectors created in the north-west tile

After a validation process, Tile 1 had five soak sites that showed evidence of a water body historically and a further four soak sites from the second tile. Appendix Figure A1 shows a map of all potential soak sites digitized through this process.

3.5 Computer Training and Analysis

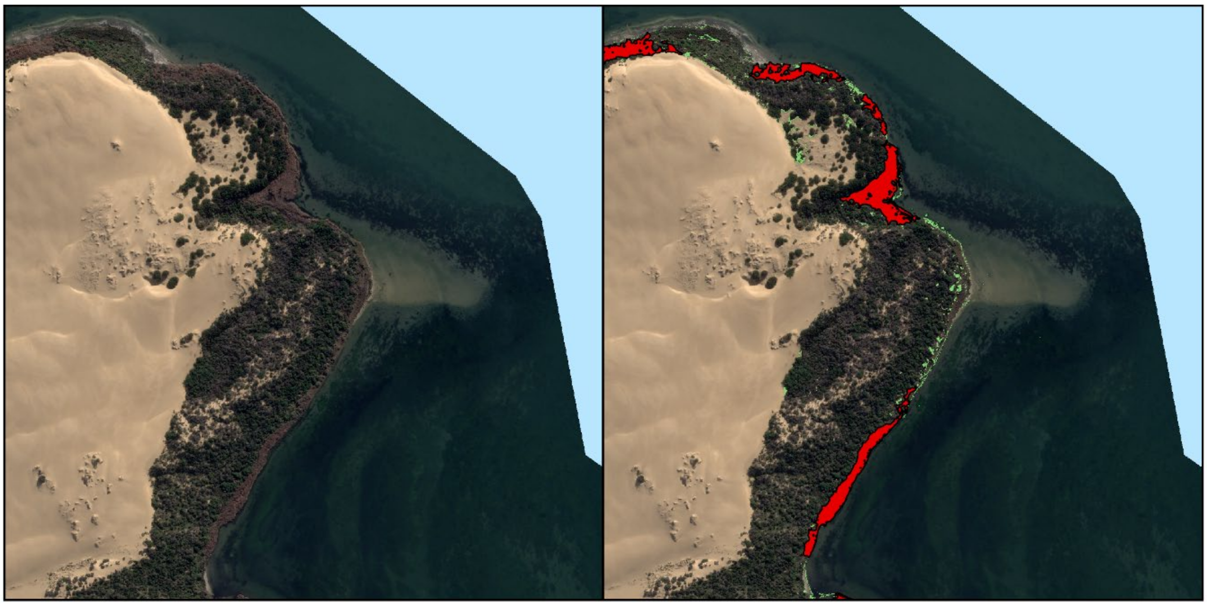
Elevation was a common factor affecting soak and common reed locations and was composited with the rectified satellite image mosaics. Using this composite training, samples for multiple land-cover types (e.g. Light/dark vegetation, reeds, water, sand and shadow) were created. Using the Random Trees (ESRI ArcGIS Pro version of Random Forest) supervised classification algorithm, the composite raster was classified. Here the objective was to use robust classifier applied to more than just spectral data to achieve a land cover classification with corresponding accuracy statistics. Parameters of a maximum number of 200 decision trees, a maximum decision tree depth of 30 and maximum number of samples per class of 2,000 pixels were used. The classification for reeds was then extracted by a reclassification process with not reeds set to 'NoData'. Boundary Clean and Majority Filter spatial tools were then applied to smooth object boundaries, "cleaning" the reed classification layer, followed by conversion into a polygon layer. A final filtering of the polygons was applied by removing any polygons with an area less than 300 m^2 (Figure 15). The fully cleaned reed classification polygon layer was then used in a proximity tool, comparing the distance from the mid-point of each potential soak vector with the nearest reed polygon boundary to the soak site. Lastly, a threshold was set to determine the distance from a potential soak to nearest reed polygon. In this case, if a potential soak was located within 35m of classified reeds, it was considered potentially a low salinity soak. In many cases reeds were located much closer than 35m.

The output was created after multiple iterations of the classification algorithm training across the two PN tiles used in the mosaic (Figure 14). The classifier resulted in an internal random forest accuracy of 95.7%, with the variable importance / weight for each band shown in Table 1.

Table 1. Variable Importance of each band from the Random Forest classification on two PN mosaiced tiles.

NUMBER	BAND	VARIABLE IMPORTANCE (%)
1	Red	16.40
2	Green	11.75
3	Blue	8.56
4	Near-Infrared	18.71
5	Red-Edge	13.54
6	Deep-blue	7.41
7	DEM	23.64

Figure 14: Classification output on two PN tiles after multiple iterations of training.



a) Section of NW tile with no classification

b) Section of NW tile with initial and clean reed classification

Legend

Cleaned Reed Polygons

Uncleaned Reeds

Figure 15. Section of reed classification, demonstrating the change before and after the cleaning method described above.

After the cleaning process was applied to the extracted reed polygons, 48 individual polygons representing classified reeds, covering a total of 71,229 m^2, remained Using the distance from potential soaks to reeds each potential soak was predicted as low-salinity or high salinity, using the distance threshold as described above. This threshold returned a total of 28 soaks that were identified as high-salinity soaks and 15 soaks identified as potentially low-salinity soaks.

Table 2 below shows the data for each potential soak, distance to nearest reeds, salinity prediction, and result from ground-truthing (if applicable) (Section 3 and classification accuracy).

Table 2. Summary of digitised potential soak sites with their respective ID, distance to closest reeds, ground-truthing (GT) data and accuracy checks (where relevant). Y = estimated low salinity, N = estimated high salinity

SOAKID	LATITUDE (DEGREES)	LONGITUDE (DEGREES)	DISTANCE TO REEDS (M)	GT	GT DATE	GT RESULT (MS/CM)	MODELLED SALINITY CLASSIFICATION	FIELD VALIDATION
S-01-01	-35.63128601	139.0485096	681	N	N/A	N/A	N	No GT
S-01-02	-35.6329781	139.0614789	15	N	N/A	N/A	Y	No GT
S-01-03	-35.63534404	139.0628815	2	Y	Oct-25	41696	Y	N
S-01-04	-35.63549564	139.0627978	2	Y	Oct-25	35028	Y	N
S-01-05	-35.64988927	139.0814028	0	N	N/A	N/A	Y	No GT
S-01-06	-35.65859175	139.0994052	2	Y	Oct-25	35374	Y	N
S-01-07-1	-35.65894909	139.0999287	3	Y	Oct-25	11266	Y	Y
S-01-07-2	-35.65888499	139.0991444	1	Y	Oct-25	7340	Y	Y
S-01-08	-35.66029277	139.100545	8	N	N/A	N/A	Y	No GT
S-01-09	-35.66195371	139.1034909	116	Y	Oct-25	133432	N	Y
S-01-10-1	-35.66328793	139.1063116	1	Y	Oct-25	3668	Y	Y
S-01-10-2	-35.66290594	139.1053296	15	Y	Oct-25	3474	Y	Y
S-01-11	-35.66364207	139.1097379	38	N	N/A	N/A	N	No GT
S-01-12	-35.66570677	139.1122873	1	N	N/A	N/A	Y	No GT
S-01-13	-35.67150135	139.1125025	1	N	N/A	N/A	Y	No GT
S-01-14	-35.67286506	139.114803	152	N	N/A	N/A	N	N
S-01-15	-35.67302686	139.1145947	149	Y	May-25	49117	N	N
S-01-16	-35.67302142	139.1150828	182	Y	May-25	63785	N	Y
S-01-17-1	-35.6740504	139.1190711	3	Y	Oct-25	22392	Y	N
S-01-17-2	-35.67392113	139.1184683	32	Y	Oct-25	5766	N	N
S-01-18	-35.67875111	139.1226062	4	Y	Oct-25	2891	Y	Y
S-01-19	-35.68150977	139.1267226	449	N	N/A	N/A	N	No GT
S-01-20	-35.69421016	139.1433328	1102	N	N/A	N/A	N	No GT
S-01-21	-35.69431035	139.1431348	1109	N	N/A	N/A	N	No GT
S-01-22	-35.69430657	139.1427783	1135	N	N/A	N/A	N	No GT

S-01-23	-35.6968622	139.1497563	481	N	N/A	N/A	N	No GT
S-01-24	-35.69879544	139.1507122	263	N	N/A	N/A	N	No GT
S-01-25	-35.71143871	139.1740067	683	N	N/A	N/A	N	No GT
S-01-26	-35.72826964	139.1948237	556	N	N/A	N/A	N	No GT
S-02-01	-35.73939326	139.2131638	602	N	N/A	N/A	N	No GT
S-02-02	-35.74863983	139.2180252	38	N	N/A	N/A	N	No GT
S-02-03	-35.74895647	139.2180839	7	N	N/A	N/A	Y	No GT
S-02-04	-35.75071464	139.2222042	378	Y	Feb-26	68856	N	Y
S-02-05	-35.75081725	139.2225068	408	Y	Feb-26	60390	N	Y
S-02-06	-35.7528336	139.2232939	590	Y	Oct-25	57352	N	Y
S-02-07	-35.75301814	139.2231006	591	Y	Oct-25	11975	N	N
S-02-08	-35.75900329	139.2337402	1314	N	N/A	N/A	N	No GT
S-02-09	-35.75968274	139.2338655	1247	N	N/A	N/A	N	No GT
S-02-10	-35.76304429	139.2428025	617	N	N/A	N/A	N	No GT
S-02-11	-35.76364128	139.2427986	550	Y	Oct-25	84577	N	Y
S-02-12	-35.76875974	139.2428963	36	N	N/A	N/A	N	No GT
S-02-13	-35.79294363	139.2784722	4222	N	N/A	N/A	N	No GT
S-02-14	-35.81451426	139.2978745	7136	N	N/A	N/A	N	No GT

3.6 *Field Validation*

Before each of the field trips occurred, maps were created using a sub-set of potential soak sites which were aimed to be visited during the trip (Figure 16). When visiting a soak site, there was a 3-step procedure. Firstly, a Trimble R10 GNSS-RTK device was used to record accurate locational data for the soak site. Secondly, the Aqua TROLL device was used to measure the water quality variables, including a salinity measurement where water depths permitted such measurement. Thirdly, terrestrial images and notes were taken about the soak site, and in some cases drone imagery was also captured using the DJI Mavic 3 Multispectral drone. Device information described in Section 3.2 Data Sources.

Figure 16. Example map of 2 soak sites located on the boundary of the 2 PN tiles, planned for visit during the February 2026 field work.

Throughout 2025 and early 2026, three field trips (May and October 2025, and February 2026) were conducted to collect ground-truth water quality data and imagery of soak sites along the Younghusband peninsula. Across the three trips, a total of 18 soak sites were visited with water quality data (including salinity) captured. Refer to Appendix 9.2 and Appendix 9.3 for a map of all the sites visited across the three field trips.

