Biodiversity and Conservation Science

Petrophysics of peat in the Muir-Byenup wetlands – why they dry, generate acid, and burn: Part 2 – focus on Tordit-Gurrup Lagoon

Prepared for the South West Catchments Council (SWCC) Project No. 022LM.5640 – Milestone 4

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Cover image reference

Tordit-Gurrup Lagoon March 2020: peat core (TGN08) (upper left); Tordit-Gurrup Lagoon depth board (upper centre); Tordit-Gurrup Lagoon peat desiccation (TGN10) (photographs by Rachael Hamilton) (upper right) and Tordit-Gurrup Lagoon July 2020 view to the west, from the eastern bank (photograph by Jasmine Rutherford)

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Summary

A research project to investigate the resilience of peat wetlands in the Muir-Byenup Ramsar site was carried out over a five-year period between 2015 to 2020. The main threat to the sustainability of these systems is drought, which increases the risk of drying, fire, salinisation, acidification and mineralisation. The aim of the research was to improve knowledge of the hydrological function of peat wetlands, assess how changes to the water balance alters geochemistry, and recommend remediation and management strategies for their conservation.

Geophysical interpretations have provided a new understanding of the connectivity of shallow aquifers across wetlands in the Muir-Byenup Ramsar site. Geological discontinuities that disrupt, and sometime reverse, groundwater flow gradients are now mapped and help explain complex groundwater level patterns observed since 2004.

An analysis of catchment-scale rainfall confirms that three discrete (around 10%) step changes in mean annual rainfall have occurred since the 1950's, and these have reduced groundwater recharge. Since 2016 this has affected minimum groundwater levels, with record minimum recorded in most bores at the end of summer 2020. Similar climatic trends, observed at the catchment scale, have also been noted at the wetland-scale, with a study of Tordit-Gurrup Lagoon, a large (>600ha) and important peat wetland undergoing desiccation and acidification.

Groundwater level data collected within the lagoon shows aquifers in the north disconnected from the overlying peat in the summer of 2020, while in the south they appear to remain partially connected. Groundwater level decline in summer encourages acidified peat soil-water to move downwards to the water table and move laterally to the southern water body in the winter months. The seasonal groundwater dynamics produce a consistent seasonal (flux) source of solutes and low pH groundwater to the shallow aquifer, and over time, to the lagoon water body.

Carbon isotope and loss-on-ignition methods were used to quantify peat wetland organic carbon stores. Catchment estimates for the upper metre at around one million tonnes. The drying of organic carbon resulted in around a 65% reduction in organic carbon. Entrained sediments in competent peat comprise mainly fine quartz sands, clay minerals, iron oxyhydroxides, pyrite and minor evaporite minerals. Drying produced an order of magnitude increase in peat soil-water salinity and evaporite minerals. In Tordit-Gurrup Lagoon this change takes place in desiccated peat and in sediments beneath the southern water body.

Similar zonation is evident in potential acid stores, with desiccated peat estimated to contain over half the sulfur-based acidity stored within the lagoon. Sulfur is mainly present in a reduced state (e.g. pyrite), but is also present as oxidized forms (e.g. gypsum, jarosite, alunite and hexahydrite). Persistence of pyrite in desiccated peat is most likely due to the presence of anoxic conditions in the profile, which is helped by its hydraulic properties and high-water retention, which limits solute exchange and redox fluctuations.

Persistence of these conditions can be both an advantage and disadvantage. In a drying climate, a peat wetland can retain soil moisture during long dry periods, store a range of elements, and in some areas, potentially moderate pH through the weathering of carbonates.

Recharge from rainfall and groundwater is also slow and prolonged drying can change physical properties and alter wetland hydroperiods. Finally, the loss of organic carbon may jeopardize carbon sequestration conservation goals. In closed basins this may result in the storage of highly concentrated solutes and acidity.

The negative aspects of peat physico-chemical properties were evident in the drying and acidification of Tordit-Gurrup Lagoon in 2013 and 2020. While the lagoon has some capacity to self-buffer, where this is slow, the application of alkalinity may assist in reducing the risk of future acidification events and restoring the lagoon's ecosystem utility.

Management decisions to treat Tordit-Gurrup Lagoon would therefore need to be underpinned by an understanding of biodiversity values (e.g. flora, fauna carbon sequestration etc.) as a fresh, circumneutral, or saline acidic system and the cost-benefit achieved through treatment. Risks associated with the potential damage to the biodiversity should also be considered. The frequency of repeat acidification events is difficult to assess as this is dependent on future climate and catchment changes.

1 Background and project aims

Peat wetlands within the Muir-Byenup Ramsar site have important ecological value as they form refugia for local flora and fauna (e.g. Storey 1998; Gibson and Keighery 1999; Farrell and Cook 2009). In 2015, the Department of Biodiversity, Conservation and Attractions (Department) developed a project dedicated to understanding the drying and resilience of peat wetlands in the Muir-Byenup Catchment (BCS project SP 2014-24). In July 2019 this project was extended to assess seasonal acid fluxes in Tordit-Gurrup Lagoon's southern water body (near TGS01 Appendix 1).

The project extension was facilitated through funding provided by the South West Catchments Council–Project number 022LM.56. The aims of the project extension are to study a peat system undergoing drying and acidification in order to;

- Improve our understanding (via a conceptual model) of the key regional and local scale hydrological and hydrochemical processes that sustain the physical and chemical character of peat and organic rich substrate material within the Muir-Byenup wetlands.
- Incorporate updated conceptual models into numerical models capable of simulating the physical and geochemical behaviour of peat wetlands.
- Determine and predict the frequency and duration of current and future acidification events in Tordit-Gurrup and other Muir-Byenup peat wetlands.
- Assess remediation strategies of acidified Muir-Byenup wetlands, including recommending laboratory/mesocosm–scale investigations.
- Develop a basis on which to prioritise the conservation of peat wetlands within the Muir-Byenup system based on the likely resilience of wetlands to hydrological change (Perup Management Plan Hydrology and Altered Hydrology Regime Objective).

Data collection for the project extension commenced in October 2019. The location and nature of the data being collected are shown in Figure 1 and Appendix 1. The investigation design and preliminary monitoring results are reported in Rutherford (2019). Subsequently, Rutherford (2020) integrated geophysical and physico-chemical data with geochemical modelling results within a 2-D framework to explain the storage of potential contaminants. This included salt storages (e.g. predominantly NaCl) and potential acid storages (e.g. sulfur and iron as pyrite and other iron-, aluminium-, and sulfur-rich minerals in the near surface environment).

This report concludes the data interpretation and synthesis through undertaking the following key tasks;

- Develop a sub-catchment scale hydrological framework to review catchment water, carbon and acid storages and fluxes (Appendix 2).
- Identify and assess sub-catchment scale hydrogeological controls that could promote or delay groundwater movement (e.g. geological structures and basement topography; Appendix 3).