During the May 2025 fieldwork, only two soak sites were able to be visited and have water quality data captured for further analysis, both in the northern section of the first tile.

The October 2025 fieldwork was able to gather additional data on potential soak sites over two days, where water quality data at 14 sites were collected. These sites were generally spread across the north-western tile; some soaks being sampled near the top boundary of the south-eastern tile.

In February 2026, final fieldwork was conducted primarily focusing on the south-eastern tile and potential soaks in the area. However, throughout this fieldwork many of the soak sites visited were dried out and could not be sampled for water quality measurements (example image in Figure 17, left). There was a single site of three soaks that was able to be sampled in two locations accessible (Figure 17, right).

Figure 17. Images taken on 24 February 2026 field work, (Left) Example of a dried soak site, (Right) Drone imagery captured of a site with three water soaks containing water.

3.7 Results: Accuracy Assessment

Once image processing and fieldwork was completed, an accuracy assessment was performed to determine how accurately the method and classification could predict if a digitized potential soak was low salinity or high salinity.

To assess the accuracy of the method, another threshold was set to determine what was classed as low salinity or high salinity. Based on Bailey et al. (2002), *Phragmites australis* was recorded in an instance to live up to a salinity concentration of 15,000 μS/cm, before dying. Therefore, soaks found with a salinity less than this threshold were considered low salinity and soaks with a salinity greater than the threshold considered high salinity.

For the set of soaks checked in the field, predicted vs observed salinity class was cross-tabulated to determine the overall accuracy of classification from the imagery. Using the predictions for each potential soak (described above), ground truth data for the 18 soak sites visited was applied to determine the accuracy of the proposed method. Using this data (Table 2), a confusion matrix was calculated (Table 3).

Table 3. Confusion matrix demonstrating the performance of the reed classification method using ground-truth data.

	PREDICTED LOW SALINITY	PREDICTED HIGH SALINITY
Actual Low Salinity	7	4
Actual High Salinity	1	6
	Accuracy	72.2%
	Precision	60.0%
	Recall	85.7%
	F1 Score	70.6%

Based on the results shown in Table 3, the classification accuracy of 72% suggests the model was reasonably accurate when predicting whether a soak was low salinity or high salinity. A recall of 85.7%, suggests the model was moderately successful in identifying low-salinity soaks. However, the precision of the method was only 60%, which suggests there is a 40% chance of a positive result being inaccurate; slightly better than random. These small sample sizes need to be enlarged before meaningful statistics can be established.

4 Current occurrence: Hydrology

Bickert and Winter (2001) reproduce a geo-ecological schematic from a 1977 publication as background to their study of a select group of Coorong soaks (Figure 18). The figure proposes a geological structure where that would control the flow of infiltrated water through the dune and towards the edge of the Coorong, where the soaks are typically found. The report's following figure, however, proposes a symmetrical freshwater lens within the dunes, flowing out into the Coorong and sea on either side. To our knowledge, there has been no modern ground-truthing of the dune structure specifically to better understand controls on the hydrology of the soaks. Therefore, the objectives of the current project were to use hydrological and hydrogeophysical methods to better characterise the water balance of the soaks. Fieldwork was conducted in May and October 2025.

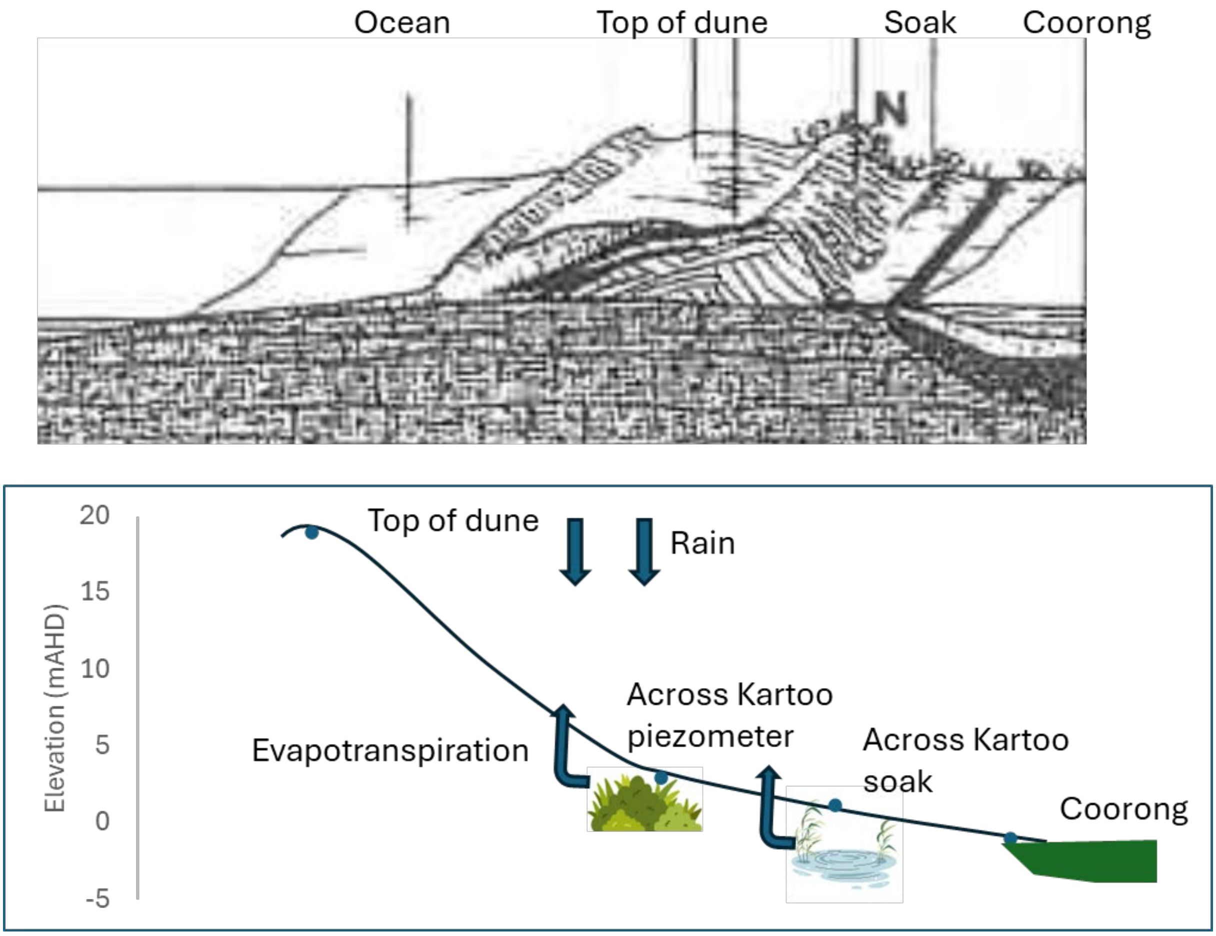


Figure 18. Proposed schematic of Younghusband Peninsula geology taken from Bickert and Winter (2001) (top). Comparative conceptual model of dune-Coorong interface at the Across Kartoo soak based on survey measurements (bottom). Labelling on the top diagram was added for comparison; it does not appear in Bickert and Winter (2001).

A previous project led by the South Australian Department for Environment and Water (DEW, 2024), had identified two soaks for detailed study; one that the project labelled "Across Kartoo" in the northern end of the peninsula (Figure 1 and Figure 19) and one at Wreck Crossing at the southern end of the peninsula (Figure 20). B

Figure 19. Across Kartoo soak as seen from drone imagery, May 2024.

Figure 20. Fieldwork at the dry Wreck Crossing soak in May 2025, supervised by Boandik Uncle Terry and Kyla McHughes.

Boandik and Ngarrindjeri Elders had directed DEW staff to these soaks for study. Geophysical surveys were focussed at Across Kartoo soak, complemented by surveying of a newly installed piezometer, the open soak, and the Coorong to understand head differences. Physical and chemical water quality measurements and stable isotopes were collected at both Across Kartoo and Wreck Crossing to add a longer time series onto the DEW (2024) study results and better understand how these soaks may be representative of other soaks throughout the Younghusband Peninsula.

Methodology and results are described in the following sub-sections.

4.1 Loupe TEM surveys

4.1.1 Methods

Near-surface hydrogeophysical surveys were performed using a Loupe transient electromagnetic (TEM) system, specifically designed for rapid surveys of subsurface conductivity measurements down to depths of approximately 40 m (Figure 21). This geophysical method is a quick and non-destructive way of mapping shallow subsurface conductivity over an area. A southwest to northeast survey across the Younghusband Peninsula was completed at Across Kartoo site in each of May 2024 and May 2025.

The Loupe TEM receiver and transmitter are each carried by one person on a backpack. Loupe incorporates a three component coil sensor with 100 kHz bandwidth, a fast-switching transmitter loop, a user-interface integrated with an accurate GPS for position location. The system records full time-series TEM data to memory and processes it in real-time and uses signal processing methodologies developed for SMARTem receiver systems (Duncan et al., 1998).

The datasets were inverted using the University of Aarhus AarhusInv 1D inversion code in the Aarhus Workbench software (http://hgg.au.dk/software/aarhusinv/)(Auken et al., 2015). The QA/QC processed raw data was inverted using a laterally constrained inversion (LC), 35-layer smooth model. Each sounding, which is collected at a 1second interval (approx. 3 m spacing) is inverted individually; the result is a vertical "sounding" made up of many layers, each assigned an estimated resistivity, which varies smoothly with depth. Because conductivity and resistivity are mathematical inverses of one another, you can easily convert between the two; in Australia and the types of environments that we work in it is common to use conductivity, measured in milli-Siemens per meter (µS/cm). It is worth noting that the apparent or bulk conductivity results from TEM systems is different from fluid electrical conductivity that is measured with a water quality meter; the former is influenced to a greater extent the salinity of the water within the pore spaces of the subsurface but also the lithology type (e.g., clay versus sand), porosity and to a lesser extent temperature. Results for a survey transect line in this report are presented as a conductivity-depth section or depth slice (providing there are multiple, closely spaced soundings) by using an LCI. The Root Mean Square Error (RMSE) is also shown on the figures to evaluate how well the geophysical inversion model fits the observed field data.

Figure 21. Loupe survey transversing the dune at the Across Kartoo site.

The measured response in the Loupe, as with other electromagnetic induction systems, is dependent on the distribution of subsurface conductivities, which includes the water quality (e.g., salinity) of the water within the pore spaces, the porosity (e.g. water content) and the material and mineralogy (e.g. sand versus clay) (Lesmes & Friedman, 2005). There is a very broad range of conductivities for different unconsolidated and consolidated sedimentary, alluvial and regolith material depending on water quantity and quality within the moisture-filled pore spaces within the matrix of the material.