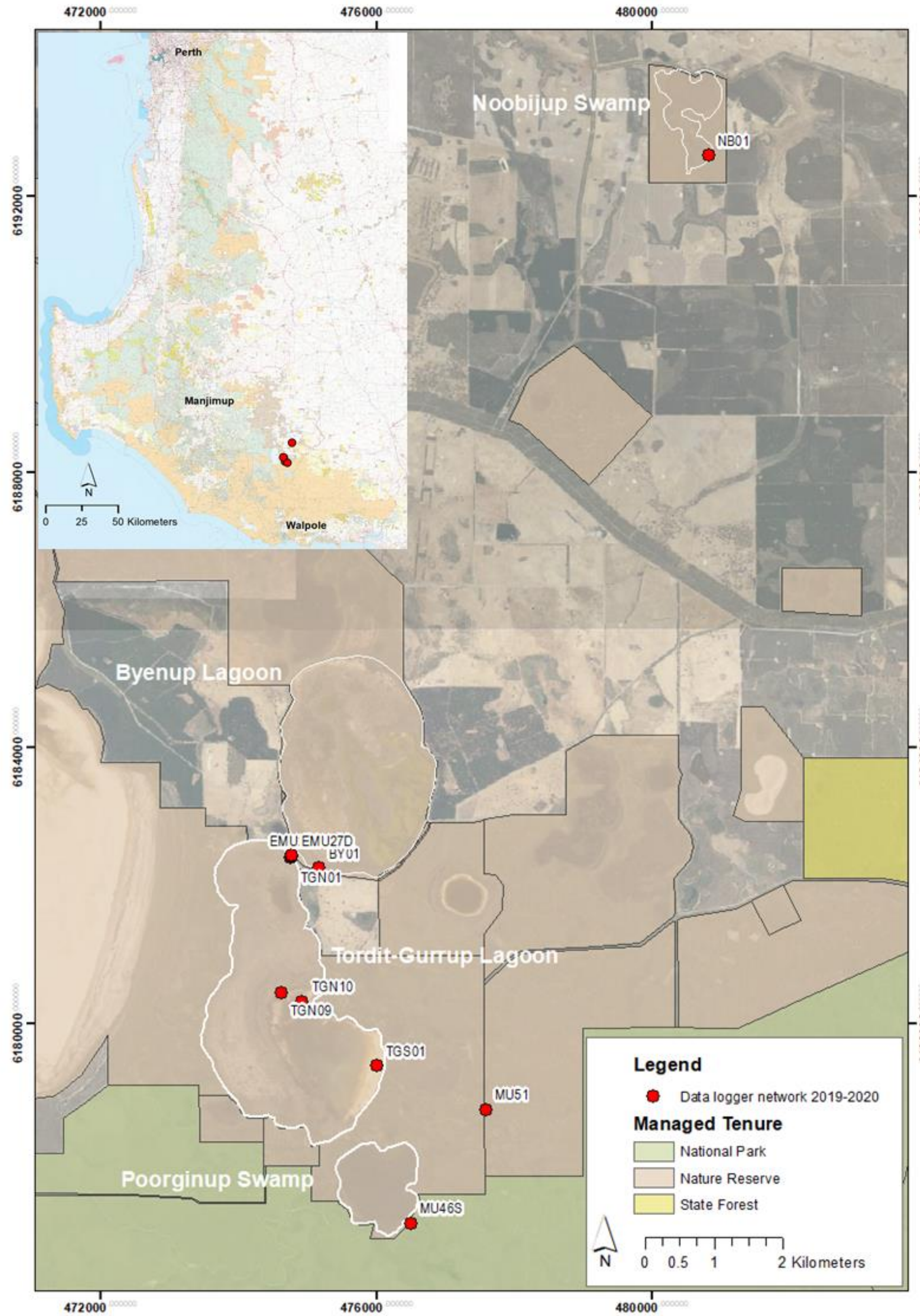

Figure 1: Location of DBCA managed tenure in relation to the Muir-Byenup Ramsar listed peat wetlands investigated in this study; groundwater data logger sites are in red.

- Review catchment scale groundwater recharge and gradients under wet and dry climate cycles (2000 to 2021) (hydrographs of monthly and biannual data; Appendix 4).
- Assess Tordit-Gurrup Lagoon's water storage capacity (depth-volume and depth-area) and variation in seasonal groundwater recharge and flow (Appendix 5 and 6).
- Integrate data and findings to construct a water and salt balance model for Tordit-Gurrup Lagoon (Appendix 7)
- Interpret and upscale geochemical data to estimate peat wetland organic carbon, salt and potential acid storage (Appendices 8 to 10 & 13) and
- Completed geochemical modelling to verify hydrological interpretations of peat and lagoon water interactions (lagoon water and groundwater) (Appendices 11 and 12).

2 Water Balance – catchment storages and gradients

2.1 Hydrology

The Muir-Unicup Catchment covers an area of approximately 60,000 hectares and is characterised by mainly ephemeral drainages and topographically defined wetland storages that account for around 15% of the area (Smith 2003; Horsfield 2015) (Appendix 2; Map 1).

Peat wetlands are generally perennial and have varying connections with groundwater (Smith 2003). They comprise around 4% of the catchment area (Figure 2). Some wetlands show signs of vegetation stress, which is thought to be due to salinisation (e.g. Byenup Lagoon; Appendix 3; Map 2).

2.2 Geology and hydrogeology

Predominantly granitic crystalline basement rocks outcrop, or are close to the ground surface, immediately to the south of the Ramsar site (Wilde and Walker 1984) (Appendix 3; Map 3; Table 4). Cenozoic sediments overlie fresh and weathered basement and obscure the location of palaeovalleys (Wilde and Walker 1984). This feature makes it difficult to map aquifers and assess groundwater storages and gradients. Thick sedimentary sequences were believed to coincide with the contemporary fault-controlled valley forms and drainages (De Silva 2004). The acquisition of airborne magnetics helped identify geological structures and to design drilling investigations in the early 2000's (Chakravartula, and Street 2000) (Appendix 3; Map 4).

High resolution airborne magnetic data acquired in 2013 show major north-west fault segments in the Ramsar site aligned with the long axis of some lakes (e.g. Tordit-Gurrup and Byenup Lagoons). An airborne electromagnetic (AEM) survey in June-July 2008 was undertaken to resolve the top of unweathered rock (geological basement), the thickness of the overlying sediments and soil and groundwater salinities (Appendix 3; Map 6).