4.1.2 Results

Results from the 2024 and 2025 surveys show subsurface conductivity ranging from 2 to 2,000 µS/cm (Figure 22). There are some clear subsurface conductivity features in these cross-sections from the Southern Ocean at the southwestern end of the section to the Coorong at the northeastern end of the section. There is a distinctive low conductivity beach dune system from 1000 m to 1700 m at an elevation above 0 mAHD. There is also some possible evidence of a low salinity lens between 300 and

1000 m and between 0 and -30 mAHD. Overall, the surveys identify distinct regions of potentially lower salinity water, constrained either by saltwater or by lithology below -30 mAHD and up to 0 mAHD by saltwater on both Coorong and Ocean sides of the Younghusband Peninsula. The lower salinity water in the dunes that are perched above sea level on the Coorong side of the dune provide a 20 m high and almost 200 m wide water source, which potentially drains towards the Across Kartoo soak, maintaining water in the soak year-round.

The 2025 transect was completed at the same location as the May 2024 transect during the DEW project, allowing temporal comparison. Between the two Loupe surveys there are some subtle changes in the subsurface conductivity. The most pronounced difference is that the conductivity values are lower in 2025 at -5 mAHD between 1000 and 1500 m along the cross section. This change appears to suggest a freshening across that layer; however, the period leading into May 2025 was extremely dry.

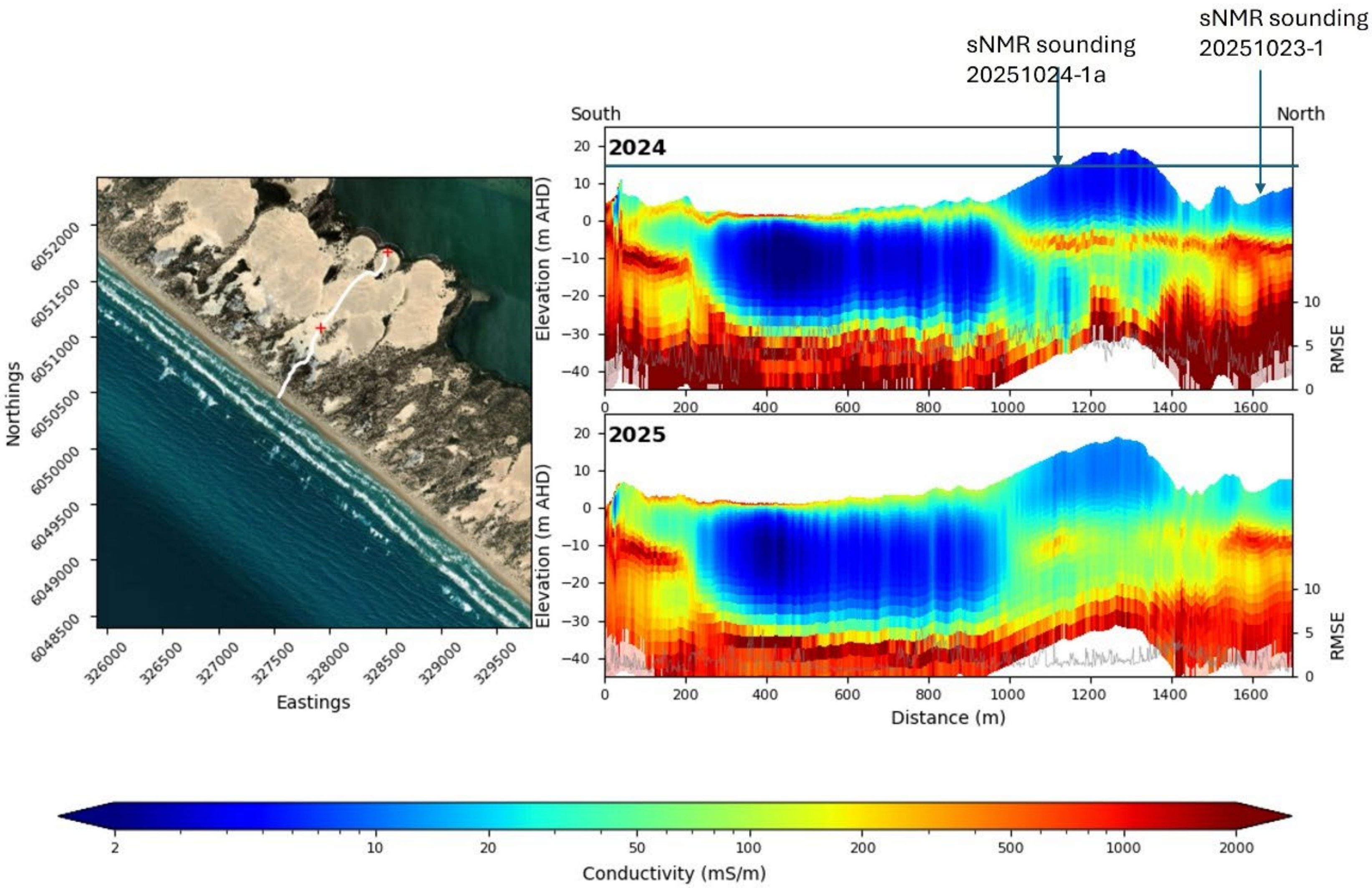


Figure 22. A comparison of Loupe TEM survey results from May 2024 and May 2025. In the saturated material (below the watertable), the darker red colours are higher conductivity (likely saltwater) and those that are darker blue are less conductive (fresh or brackish water). Grey line is the RMSE. Red crosses on location map represent 1000 m distances along the line. Also shown are the two sNMR locations.

4.2 Surface Nuclear Magnetic Resonance (NMR)

4.2.1 Methods

Surface nuclear magnetic resonance (sNMR) surveys were undertaken using a Vista Clara Pty Ltd GMR Flex system in October 2025 adjacent the Across Kartoo soak (Figure 23). This instrument directly measures water content and aquifer saturated porosity, as well as providing an estimate of hydraulic conductivity. The GMR Flex system provides up to ~50 m depth penetration (depending on subsurface properties and site conditions) and is the only geophysical technique that can directly measure subsurface water content. Datasets were processed and inverted using the Vista Clara Pty Ltd GMRPro inversion software.

Figure 23. NMR sounding on the dune above Across Kartoo soak, October 2025. To complete a sounding, cables are laid out on the surface in a specific configuration.

4.2.2 Results

The results from the two sNMR surveys corroborate with the Loupe surveys and the presence of significant water beneath the dunes of the Younghusband Peninsula at the Across Kartoo site (Figure 24 and Figure 25). The dunes, being predominantly well sorted, clean sand have a high porosity of 25-40% at a depth of 25 m below ground. The water table appears to be about 10 m depth at site 20251024-1A and 5 m depth at site 20251023, which is representative of the elevation of each of these sites on the Younghusband Peninsula and at an elevation higher than mean sea level (0 mAHD). Estimated hydraulic conductivity of the saturated dune sediments is also high (~80 m per day) suggesting that groundwater within the perched aquifer system has the potential to travel relatively quickly from the recharge to the discharge areas through the dune.

The sNMR model inversion results are based on a resistive earth model. Because of the conductive environment of the Younghusband Peninsula, additional modelling would be necessary to constrain the depth resolution of the sNMR surveys. This would require a conductivity model based on the results from the Loupe TEM system.

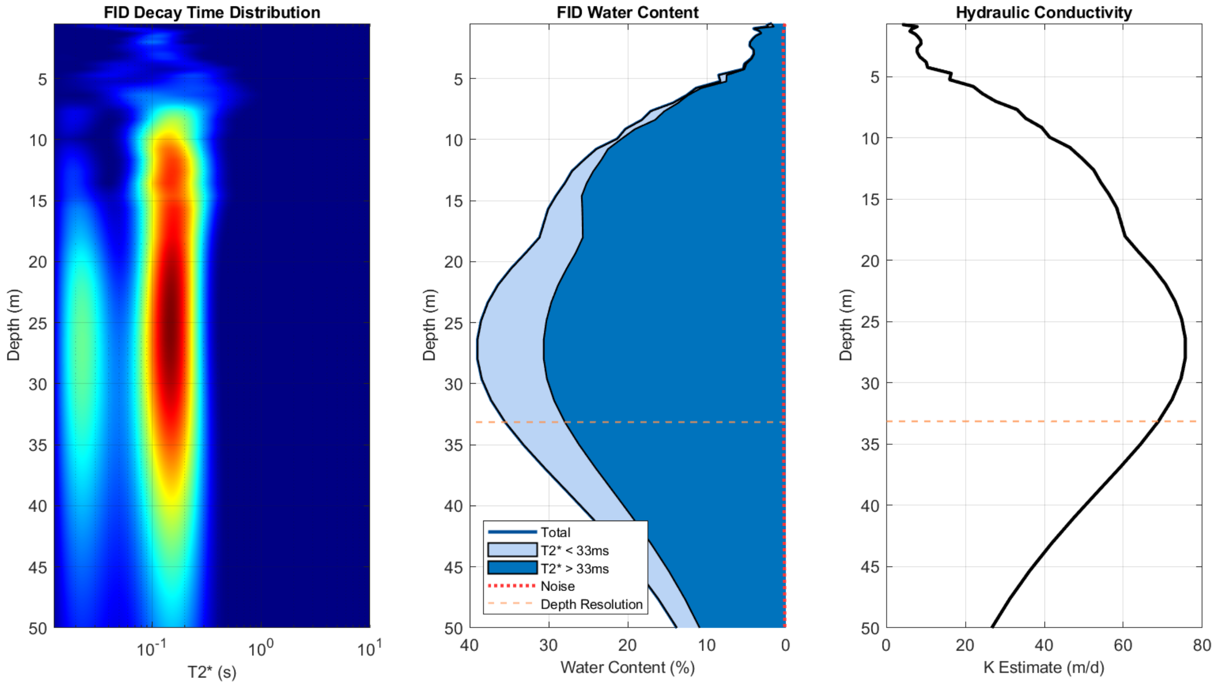


Figure 24. NMR results from SITE 20251024-1a (see Figure 22 for locations along the Loupe cross section).