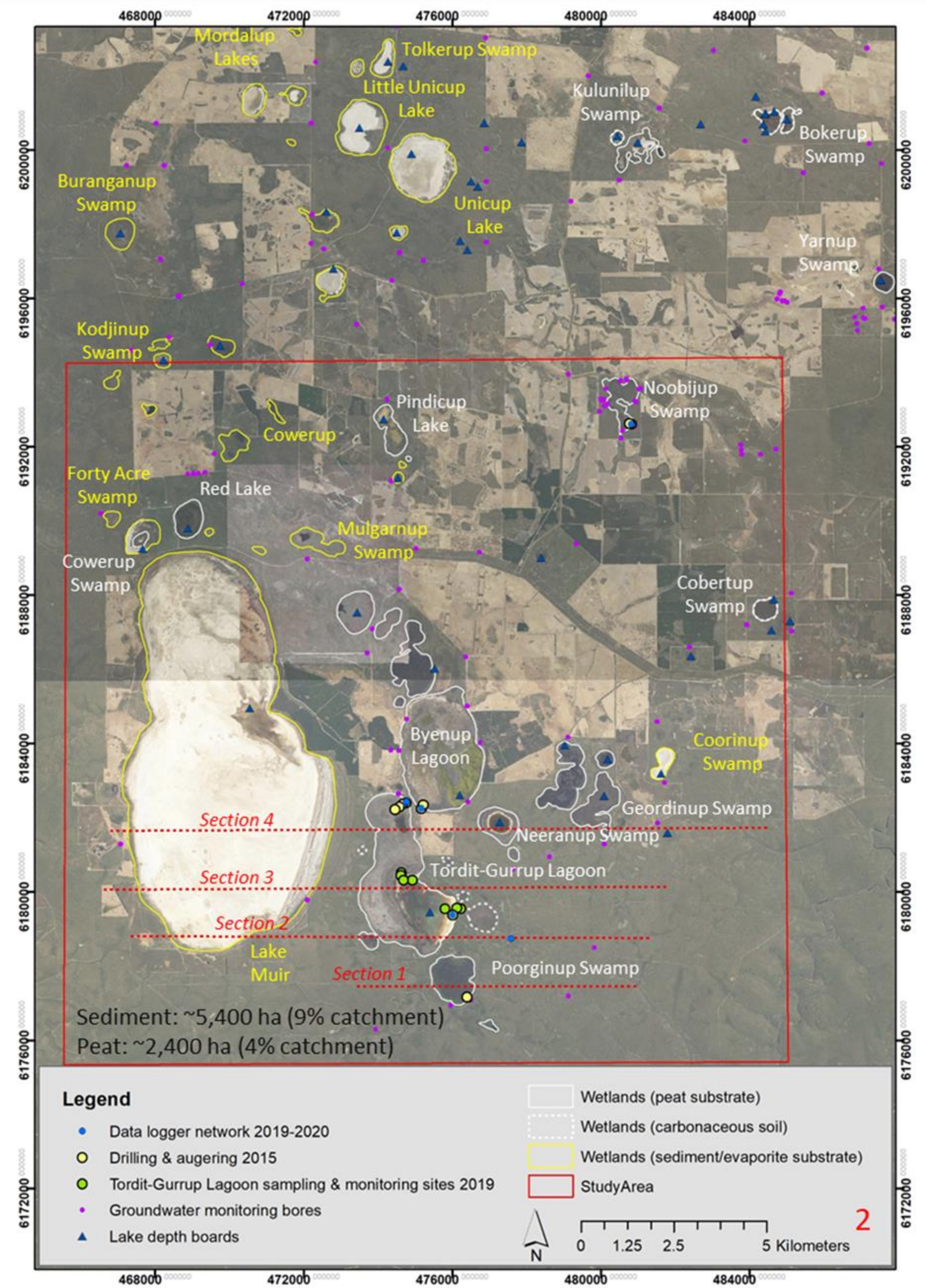

Figure 2: Muir-Unicup Catchment wetland substrate classification (source pers. comm. R. Hearn 2014).

In the AEM investigation difficulties were encountered resolving basement where there was high salt storage in regolith beneath terminal lakes, such at Lake Muir, Tordit-Gurrup and Byenup Lagoons (Søerensen et. al. 2019). In these areas the electrical conductivity structure could be resolved to depths of around twenty metres below ground level. An interpretation of outputs to this depth shows that palaeovalleys in the southern Muir-Byenup Ramsar site trend north-west, and topographically driven groundwater moves east to west, where it is not obstructed by crystalline basement rocks (Appendix 3; Map 6).

In the central to northern areas of Tordit-Gurrup Lagoon groundwater may connect with aquifers in Lake Muir (Appendix 3; Map 6 Section 4). Groundwater elevations from bores presented in Smith (2010) indicated groundwater flow is east to west (towards Lake Muir) in the southern Ramsar site, although it was known to be interrupted where the granite basement was close to the ground surface. Therefore, uncertainty around this conceptual model remained high without the AEM data to map and interpret aquifer connectivity, transmissivity, and the location of barriers to groundwater flow (e.g. geological faults and basement).

Ground-based investigations in the 2000's were hampered by perennially high groundwater levels. In the Muir-Unicup Catchment valley floor aquifer groundwater levels tend to be close to the ground surface, generally within a few metres. In the early 2000's this perennial waterlogging and subsequent salinisation was viewed as a major threat to vegetation and soils (Farrell and Cook 2009).

2.3 Rainfall

The study area is prone to waterlogging as heavy soils are common and this can delay deep drainage and groundwater recharge. Average rainfall in the area is high, generally exceeding 650 mm/a, and in the 1950's sometimes exceeded 1000 mm/a. Rainfall data is collected from two Bureau of Meteorology weather stations; Bangalup (BoM#9556) and Rocky Gully (BoM#9661), which are located within a 40km radius of Lake Muir (see Appendix 4 for graphed rainfall data).

Annual average rainfall has been in decline since the 1950's. Bangalup has the longer record (100 years) and applying a 3 and 7 point moving average shows rates of decline, at around 10%, are pronounced over 3 to 8 year periods in the 1950's, 1970's and the 2010's. Rocky Gully has a shorter record (~65 years) and the same approach suggests 5 to 9 year periods of reductions in rainfall in the 1970's and 2010's respectively (see Appendix 4 for graphed rainfall data).

2.4 Groundwater monitoring (2004 to 2020)

Groundwater monitoring bores were installed in the early 2000's. Hydrographs of groundwater level data from ten monitoring sites in the southern Ramsar site are shown in Appendix 4 (Graphs 1 to 10). Groundwater data are superimposed on monthly rainfall data (Rocky Gully BoM#9661), presented as cumulative deviation from mean (CDFM) rainfall for the period 2000 to 2021. Eight of the ten sites have nested bores that monitor groundwater levels in shallow (sediments) and deeper aquifers (weathered basement) (see Appendix 4 table).