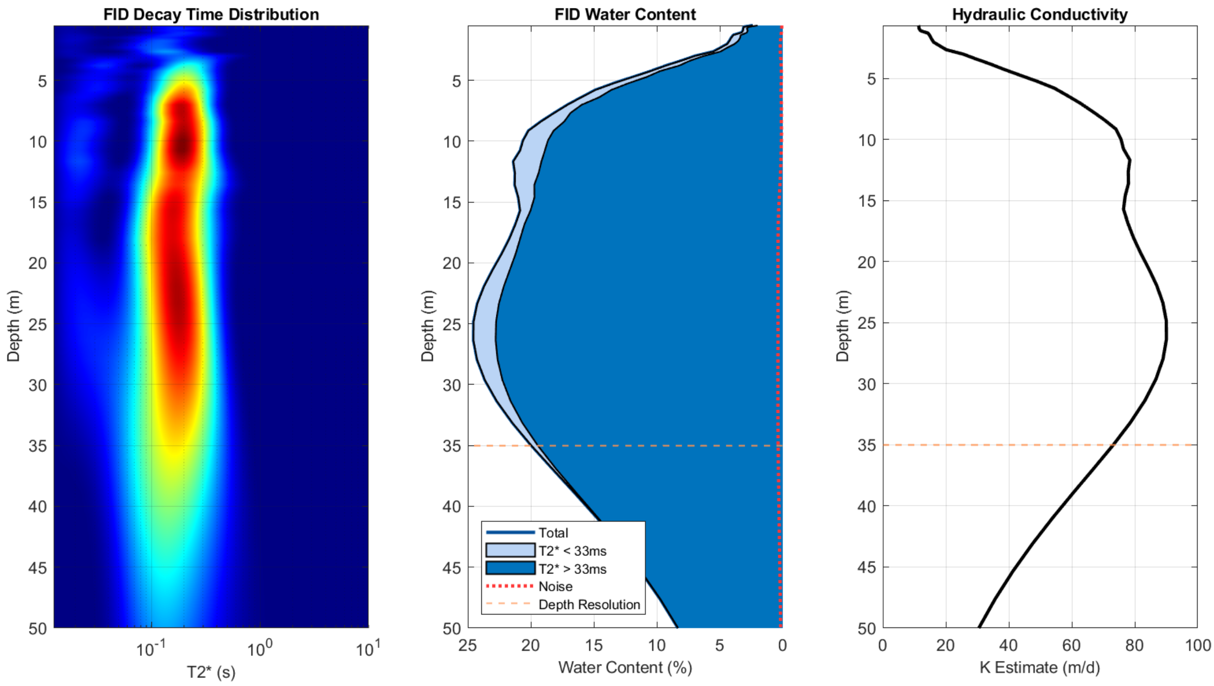


Figure 25. NMR results from SITE 20251023-1 (see Figure 22 for locations along the Loupe cross section).

4.3 Water level measurements

4.3.1 Methods

Over the week of 5–9 May 2025, the piezometers installed by DEW in 2024 at the Across Kartoo and Wreck Crossing sites were revisited. Existing water level loggers at both sites were downloaded and barometrically compensated using barometric pressure from the Bureau of Meteorology Meningie site (Figure 26 and Figure 27). At Across Kartoo, the logger was directly in the soak, as the previously installed piezometer had dried and filled with sand within a month of installation.

A new piezometer was installed within the dune to better understand the groundwater levels that feed the soak. The piezometer is in the vegetated area tucked up against the dune and approximately 40 m inland from the Coorong (Figure 18). The piezometer consists of a ~2 m PVC pipe with approximately 0.3 m of slotted casing at the bottom. A small hole was dug to remove the loose sand at the surface, and then an auger was used to manually remove material down to a depth of 1 m. The standing water level was 0.3 m below ground on 7 May 2025. The slotted end of the PVC was covered in a sock material to prevent intrusion of sand, and inserted into the dune, which collapsed around it. The initial water level and physical water quality were measured with an In-Situ Aquatroll 600 multi-parameter water quality meter, and a sample for stable isotopes of water was collected using a peristaltic pump, then the water level logger was inserted. The piezometer ground elevation and top of casing was surveyed using a Trimble Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) Catalyst DA2 receiver.

A similar process was completed at the Wreck Crossing soak, which was wet when infrastructure was installed by DEW in early summer 2024 but appears to have dried by mid-March (DEW 2024) and remained dry until the time of removal in May 2025. The PVC was removed and the hole was deepened from approximately 0.3 m until water was reached at <2 m below ground. New, slotted PVC covered with sock and inserted. Water quality parameters were measured with an In-Situ Aquatroll 600 multi-parameter water quality meter, a stable isotope sample was collected, the piezometer elevation was surveyed, and a logger installed.

4.3.2 Results

The water level in the Across Kartoo soak rose approximately 0.05 m in response to winter rainfall, then declined more than 0.2 m during the extremely dry conditions that prevailed from August 2024 until the logger was removed in May 2025. In comparison, the water level in the piezometer only changed by approximately 0.07 m between May 2025 and May 2026. However, the accuracy of the measurements in the piezometer was questionable; during the May to October period, the temperature fluctuated considerably, while there was almost no fluctuation in water level after October 2025. The unstable dune environment continues to be challenging for collecting water level measurements.

As with Across Kartoo, the Wreck Crossing soak water levels show a distinct seasonal pattern, with water levels rising during the winter and falling during the dry spring-autumn. Observed water level variation was approximately 0.5 m. The water level was confirmed to be below ground level when visiting in May 2024, May 2025, and February 2026; this soak likely only has water at the surface for a few months per year during below average rainfall years.

4.4 Evapotranspiration

4.4.1 Methods

Water levels were used to determine evapotranspiration using White's method. Evapotranspiration was calculated using a modified version of White (1932). The basic method for using daily fluctuation in saturated groundwater levels to discern evapotranspirative removal from the aquifer (ETG) was proposed by White (1932) as:

$$Sy(\Delta s/t + R) = ETG$$

where Sy is the specific yield (dimensionless), Δs is the change in storage over time t (typically 1 day), and R is the recovery rate (L/T). The change in storage is calculated as the difference in the minimum daily depth to water over consecutive days. Because plants transpire only during daylight hours, the recovery rate is calculated from the slope of the change in depth to water over night, typically from midnight until 4 a.m. or 6 a.m. This method assumes that the recovery rate is constant in time.

Building on the work of White (1932) and others, S. I. Loheide (2008) presented a general method for using these same water level fluctuations to estimate ETG on a sub-daily time scale. First, the slope (m) and intercept (b) of the overall trend in the water table record are calculated across the recovery periods before, during, and after the day for which ETG is being calculated. This trend is then subtracted from the record to account for changes in the level of the nearby water table as water moves into the observation location from the surrounding aquifer during the recovery period. Using this detrended water table data (WTDT), a new recovery rate (RDT) can be calculated using the nighttime water levels as:

$$Sy\ (\Delta WTDT/t + m) = RDT$$

In this study, data from midnight to 6 a.m. over three consecutive nights (i.e., bracketing the day under consideration) were used to calculate this detrended recovery rate. Finally, the detrended water levels and recovery rates were used to calculate ETG for any time step using the equation:

$$RDT - Sy\ (\Delta WT/t) = ETG$$

For this analysis, the above process was performed in MATLAB using the water levels collected at Across Kartoo and Wreck Crossing.

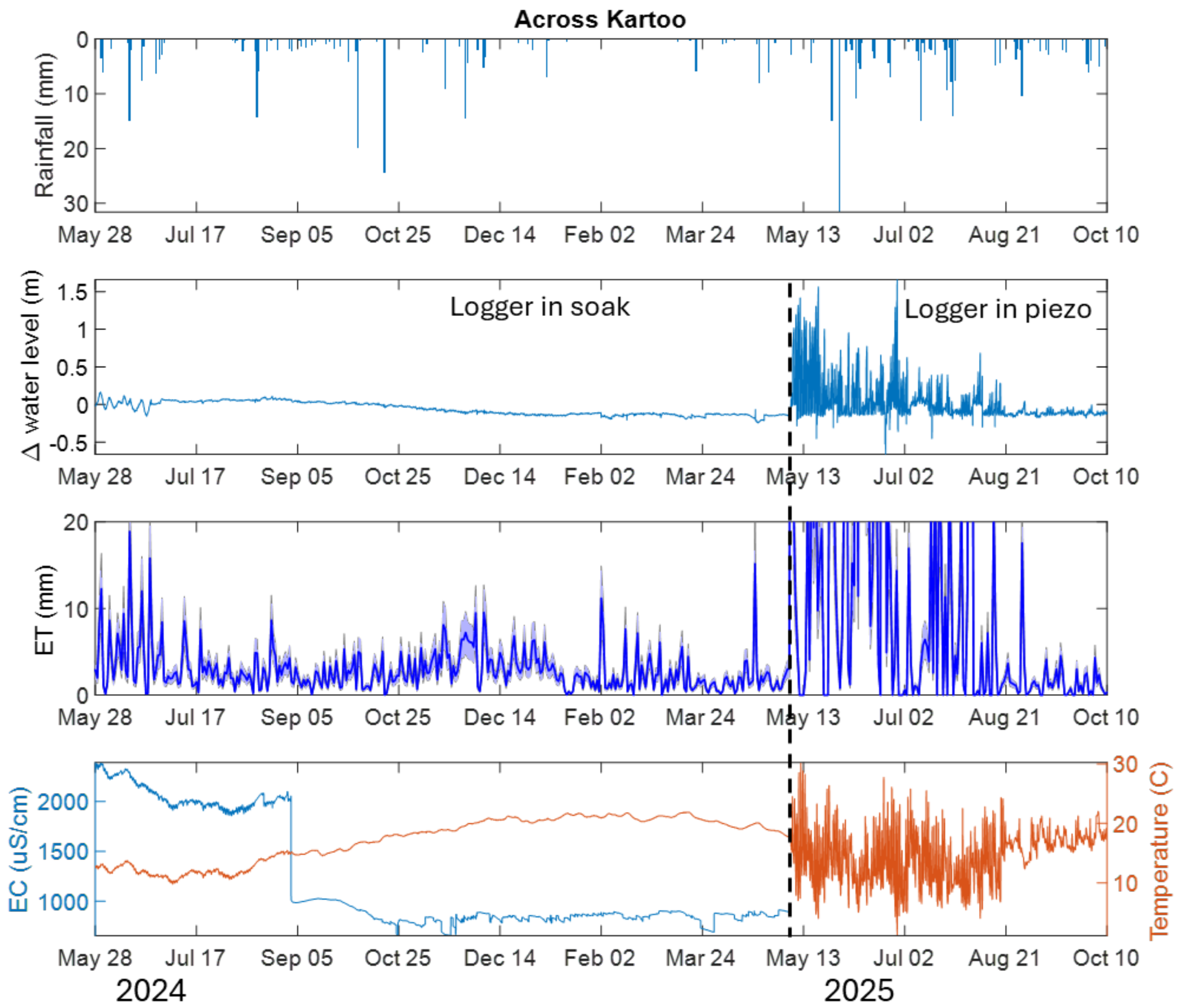
This method requires an estimate of specific yield, which is rarely measured in the field. Experimentally determined Sy values for a range of sandy shallow aquifers are 0.10–

0.20 (Johnson, 1967); therefore, ETG values for each time series were calculated using Sy values of 0.10, 0.15, and 0.20 for comparison.

4.4.2 Results

Estimated evapotranspiration at Across Kartoo was relatively constant over most of the survey period, except for noteworthy spikes in evapotranspiration following summer rainfall (Figure 26). Average daily evapotranspiration averaged approximately 3.2 mm per day assuming a specific yield of 0.15; this estimate increased to 4.2 mm per day when specific yield was increased to 0.2 or decreased to 2.1 for a specific yield of 0.1. This corresponds to annual ET between 766 and 1,533 mm.

Estimated evapotranspiration at Wreck Crossing was relatively constant over the survey period and slightly lower than at Across Kartoo, averaging approximately 2.4 mm per day assuming a specific yield of 0.15 (Figure 27). This estimate increased to 3.2 mm per day when specific yield was increased to 0.2 or decreased to 1.6 for a specific yield of 0.1. This corresponds to annual ET between 577 and 1,153 mm.



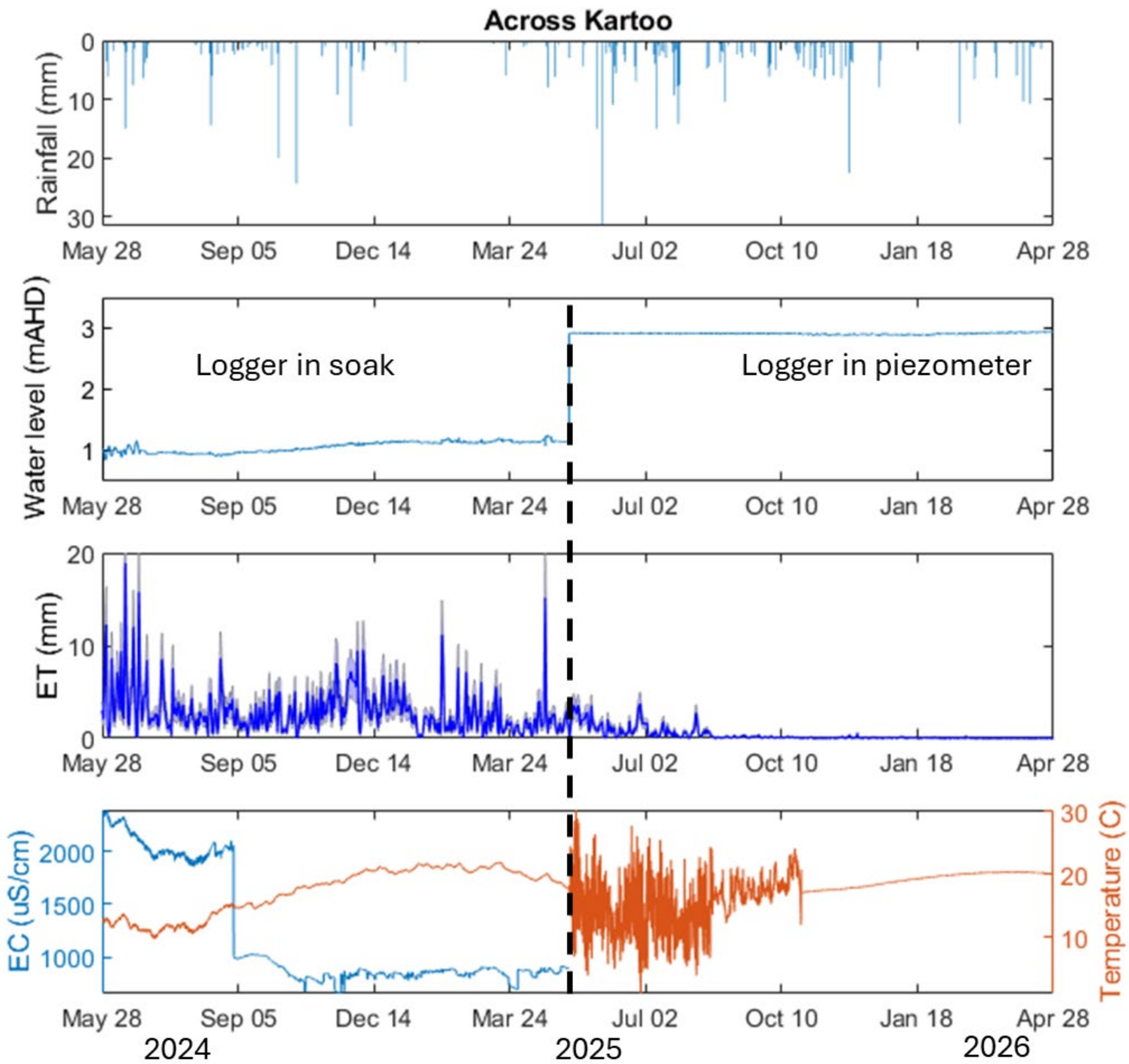


Figure 26. Daily rainfall at Meningie (top), water levels, estimated evapotranspiration, and electrical conductivity and temperature (bottom) at Across Kartoo between May 2024 (loggers left in soak by DEW (2024) project) and May 2026. The solid line in the bottom figure assumes a specific yield of 0.15; the shaded area shows estimates of 0.1 and 0.2. The reason for the sudden drop in electrical conductivity in September 2024 is unknown but is unlikely to reflect an actual change in conditions. Water level and conductivity were measured by separate probes in separate piezometers.

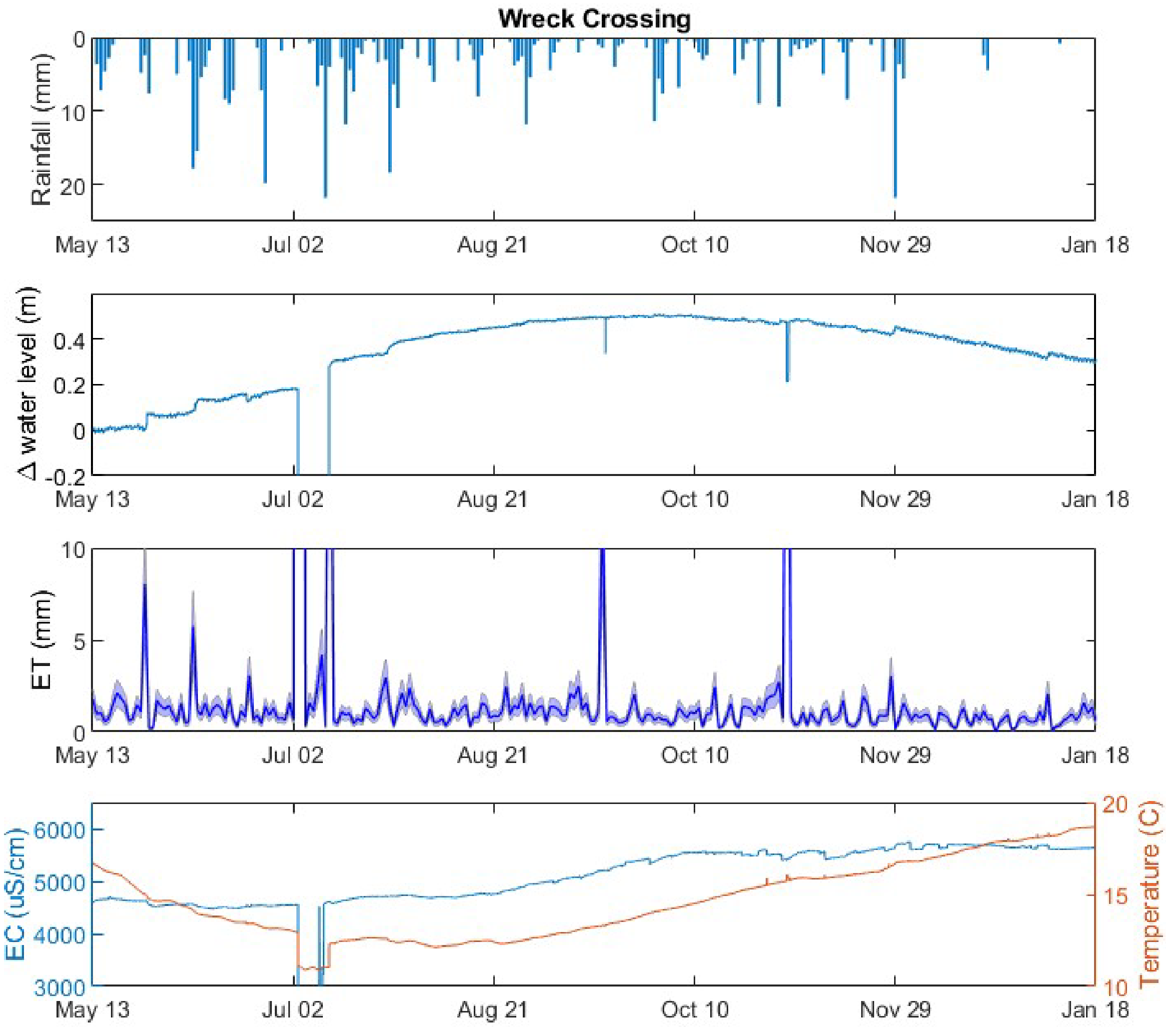


Figure 27. Daily rainfall at Kingston (top), water level, evapotranspiration, and temperature and electrical conductivity (bottom) measured within the Wreck Crossing soak from May 2025 to February 2026. It is unknown why the logger failed from 3–11 July and showed short drops in September and late October 2025. The solid line in the evapotranspiration panel assumes a specific yield of 0.15; the shaded area shows estimates of 0.1 and 0.2. Aberrations in water level cause unrealistic spikes in estimated evapotranspiration, which accounts for the deviations in estimated evapotranspiration at the beginning of July, mid-August, and the end of October.

4.5 Chemical and physical water quality

4.5.1 Methods

Water was sampled for physical water quality parameters in the field during the May 2025, October 2025 and February 2026 field campaigns using an Aqua TROLL 600 Multiparameter Sonde. Sampling sites included the newly installed piezometers at Across Kartoo and Wreck Crossing, within Across Kartoo soak, in the Coorong at Across Kartoo, and at ground-truthed soaks (Tables 4 and 5). Water in the soaks and Coorong was sampled by directly dipping the sonde into the water and noting values once stabilised. Water from the piezometers was sampled by pumping water out of the piezometer at a very low rate using a small peristaltic pump and placing the sonde within a vessel into which the pumped water flowed continuously. Given the low pumping rate, the temperatures are not reported for the piezometers.

4.5.2 Results

Most of the soaks that were ground-truthed over the course of the project appeared to be brackish to hypersaline (Tables 4 and 5, Figures A2 and A3). Across Kartoo and Wreck crossing were among the lowest salinity soaks; only a handful were at the low end of brackish; less than half of the eighteen ground-truthed soaks were saline. The water in these soaks is currently above Australian Drinking Water Guidelines (ADWG). The ADWG specify drinking water should be less than 500 mg/L, with a maximum acceptable level of 1000 mg/L total dissolves solids (TDS). Using a conversion factor of 0.5 to 0.7 typical for converting between electrical conductivity TDS and salinity, this equates to a TDS over three times the ideal value and 1.7 times the maximum acceptable value. The water at Wreck Crossing is roughly twice as saline as at Across Kartoo, while other soaks sampled during the project were often much saltier. Note that the observed salinities are on par with values noted by Bickert and Winter (2001).