Groundwater is close to the ground surface in the study area, ranging from around seven to zero metres below ground level. The thin unsaturated zone assists aquifers to respond quickly to seasonal rainfall recharge, which confirms vertical gradients are dominant. Data collected from nested bores show deep and shallow aquifers are generally connected and have an internally consistent response to rainfall recharge (timing and magnitude). Seasonal responses vary between sites due to the different physical properties of the aquifers (Rutherford 2020). Downward heads occur at couple of sites and may develop due to a combination of complex gradients and delayed recharge (e.g. EMU27), or where water is being managed (e.g. MU46).

Groundwater level trends in most aquifers display sensitivity to changes in mean rainfall that mimic the rainfall CDFM, in particular, periods of below, or above average, rainfall. Key periods of interest in this study relate to the drying of Tordit-Gurrup Lagoon in 2013 and 2020 and response to above average rainfall in 2016 and 2020.

The decline in average rainfall in 2011 reduced groundwater recharge and groundwater levels. However, the decline was short-lived. A return to average annual rainfall in 2012 and above average rainfall in 2016 increased groundwater levels to pre-2011 conditions. Below average rainfall conditions between 2017 to 2020. March/April 2020 produced the lowest recorded groundwater levels on record for over fifty percent of the groundwater sites reviewed. The exception was groundwater in aquifers upgradient of Tordit-Gurrup Lagoon, where groundwater levels have not recovered since their decline in 2011 (e.g. bore MU51; see Appendix 4; Table, Map and Graph).

Groundwater level data were plotted in mAHD to review if groundwater gradients follow the sub-catchment scale topography to the east of Lake Muir, which decreases in elevation from south to north (e.g. Appendix 2: Map 1; ephemeral drainage patterning). To achieve this data for shallow aquifers (screened at depths less than twenty metres below ground level) were graphed with Tordit-Gurrup Lagoon water levels and are divided into bores located up and down gradient from the lagoon (Appendix 4; upgradient bores; Graph 11 and downgradient bores; Graph 12). Results show that minimum groundwater levels in bores upgradient of Tordit-Gurrup Lagoon (bores MU52S and MU46S; Appendix 4 Graph 11) are similar to lagoon water levels. Gradients following winter rains are south to north, towards Tordit-Gurrup Lagoon.

Down gradient of Tordit-Gurrup Lagoon shallow gradients trend from south to north but are more subtle. Groundwater here may also flow to the east, into Lake Muir, where barriers to flow are absent and groundwater elevations in the lake are lower (MU58S and MU59S; Appendix 4 Graph 12). Groundwater levels in downgradient bores are frequently below water levels measured in Tordit-Gurrup Lagoon, with the exception of groundwater on the northern margin of Tordit-Gurrup Lagoon (e.g. bore EMU27D, see Appendix 4; Graph 12). Elevated groundwater levels on the northern margin of Tordit-Gurrup Lagoon and southern margin of Byenup Lagoon help these lagoons retain water. This is discussed further in Section 3.

3 Water Balance – Tordit-Gurrup Lagoon

The Tordit-Gurrup Lagoon water balance was examined to understand changes in wetland scale water storages and focused on the input and redistribution of water. Hydrological parameters considered were groundwater interactions, spatio-temporal variation in lagoon water storages and local rainfall-runoff and evaporation.

Regolith beneath and margin to the lagoon was dominated by sandy clay and clays. Lateral flow of groundwater in these materials is slow, ranging from 0.15 to 1.5 m/day, with an average of 0.5 m/day (Rutherford 2020). Therefore, potential annual groundwater flow into the lagoon is limited to an area ~200 metres up gradient. The low groundwater flow rate and aquifer specific yield confirmed lateral groundwater inflow, or outflow, from the lagoon is not significant and doesn't require to be included in the Tordit-Gurrup Lagoon water balance. Vertical flow was accounted for using an average lakebed conductance, which was estimated from nuclear magnetic resonance (NMR) measurements of peat and sediments (Rutherford 2020).

By convention, the vertical movement of water will be an order of magnitude lower than lateral groundwater flow, with average rates of recharge to competent peat and the southern water body sediments are 1.5 and 15 cm/day respectively. Consequently, a half metre decline in groundwater levels in these different materials should require 33 and 3 days to recharge, provided there is a constant source of water and vertical infiltration dominates.

Recharge rates were tested though the collection of hourly groundwater level and quality data from the peat wetland bore data logger network established in 2015. The network was expanded in 2019 to include desiccated peat on the margin of Tordit-Gurrup Lagoons' southern water body. LiDAR data, aerial photography and ground observations were used to delineate four landscape units and select suitable desiccated peat sampling and monitoring sites (Figure 3; Appendix 5).

Monitoring results show that below average rainfall in 2019 produced correspondingly lower groundwater levels in shallow aquifers (6 to 20m below ground level) at the northern Tordit-Gurrup Lagoon shoreline. Groundwater at BY01, TGN01 and EMU27D dropped to their lowest levels since monitoring commenced (Appendix 4 and 6; Graphs A, B, C, J & K).

In the northern area of Tordit-Gurrup Lagoon, groundwater levels in the underlying sediments and saprolite fall below the lowest measured lagoon elevation (depth gauge) between March and May 2020 (TGN01 & EMU27D; Appendix 6; Graph K). Gradients during this time were not towards the southern water body and this coincides with the lagoon drying. Data from shallow (~1m) piezometers installed in the peat (TGN09b and TGN10b) show peat groundwater is not connected to these aquifers (Appendix 6; graphs D, E & J). Peat appears to be connected to aquifers in sediments in the south area of the lagoon (e.g. TGS01), but the hydrological relationships are unclear.