Continuous monitoring of electrical conductivity in Wreck Crossing over almost one year suggests that the salinity in the soak varies seasonally, increasing during the summer period of high evaporation and vegetation transpiration and freshening in response to winter rainfall (Figure 27). At Across Kartoo, this pattern was not apparent (Figure 26); however, that may be due to difficulties with the logger, which recorded a sudden shift in late 2024. Note also that absolute electrical conductivity values measured with the loggers differed from the point estimates, but this is not unexpected given that the loggers have been in the field for two years without calibration, while the sonde is calibrated before each day in the field.

All sites showed neutral pH values, as expected for natural waters. The lowest pH was observed in the new piezometer at Across Kartoo, which was just below neutral. This is likely due to the anoxic state of the groundwater at that site, which is common for groundwater.

Table 4. In-situ Aquatroll 600 water quality parameters measured during the May 2025 field campaign.

SITE	DATE	SPECIFIC EC (µS/CM)	DISSOLVED OXYGEN (MG/L)	PH	TEMPERATURE (°C)
Across Kartoo Piezometer	8/05/2025 11:13	3,596	1.26	6.84	-
Across Kartoo Soak	8/05/2025 11:32	3,362	5.13	7.79	16.1
Coorong at Across Kartoo	8/05/2025 11:32	48,532	9.18	8.03	17.5
Tile 1 (S-01-15)	8/05/2025 12:55	49,117	12.97	7.91	17.4
Tile 1, (S-01-16)	8/05/2025 12:57	63,785	12.43	8.27	17.4
Wreck Crossing Piezometer	9/05/2025 12:00	7,440	7.91	7.68	-
Coorong near Jack's Point (mainland side)	8/05/2025 17:19	101,131	7.64	8.14	-

Table 5. In-situ Aquatroll 600 water quality parameters measured during the October 2025 and February 2026 field campaigns.

SITE	DATE	SPECIFIC EC (µS/CM)	DISSOLVED OXYGEN (MG/L)	PH	TEMPERATURE (°C)
Coorong by S1	23/10/2025 11:25	36,020	7.19	7.57	17.2
Tile 1, S1	23/10/2025 11:58	3411	6.57	7.59	17.0
Tile 1, S02	23/10/2025 12:24	6670	11.24	7.83	17.9
Tile 1, S03	23/10/2025 12:33	25,127	5.97	7.71	19.3
Tile 1, C02	23/10/2025 15:01	41,906	6.50	7.69	17.8
Tile 1, S04	23/10/2025 15:14	38,607	9.37	7.96	20.6
Tile 1, new S05	23/10/2025 15:35	7499	21.65	8.36	23.9
Tile 1, S06	23/10/2025 16:20	12,351	22.67	8.60	20.4
Tile 1, S07	23/10/2025 16:33	3805	6.18	8.02	20.4
Tile 1, S08	23/10/2025 17:36	130,807	10.47	8.01	26.1
Tile 1, S09 (soak3)	23/10/2025 17:51	4056	7.41	8.10	20.0
Tile 1, C03	23/10/2025 18:30	40,958	9.89	8.13	19.1
Tile 1, S0a	23/10/2025 18:36	34,456	19.74	8.57	19.74
Tile 1, S0b	24/10/2025 17:45	48,899	6.98	7.84	6.98
Tile 1, S12	24/10/2025 17:52	90,700	7.28	7.67	7.28
Coorong adjacent S12	24/10/2025	77,522	9.27	8.16	9.27
Tile 1, S7	24/10/2025				
Tile 1, S9	24/10/2025	46,720	9.70	7.96	9.70
Coorong adjacent S9	24/10/2025	71,944	8.94	7.90	8.94
Coorong adjacent S12	24/10/2025	73,591	9.21	8.07	9.21
Tile 1, S10	24/10/2025	11,741	16.19	8.76	16.19
Tile 2, (S-02-04)	24/02/2026 14:05	68,856	12.97	8.75	26.9
Tile 2, (S-02-05)	24/02/2026 14:08	60,390	9.44	8.09	26.3

4.6 *Stable isotopes*

4.6.1 Methods

Stable isotopes of hydrogen and oxygen in the water molecule are commonly sampled to understand precipitation origins, evaporation rates, and groundwater recharge. They are commonly used to distinguish between waters dominated by storms in different seasons or flow paths.

During the May field campaign, water samples were collected at all sampled sites using a syringe and filtered through a 0.45-micron membrane filter into 2 mL glass vials in the field. Water sample stable water isotope compositions of deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) were measured using a Picarro L2140-I Cavity Ring Mass Spectrometer at Flinders University in Adelaide, South Australia. The results are reported as a deviation from Vienna Standard Mean Ocean Water (vs. VSMOW) in per mil (‰) difference using delta (δ) notation. The analytical precisions for $\delta^{18}O$ and δ^2H were ±0.025‰ and ±0.1‰, respectively.

4.6.2 Results

Deuterium and oxygen-18 values ranged from -30.0‰ and -5.2‰ for Wreck Crossing to 2.0‰ and 1.1‰ in the open waters of the Coorong and sampled soaks (Figure 28). The groundwater measured at both Across Kartoo piezo and Wreck Crossing plot near the weighted average Adelaide rainfall, which is representative of winter rainfall groundwater recharge. The Coorong and open soak waters plot to the right of the local meteoric water line (LMWL) for Adelaide, which indicates that the water has been subject to processes of evaporation. These samples plot along an evaporation line with a slope of 5.1 (R^2= 0.97), which is common for open-water surface bodies in arid and semi-arid environments (Barnes and Alison, 1988). There is an obvious difference between the groundwater samples (Across Kartoo piezo and Wreck) and the Coorong water, which are isotopically more enriched. The difference in the Coorong water samples relates to the location from where they were collected and show some variation along the evaporation line. The Across Kartoo soak water samples from May 2025 (δ^2H=2.22‰ and $\delta^{18}O$=1.05‰) and October (δ^2H=2.78‰ and $\delta^{18}O$=0.73 ‰) 2025, were fairly similar and are representative of evapo-concentrated groundwater. The Coorong water collected in May 2025 adjacent to the Across Kartoo soak also has a very similar isotopic composition but much higher EC (48,532 mS/cm). Some of the soaks such as S8 (23/10) is very isotopically enriched and plots to the far end of the evaporation line and has an EC of 130,808 mS/cm. The δ^2H and $\delta^{18}O$ data show that the sampled groundwater and the soaks have a distinct rainfall end member, which is dominated by a winter rainfall signature. Higher frequency sampling of both stable isotopes and salinity across the different seasons may improve understanding of how the soaks respond to different episodic rainfall events.

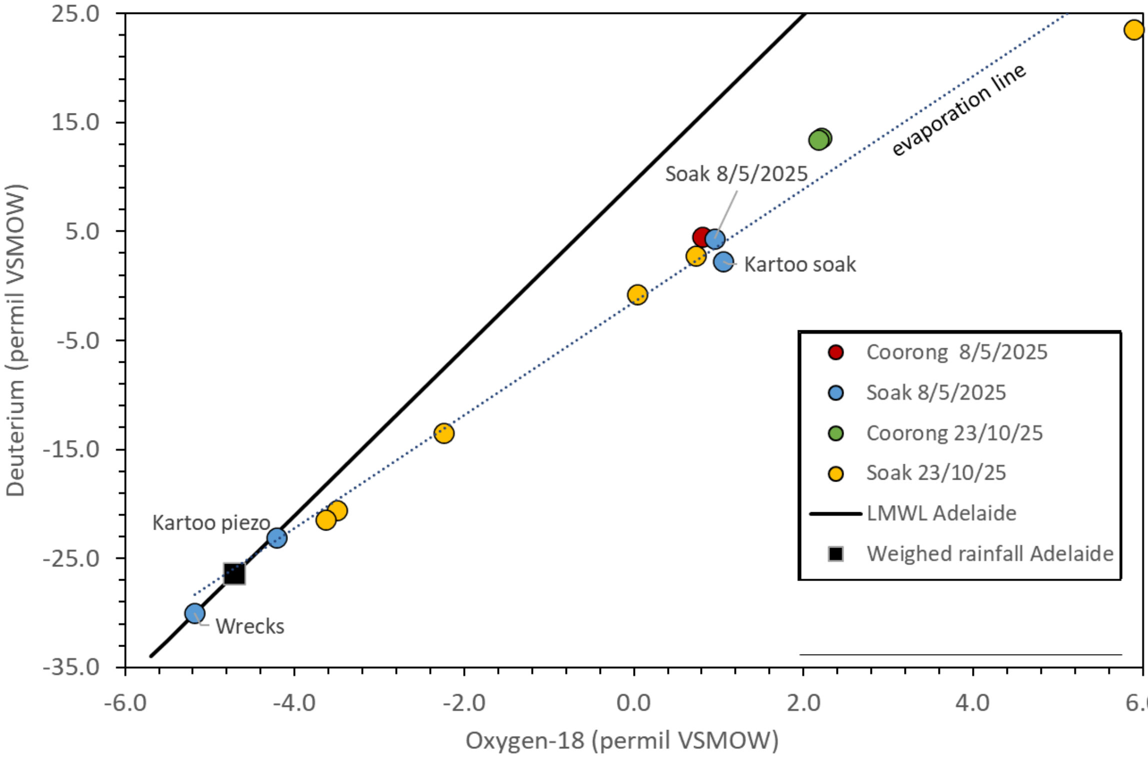


Figure 28. Stable isotopes of water. Deuterium versus Oxygen-18 plotted with the Local meteoric water line for Adelaide rainfall and evaporation line

5 The future of soaks on the Younghusband Peninsula

5.1 Historical vs. current occurrence of soaks

Examination of historical maps by Tindale shows a relative abundance of open waterholes along the length of the Younghusband Peninsula in the 1930s. Subsequent consultation with living Elders confirms that these waterholes were important sources of freshwater for Indigenous people living at least seasonally on the Younghusband Peninsula. During our July 2025 yarning, Elders spoke of childhoods migrating up and down the Coorong, living off the land. All these stories suggest that the soaks provided a high quality, freshwater source that supported humans in recent times.

Initial examination of Google Earth Imagery suggests that almost all the soaks marked on the historical maps may have disappeared; a few may continue to appear seasonally, while others may now be filled in with sand. We found that few to none of the soaks noted on the Hundreds maps from the early 1900s appeared visible in current imagery. This implies that there has been a significant shift in soak location along the Younghusband Peninsula over the past 100 years. Dunes are often highly dynamic, and high variability in water levels is a fundamental characteristic of the dune-slack soaks. Grootjans et al. (1998) describes groundwater level variations of up to 2 m, with dune slacks appearing in winter and disappearing in summer. This is similar to the characteristics observed at the Wreck Crossing soak, where the groundwater rises to the surface seasonally and water level variations on the order of less than 1 m were observed. The Across Kartoo soak is more akin to the "dune lake" features described by Semeniuk & Semeniuk (2011) as dune features become more stable; that is, this large soak is perennially wet. The salinity of this soak was comparable to that measured in previous study (Bickert and Winter, 2001).