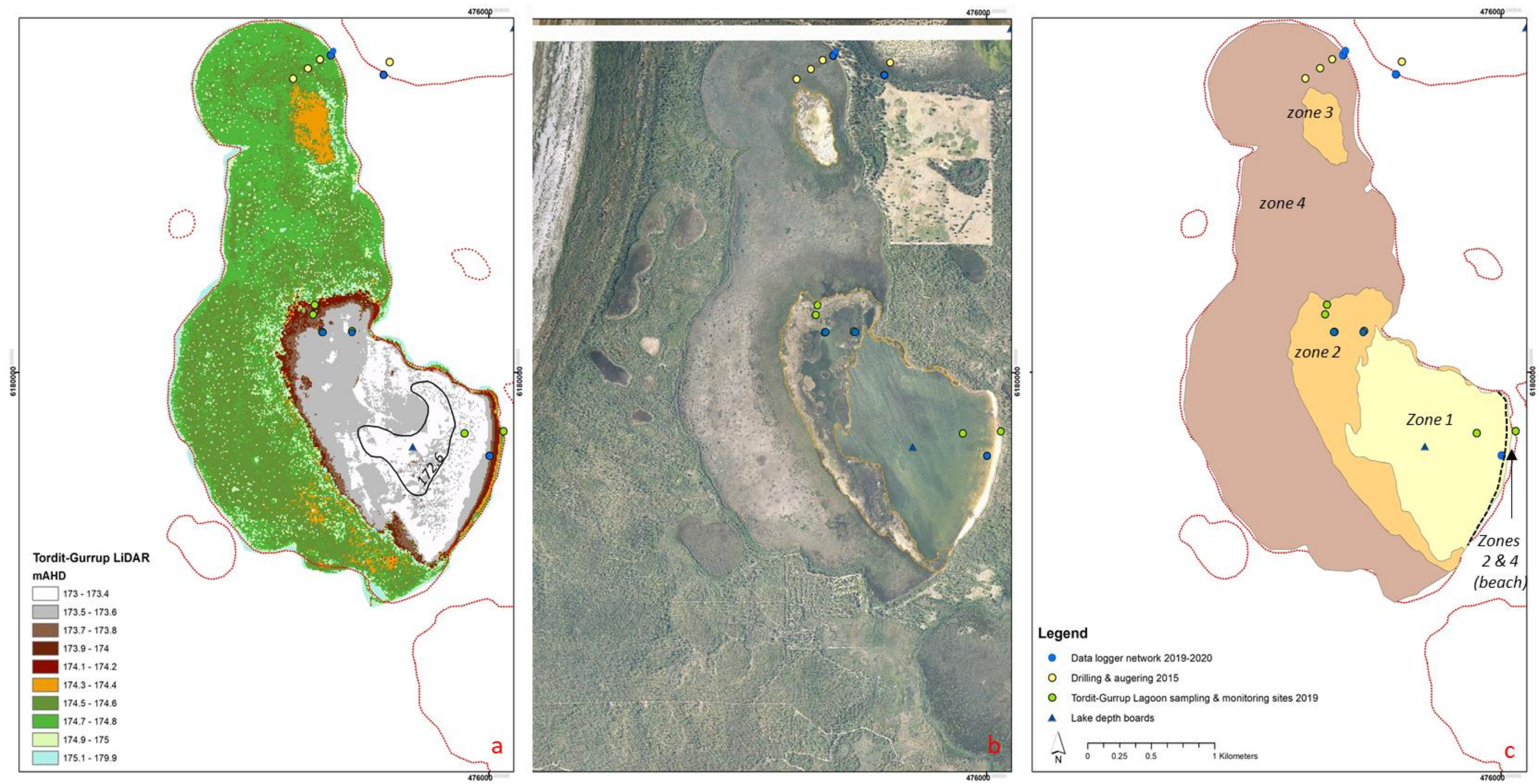

Figure 3: Tordit-Gurrup Lagoon topography and landscapes; a. LiDAR data and ~172.6mAHD contour; b. Aerial photography 2019; desiccated peat boundary outline in orange; c. Landscape classification. Zone 1: southern water body sediments; Zone 2: highly desiccated peat; Zone 3: northern water body/desiccated peat; Zone 4: variably competent peat (see Appendix 5 for information on southern beach).

The response to rainfall in May and June 2020 (see Appendix 6) confirm that groundwater responds quickly, which means local rainfall and runoff within the lake is important for groundwater recharge and the development of the lagoon water body. This observation is verified by the slow rates of recharge to the peat over the winter months. Rates of recharge are slower than those measured, particularly at the beginning of winter, and this is likely to result from a combination of high runoff and evaporation.

The importance of local rainfall-runoff and recharge were tested within the algebraic water balance model WatBal that was originally developed for Toolibin Lake and other Wheatbelt wetlands (Peck 2000 and Hydrologica 2016). The Department provided the scope and model input data, which included peat and sediment recharge rates, twenty-centimetre depth-volume-area data for Tordit-Gurrup Lagoon (Appendix 5) and rainfall and evaporation data from SILO (https://www.longpaddock.qld.gov.au/silo/) that were extracted from a point approximately two kilometres east of Tordit-Gurrup Lagoon (Lat -34.50 Long: 116.75).

The model covers the period 2006 to 2021 and is run on weekly time-steps. Preliminary results are presented in Appendix 7. Monthly lagoon water level and salinity data observations collected between 2006 and 2019, were used to verify the modelling outputs. Comparisons between modelled and measured data are generally reasonable, with respect to simulating the magnitude of water level response and minimum water levels. The model underestimates lagoon water levels in above average rainfall years, in 2009 and 2016, and for the same years overestimates the rate of the recession, following the inundation. Measured and modelled lagoon salinity in winter months shows regular dilution from rainfall-runoff. However, the model generally underestimates the rate of water body salinity increase and maximum levels achieved. Measured minimum salinities look to be increasing over time, so it is possible that the poor fit between measured and observed data is due to lags in the seasonal cycling of solutes.

4 Carbon, salt and acid storage

4.1 Organic carbon

Assessing organic carbon storage through isotopic methods is commonly thought to provide results comparable to the loss on ignition (LOI) approach (Agus et. al. 2011). The isotopic approach was undertaken here, with peat and vegetation analysed for carbon and nitrogen isotopes ($\delta^{13}C$, $\delta^{15}N$) using mass spectrometry analysis. Normalisation procedures were carried out according to Skrzypek (2013) and results compared with LOI data.

Fibric and hemic-sapric peat were analysed at each site (drilled and augured holes). Vegetation was sampled and analysed from shoreline drill sites. The aim of this design was to sample peat at representative sites within four peat wetlands and identify variation. Vegetation analyses were undertaken to provide a broad context of contemporary vegetation carbon contribution to the peat. The vegetation sample size is small (n=10; Noobijup Swamp (5); Byenup Lagoon (3); Tordit-Gurrup Lagoon (2)) was grouped into sedge and non-sedge classes (Figure 4).

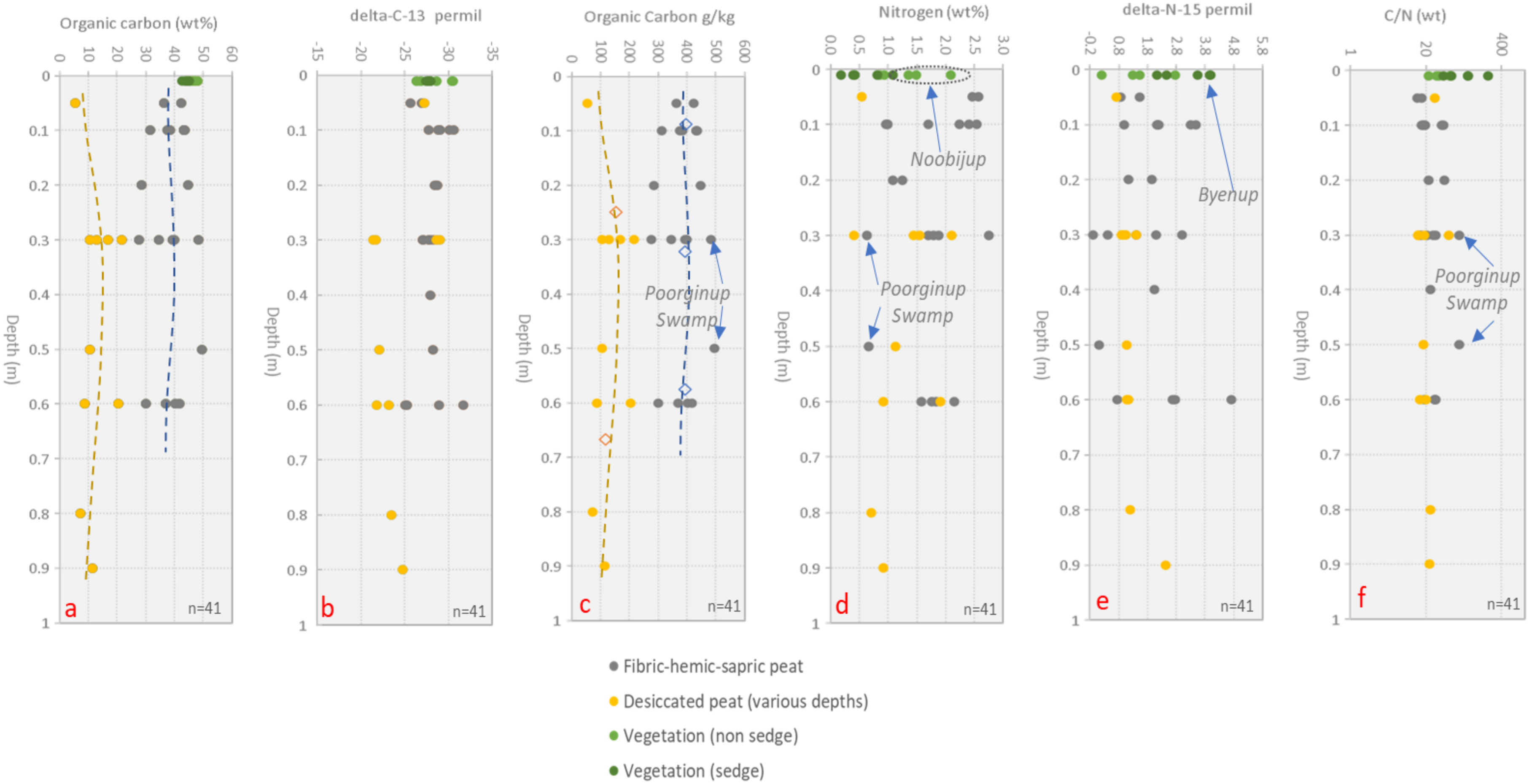

Figure 4: Carbon and Nitrogen Isotope results

Organic carbon (weight %) and $\delta^{13}C$ data are graphed against depth sampled (Figure 4; Graphs a & b). Poorginup Swamp has the highest levels of organic carbon, which is consistent with results from a microbial investigation that confirmed a high abundance of bacteria responsible of the decomposition of cellulose (e.g. acidobacteria) (Wood 2017). Organic carbon in the upper metre of the peat profile ranges from 5 to 50 weight percent (wt % OC), with peat less affected by drying retaining between 30 to 50 wt % OC. Desiccated peat displays around a 65% reduction in organic carbon (5 to 20 wt % OC) and this occurs on the margin of Tordit-Gurrup Lagoons' southern water body, and towards the centre of Noobijup Swamp. No substantial variation in average organic carbon with depth was evident for the desiccated, and less desiccated peat groupings (Figure 4; Graph c).

Converting organic carbon to g/kg proved challenging as organic carbon and sediments fluctuated in volume, and composition with depth. This made it difficult to reconcile and compare different measurements and characterize zonation in the peat, particularly with respect to bulk density and LOI. For example, variable and sometimes high quantities of fine quartz sands produced elevated bulk density measurements and LOI results from XRF fusion and furnace methods varied. Peat XRF LOI measurements ranged from 7 to 85% and a small dataset (n=5) produced a robust linear relationship ($y=0.66$; $R^2=0.94$) with isotopically derived wt % organic carbon. This relationship was used as a starting point to estimate peat wetland organic carbon, in this study area. The rationale being that spatial variation across such large wetlands is likely to introduce greater error. Adopting an average bulk density measurement, the relative estimates of average organic carbon for competent and desiccated peat were 395 g/kg and 135 g/kg (Figure 4c). This compared well with an average of around 350 g/kg reported by Watmough et. al. (in press) who analysed peat from Poorginup and Noobijub Swamps.

Peat mineralogy was identified and semi-quantified using X-Ray diffraction methods (Rutherford 2020). The relative percentages of these minerals within the peat profile were adjusted to account for the organic carbon. In desiccated peat selected samples underwent an acid digest and repeat isotopic analyses to assess measurement error and inorganic carbon content (e.g. calcite (pedogenic and shell material), dolomite and minor siderite).

Nitrogen (weight %) and $\delta^{15}N$ data are graphed against depth sampled (Figure 4; Graphs d & e). Desiccated peat has low levels of nitrogen. Exceptions are Noobijup Swamp where high nitrogen is associated with an abundance of nitrospiraceae bacteria and Poorginup Swamp where low nitrogen is associated with an abundance of acidobacteria (Wood 2017). Nitrogen levels (wt%) in vegetation (non-sedge) are highest in Noobijup Swamp, with $\delta^{15}N$ being highest in sedge species in Byenup Lagoon (Figure 3; Graphs d & e). Ratios of C/N (wt%) are higher in peat in Poorginup Swamp and sedge species (Figure 4; Graph f).

The microbial study undertaken by Wood (2017) identified other resilience indicators for Poorginup Swamp; methanotrophic bacteria are active and fungal communities are stable. These metrics are absent at Noobijup Swamp and this information, along with lower carbon levels towards the centre of the lake, was incorporated into the carbon storage classification for zone 3 of Tordit-Gurrup lagoon (Figure 3c).

Organic carbon storages were calculated using average values (depth and carbon concentration) for the peat wetlands investigated here, including their satellite wetlands. Results were then upscaled to include other peat wetlands within the Muir-Unicup Catchment. (Appendix 8). A conservative estimate of organic carbon storage in peat wetlands being around a million tonnes (Appendix 8).

4.2 Salt

Major minerals in the peat profile are fine quartz sands, iron oxyhydroxides, pyrite and clay and evaporite minerals. In Tordit-Gurrup Lagoon evaporite minerals increase in abundance from the lake margins towards the southern water body. In this area the loss of organic carbon through desiccation is associated with increases peat salt storages and soil and water salinisation.