5.2 Remote detection of soaks

This project developed a methodology for detecting current soaks using available remote sensing imagery. This is consistent with previous literature discussion on the need for efficiently determining water-body locations in water monitoring and environmental protection using remote sensing imagery (Zhang et al., 2021).

Mishra et al. (2020) has reviewed the efficacy of very-high resolution (VHR) imagery to map water bodies, which used VHR PlanetScope imagery to detect water bodies over West Africa. The study discusses how historical knowledge has often been the method for locating water bodies due to their size and variability (Mishra et al., 2020). However, remote sensing observations could be used to complement this knowledge as climatic conditions drive a need to map and frequently monitor the water bodies (Mishra et al., 2020). Their method was able to determine that high spatial and temporal resolution showed promise for water body monitoring in West Africa (Mishra et al., 2013).

Additionally, Zhang et al. (2021) examined the detection and analysis of small surface water bodies using VHR satellite imagery sourced from the Chinese satellite Gaofen-2 across Beijing, China. The study discussed the challenges around the use of remote sensing techniques due to 'spectral mixtures' caused by vegetation, shadow, and other features (Zhang et al., 2021). The paper proposed a method which used a combination of a pixel-level water index and image object detection, which found that determining water body location was feasible with the imagery and the method proposed (Zhang et al., 2023).

In this study, we identified several common morphological characteristics that assisted in identifying the soaks using remote sensing information, including the presence of reeds near the soaks. We found that a combination of human observation (digitisation) and image data analysis using both spectra and elevation was required to detect soaks and potentially distinguish those which were less from those that were more saline. This led to:

- Detection of 44 soaks across ≈ 35 km on the Younghusband Peninsula,
- Differentiation of 29 soaks as potentially saline and 15 soaks as having low salinity, and
- Overall accuracy for those sites where salinity was tested at 72%.

5.3 Soak occurrence in future climates

Statistical analysis of Meningie rainfall data does not suggest a significant trend in annual or seasonal rainfall (Sen's slope and Mann Kendall tests do not yield significant results). However, future climate projections for South Australia generally show warming temperatures throughout the state (DEW, 2026). While the southeast coastline is somewhat buffered from the warming by the sea, it will nevertheless experience increasing variability in interannual conditions. Dune vegetation, which contributes to the stability of the dune, can be impacted by temperature and rainfall variations within a single year (Miller et al., 2010); certainly at the decadal scale variations in the timing and magnitude of rainfall are visually apparent (Figure 29) and have likely contributed to the changes in soak occurrence over the past 100 years.

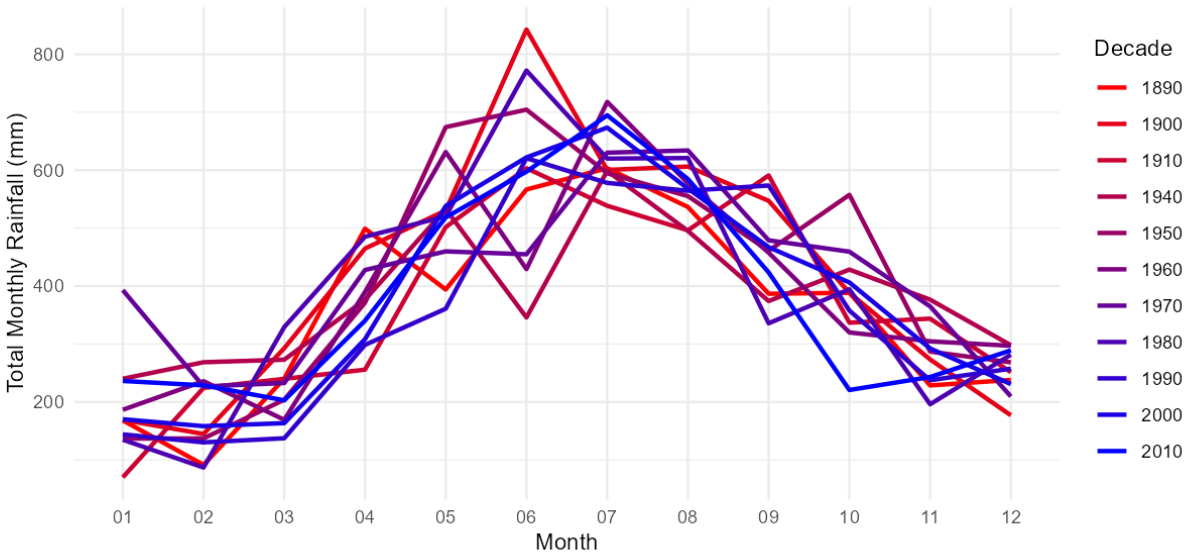


Figure 29. Monthly rainfall by decade for Meningie (BoM station 024518).

The dunes exist in a delicate hydrological balance between rainfall and ET (Figure 30). The average annual rainfall in the region is approximately 500 mm per year. In contrast, the estimated ET signal was 1–2 times that high at Wreck Crossing and 1.5–3 times as high at Across Kartoo. High evapotranspiration in the soaks was also apparent from the stable isotope signatures. The actual long-term evapotranspiration balance is likely constrained by annual rainfall inputs; otherwise the dune aquifer would progressively lose storage; this is because the ET occurs where there is vegetation and only 40–60 % of the Younghusband Peninsula is vegetated, while the rest is bare (Butcher & Rogers, 2013). Therefore, across the entire Younghusband Peninsula, evapotranspiration is not greater than rainfall but likely accounts for most of the rainfall that enters the dunes each year. Note that the percentage of the Younghusband Peninsula that is vegetated has increased significantly over 75 years (Moulton et al., 2019), which may have affected groundwater levels and therefore soak occurrence. Higher evapotranspiration in a warming climate could also affect the soak water balance and salinity.

Flow rates into or through the soak remain an unknown; however, our field investigations present important first steps in quantifying this remaining piece of the soak water balance. The results of this study identified that there is a significant amount of water stored in the Younghusband Peninsula dunes, which discharges at the dune margins, seasonally or perennially forming soaks. Geophysical surveys showed that even in late autumn, the local water table is 5–10 m below ground, and that water can move rapidly through the subsurface to maintain soak water levels. From the NMR we learned that hydraulic conductivity is up to 75 m per day, with a hydraulic head of 10 m AHD of water at the peak of the dune approximately 200 m away. This suggests a flow rate of up to almost 4 m/day into the dune, which would be quite high and suggest constant flushing of the soak. However, the high evaporation signal shown by the stable isotope analysis suggests that the residence time of the soak water is much longer. Direct flux measurements through the bed of the soak are needed to resolve this question; understanding this final piece of the puzzle would then help to predict how sensitive the plant and animal communities that rely on the fresh/brackish water of the soaks are to both interannual and long-term shifts in rainfall and temperature.

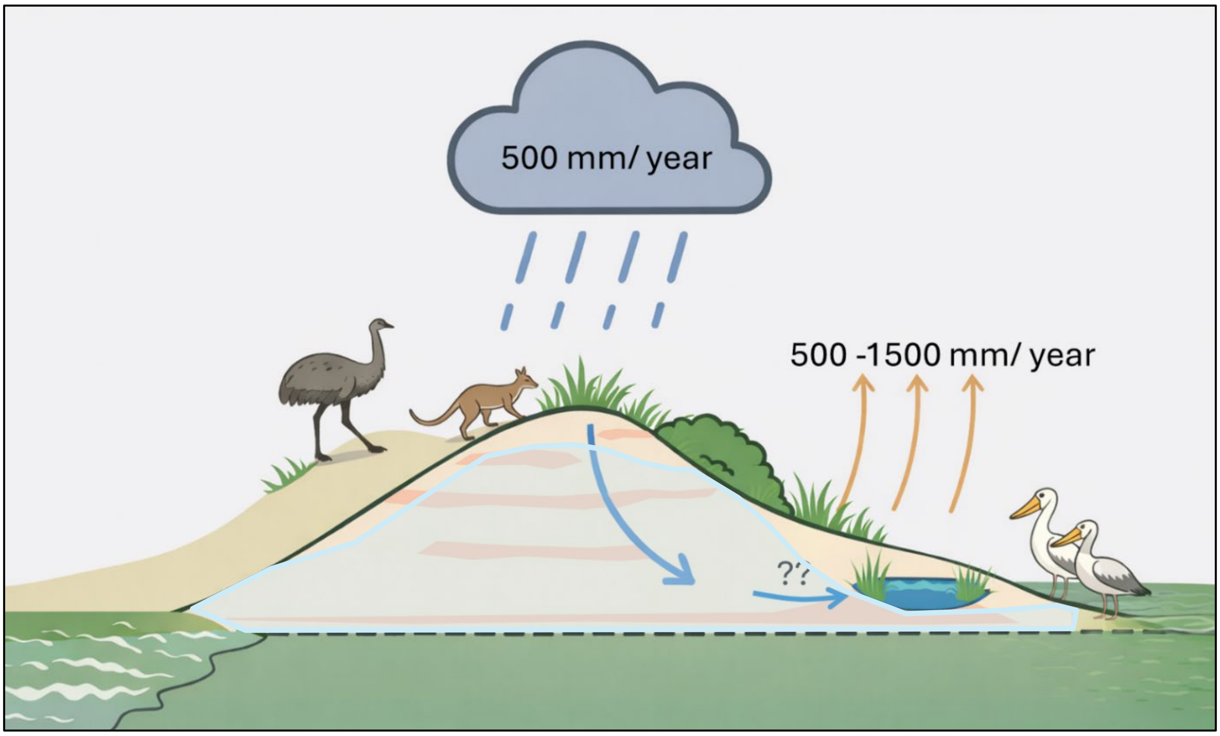


Figure 30. Conceptual model of soak hydrology where rain infiltrates through the dune and exits as evapotranspiration, directly into the soaks, and potentially into the Coorong as well. Evapotranspiration is very high and the soaks exist in a delicate balance between rainfall and evapotranspiration.

6 Future research

While much was learned about the past and current existence of the soaks and how they function during this project, it was only the beginning. The Younghusband Peninsula provides a challenging research setting due to its separation from the mainland, necessitating the navigation of the extremely shallow and often choppy water along approximately 180 km of the Coorong lagoons, which limited our ability to conduct fieldwork within the short project timespan. Further, the highly dynamic dune environment provides its own challenges to hydrological work, frustrating attempts to install monitoring infrastructure. Although previous reports on the soaks of the region called for ongoing monitoring (e.g. Bickert and Winter (2001), this has not happened to date. However, the cultural and ecological significance of the soaks within the Coorong region provide a strong driver for further research to better understand and manage these dynamic systems. Specifically, we identified the following topics that would help to solidify our understanding of the occurrence of soaks along the Younghusband Peninsula and provide the hydrological underpinnings of a monitoring program.