Results from soil electrical conductivity (EC1:5) analyses were graphed with depth sampled and displayed as conductivity (mS/m) and milligrams per litre (mg/L) (Figure 5; Graphs c & d). Salinity ranged from ~80 to around 9,000 mg/L and decreased with depth below ground level, with highest salinity in the upper metre. In peat, average salinity for competent peat doesn't vary with depth and is estimated at 500 mg/L. In Tordit-Gurrup Lagoon, desiccated peat displayed variation in salinity with depth sampled. Highest salinity in fibric peat at 5,000 mg/L and hemic-sapric peat at 4,000 mg/L.

Employing a similar mass-balance approach to that employed for organic carbon, average salt stores were calculated from point measurements (drill and augered core). This included the four peat wetlands investigated, and their satellite wetlands. These data were then used to produce a salt storage model for Tordit-Gurrup Lagoon, which showed that ~50% of the lagoon's estimated salt storage in the upper metre is contained within desiccated peat (Appendix 10).

Upscaling of salinity and salt storage results to other peat wetlands was achieved using AEM data. This was possible as groundwater salinity is the major driver of regolith conductive response and there is a good relationship between the measurements of electrical conductivity at different scales (Rutherford 2020). AEM also proved it could resolve and separate variation in average salt storage, in the upper metre, in both Byenup and Tordit-Gurrup Lagoons (Appendix 3; Map 5). AEM data derived salt storage estimates, for other peat wetlands within the Muir-Unicup Catchment are tabled in Appendix 10.

4.3 Potential acidity

Water and soil geochemical analyses confirm that the acidification of Tordit-Gurrup Lagoon's substrate is a long-lived process involving the oxidation of sulfides (mainly pyrite) and subsequent transport of metals and metalloids.

The peat profile consists of around 40-50% organic carbon, with the remaining constituents being fine quartz sands, clays and minor amounts of other minerals (Rutherford 2020). Many of the minor minerals are associated with acidification. Upgradient areas (lagoon shorelines) are characterised by pyrite (framboidal), carbonates (calcite), gypsum, micas, iron oxyhydroxides and low and high cation exchange capacity clays (e.g. kaolinite, nontronite, montmorillonite). Most minerals persist downgradient, in desiccated peat marginal to and within the water body. Carbonates, calcite, dolomite and calcite increase in abundance and sulfur is present in a reduced (e.g. pyrite) and oxidized forms (e.g. gypsum, jarosite, alunite and $MgSO_4$ (hexahydrite)) (Rutherford 2020).

Under aerobic conditions a reaction sequence to explain these observed changes starts with vegetation respiration and decay, which produces carbon dioxide through the following reaction;

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

Carbon dioxide reacts in water to form carbonic acid, bicarbonate and carbonate according to the following reversible equations;

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow H^+ + CO_3^{2-} \qquad (2)$$

The relative concentrations of carbonic acid, bicarbonate and carbonate are controlled by pH. The production of carbonic acid will reduce pH, but this could be buffered by water rock reactions (e.g. dissolution of calcium and magnesium carbonates, silicates, microbial mediated reactions). Carbonic acid controls the solubility of calcium carbonate through the reversible reaction below;

$$CaCO_3 + H_2O \leftrightarrow Ca^{2+} + HCO_3^- + OH^- \qquad (3)$$

Decay of organic carbon under anerobic conditions, in the presence of sulfate, iron oxyhydroxide and methanogenic bacteria, results in a decrease in pH that encourages further aquifer reactions (e.g. production of carbon dioxide and methane gases, ferrous ions and sulphuric acid). Decaying plant tissues, together with iron-rich mica and clay minerals provide an ideal micro-environment for pyrite formation and in sedimentary environments, such as Muir-Byenup, pyrite framboids could form in days (Rickard 2019 and Wang et. al. 2020). Once formed, the oxidation of pyrite is a slow process, which speeds up with a bacterial catalysis and available ferrous ions. In the presence of carbonates, the oxidation of pyrite encourages the precipitation of gypsum (e.g. Ritsema and Groenenberg 1993), and jarosite and alunite where micas and clay minerals weather (Long et. al. 1992). The subsequent dissolution of jarosite may continue pyrite oxidation in the absence of oxygen (Welch et. al. 2008). The evaporation of the lagoon water body concentrates solutes within the uppermost sediments (10-20cm), precipitating evaporite minerals, calcite, gypsum, halite, barite and hexahydrite (Rutherford 2020).

The physical properties of the peat profile and seasonal changes in groundwater levels constrain the geochemical gradient and the extent to which redox reactions progress (Rezanezhad et. al. 2016). The presence of reduced sulfur suggests that the physical properties of the peat and regular saturation by rainfall and lagoon water limit pyrite weathering. Alternatively, if acidobacteria are present in the peat profile, they are reducing inorganic, or organic, sulfate (Hausmann et. al. 2018). The precipitation of carbonate minerals in the peat profile suggests the material has potential to buffer acidity produced from the oxidation of pyrite, and is a general observation in organic carbon wetlands (e.g. Fitzgerald 2004). This is provided the physical properties of the peat allows groundwater to mix and react with entrained carbonate minerals.

The Muir-Byenup peat wetlands are classified as potential acid sulfate soils due to their pyrite content (Ahern et. al. 1998). Reductions in average rainfall and groundwater levels increase the risk of acidification.

4.3.1 Geochemical composition and processes

To understand how these physico-chemical processes influence sulfur and iron in the profile they were plotted as elements and oxides on ternary diagrams. Elemental data were sourced from X-Ray Florescence (XRF) analyses. XRF data acquired for Tordit-Gurrup Lagoon (n=232) were graphed, along with mineralogical (X-Ray diffraction) results to verify observations and provided insight into the geochemical evolution of the peat.

Results for Al_2O_3-Fe_2O_3-SiO_2 (Appendix 10; Graph 1) show the mineralogical and geochemical zonation of the different peat horizons. The peat geochemistry changes with depth and develops within the constraints of both the underlying and introduced sediments. For example, aluminum and iron oxides increase towards the ground surface, from the sapric to hemic peat zones, with fibric peat being more siliceous. Clay and iron oxy-hydroxide minerals deeper in the peat profile indicate that surface water inflows containing suspended solids and/or vertical groundwater movement of dissolved iron and aluminum were important processes in the past. Desiccated peat is geochemically similar to peat at the base of the profile (e.g. enriched in iron and depleted in aluminum). The absence of aluminum indicates the dissolution of clays may occur in both materials.