6.1 Continued investigation of remote sensing data to catalogue and monitor soaks

Expansion of the remote sensing work to the whole of the Coorong is possible as Pléiades Neo satellite imagery, at similar date as that used for tiles 1 and 2 used in this work, is available. However, it would be preferable to perform the classification using recently tasked imagery which coincides with field work and with lower impacts of surges from the River Murray. It may be possible to achieve similar results with a slightly lower spatial and spectral resolution from a satellite such as Pléiades Neo (0.5 m spatial resolution and 4 visible and near infrared spectral bands). It was noted (Section 3.6) that the most influential inputs for *Phragmites australis* detection were Infrared and elevation.

The soak and reed detection method used in this research potentially could be improved / automated using deep learning which would replace the manual digitisation of soaks. Successful implementation requires a large dataset of many diverse examples of soaks at varying distances from *Phragmites australis* across multiple seasons. If this work is to occur, extended ground-truthing with salinity sampling is required to support and validate the findings. This would be best carried out in spring, following the winter rainfall. The research would also benefit in a full mapping of vegetation species in soak locations. Additional ground-truthing would provide more scientifically robust data to support the inferences proposed in this research that proximity to *Phragmites australis* is a good indicator of soak salinity. That is, although we expected to find a series of "freshwater" soaks, we found a wide range of salinities in the soaks, and all were at least brackish, while some were hypersaline. We anticipate that some of the low-lying areas adjacent the edge of the Coorong may have been inundated with Coorong water when the Murray flooded in 2021–22, producing false "soaks". This hypothesis can be tested using comparison with older imagery and by additional ground-truthing. With the complete Younghusband Peninsula catalogue of soaks, we could also compare the overall abundance of soaks in today's landscape with what was documented around 100 years ago to better understand changes in the landscape.

6.2 Coupled investigation of soak hydrology and ecology

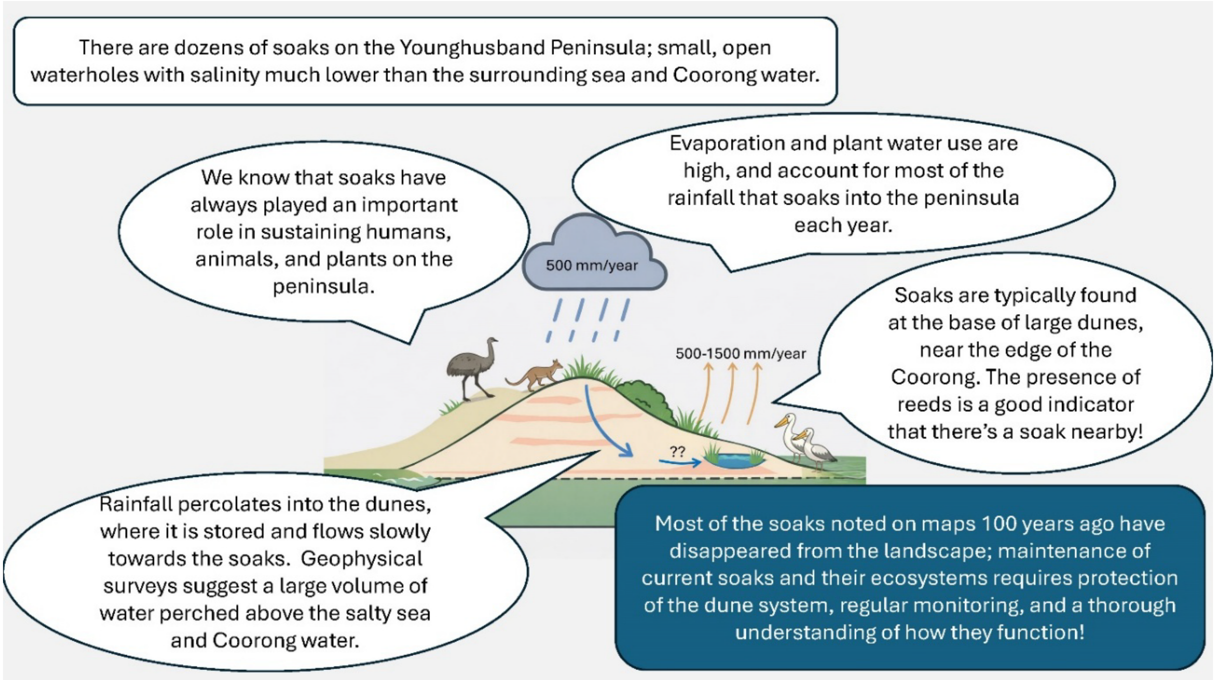
Perennial soaks such as Across Kartoo provide a unique environment for Coorong wildlife. Yet little is known about the terrestrial life they support, and even less about the aquatic ecosystem. DEW (2024) included a camera trap (including birds, fish, emus, kangaroos, and wombats) at both the Across Kartoo and Wreck Crossing soaks; additional wildlife such as Rakali was observed during this project's field campaigns, so there is still much to learn. Emus and pelicans were always observed in the vicinity of the soaks, confirming that they are also an important water source for birdlife. Few studies include coupled investigation of hydrology and ecology; however, in groundwater-dependent systems such as the soaks, a thorough understanding of the inflows and seasonality is imperative. This holistic approach would greatly assist in the management of soaks.

As part of a coupled hydro-eco investigation, additional hydrological monitoring infrastructure should be installed. In this project, as the one before it, installing monitoring piezometers (small, very shallow boreholes to check groundwater levels) was a challenge. Installation of an additional piezometer higher on the dune at Across Kartoo would provide the ability to measure hydraulic gradients from the groundwater recharge areas of the dune to the soak at the margins of the Younghusband Peninsula and estimate inflows to the Coorong.

Flow and the groundwater residence time (apparent age of the water) through the soak also remains an unknown. Further insights to the physical processes would help to close the hydrological balance of the soak and provide some indication of its resilience to climate change. Hydrogeophysical surveys conducted during the project have provided an important first step in identifying flow into the Across Kartoo soak, indicating how extensive the perched low salinity groundwater lens is beneath the Younghusband Peninsula dunes is and how quickly water can travel through the dune.

The continued strong involvement of First Nations in previous and subsequent studies is extremely valuable. During this project, the desire to spend more time on Country on the Younghusband Peninsula was expressed by Ngarrindjeri and Burrandies elders and rangers. Future collaboration to provide western science training to ranger groups to monitor water quality with a portable sonde may help facilitate this and would begin to fill the suggested soaks monitoring plan already suggested by Bickert and Winter 25 years ago.

7 Conclusions and plain-language summary



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9 Appendix

Figure A1. Map of all potential soaks identified in the Human Identification process

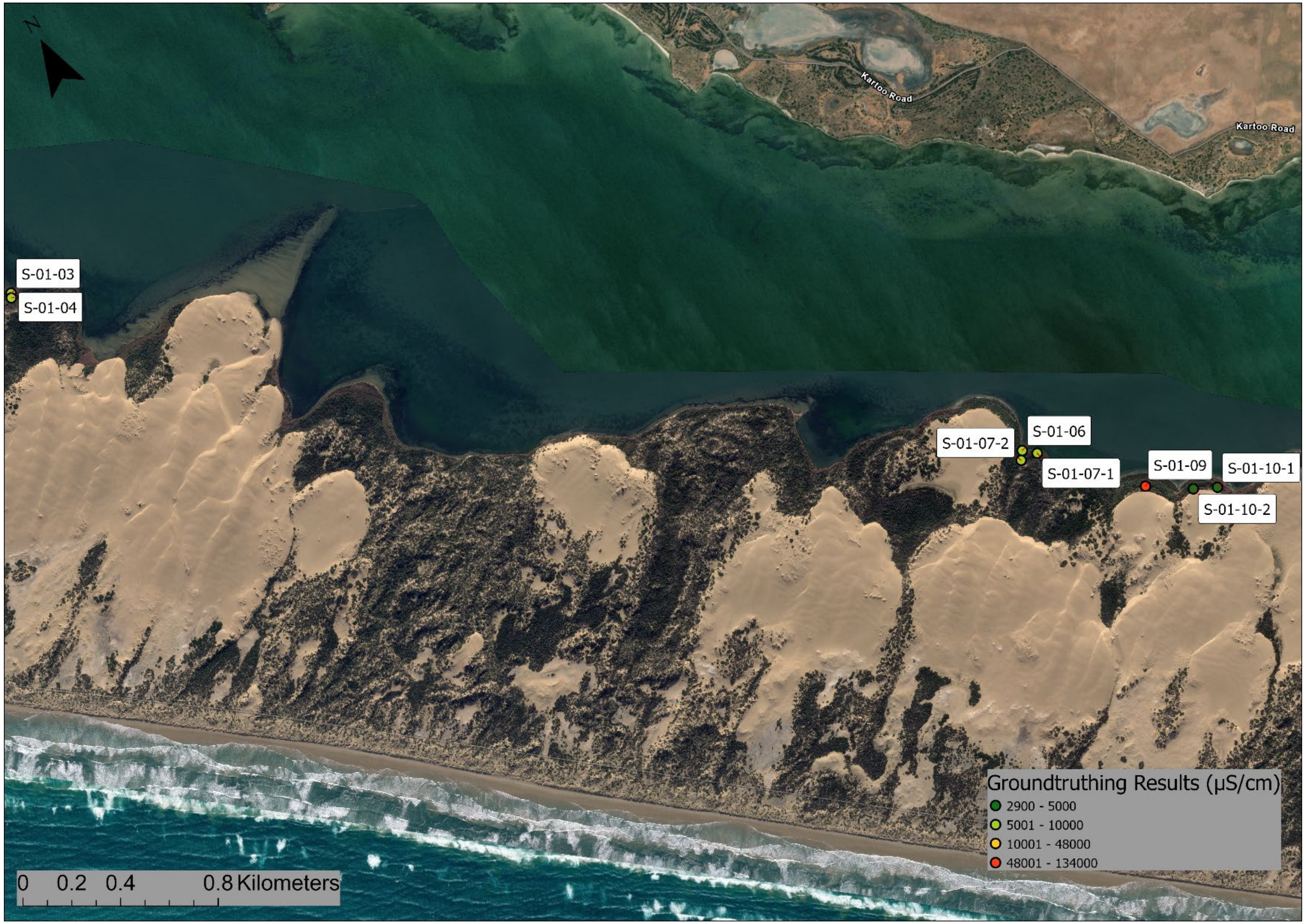

Figure A2a. Map of all ground-truthed soaks from the north-western tile (Tile 1) during fieldwork.

Figure A2b. Map of all ground-truthed soaks from the north-western tile (Tile 1) during fieldwork.

Figure A3. Map of all ground-truthed soaks from the south-eastern tile (Tile 2) during fieldwork.

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