Results for Fe_2O_3-S-Al_2O_3 (Appendix 10; Graph 2) are less clear. Sediments and saprolite are relatively depleted in sulfur and enriched in aluminum oxides. Sulfur increases to the ground surface (sapric to fibric peat), alunite forms in the upper sapric (hemic) peat where there is elevated aluminium. Iron and sulfur increase in desiccated peat, with the precipitation of pyrite and jarosite. As with the Al_2O_3-Fe_2O_3-SiO_2 ternary diagram, desiccated peat shows geochemical similarities with peat developed at the base of the profile (e.g. depleted in aluminum, enriched in iron, with variable and generally high sulfur). Jarosite and alunite are common weathering products of aluminosilicates and pyrite, and they concentrate in the near surface where evaporation rates are high (Long et. al. 1992). This is the model proposed here, with dominant framboidal pyrite forming in situ within the peat, from the reductive dissolution of sulfate and iron in the presence of decomposing organic matter (Wang et. al. 2020). Sulfate is sourced from organic carbon and oceanic aerosols.

4.3.2 Quantitative assessments of acid storage

Average potential acid storage calculated for major peat profile zones using data from the following laboratory analyses; Chromium Reducible Sulfur (CRS) and X-Ray Florescence (XRF) (whole rock fusion and portable (handheld method)) (Figure 5 Graphs e to i).

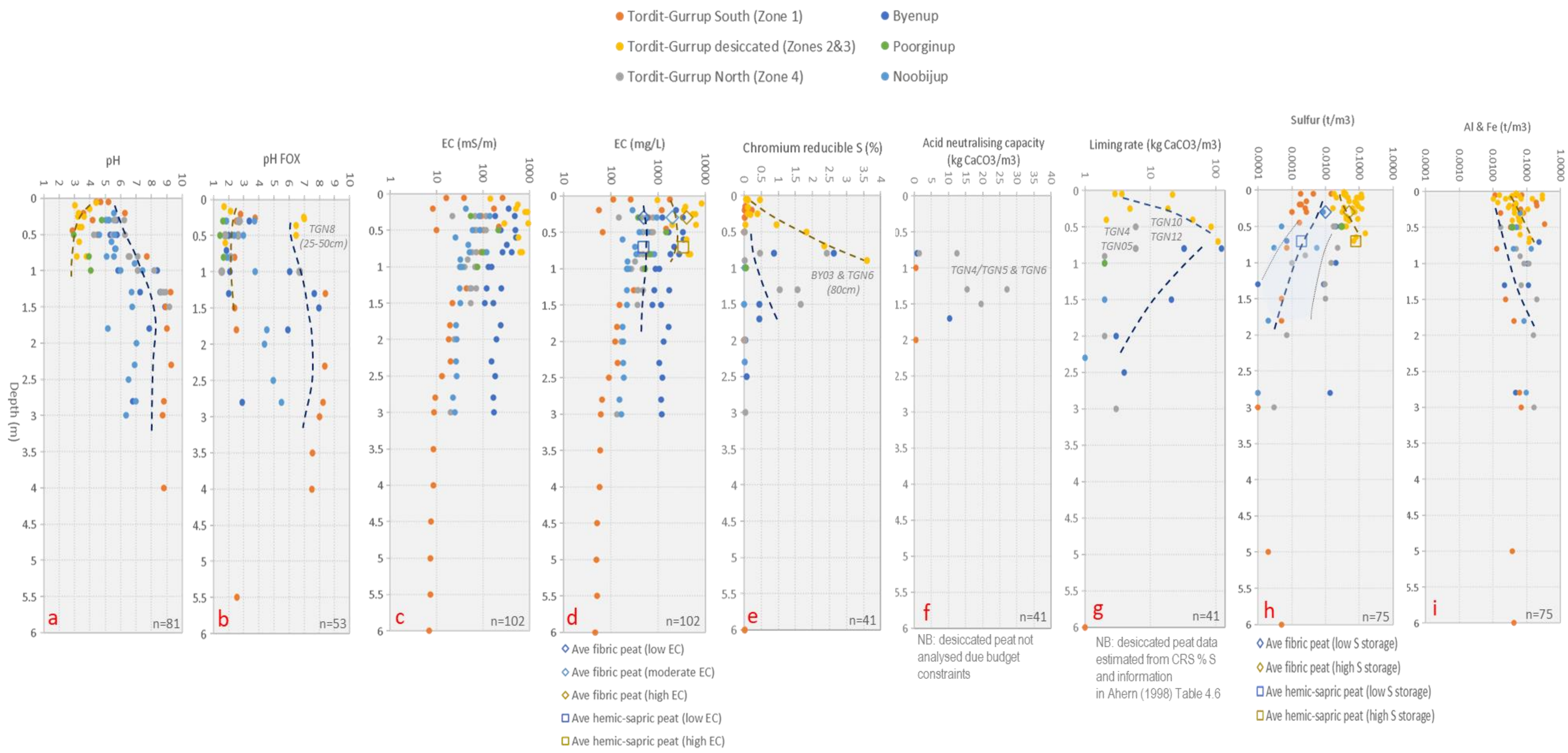

Figure 5: Salinity and potential acidity storages; laboratory analyses and data (Note; data in graphs e, f & g are derived from chromium reducible sulfur analyses and data in graphs h & I are sourced from XRF analyses)

Relationships between XRF fusion and XRF portable were robust for sulfur, iron, and aluminum (Rutherford 2020). Due to this relationship, and budget constraints, the portable XRF method was chosen to analyse desiccated peat in the acid-flux investigation of Tordit-Gurrup Lagoon.

Geochemical results for all peat wetlands were plotted against depth sampled in Rutherford (2020). Results showed that dissolved analytes increased in concentration with increases in pH and/or salinity. These comparisons are examined further in Figure 5, with analytes graphed pH, pHfox and electrical conductivity (EC) (mS/m and mg/L) (Figure 5: Graphs a to d).

Comparing pH and pHfox confirmed most materials can acidify, based on their current composition. This relationship wasn't always supported by CRS results, with the acid neutralizing capacity being highest with distance from the shoreline for peat in northern Tordit-Gurrup Lagoon (Figure 3c; zone 3; Figure 5; Graphs e to g). Results from full CRS analyses indicate liming requirement rates ranging from <1 to 124 kg $CaCO_3/m^3$, (as per the liming rate provided by CRS analyses). Due to budget limitations, partial CRS analyses were carried out on desiccated peat and liming rates derived using gravimetric relationships and considering pHfox results. Noting that derived liming rates exhibit a similar range in liming values and increase with depth below ground level.

Sulfur, aluminum (Al) and iron (Fe) XRF data were converted to tonnes per cubic metre (t/m3), with anions and cations graphed separately with depth sampled (Figure 5; Graphs h and i). Sulfur increases with depth (~2m below ground level) for desiccated peat but decreases for other materials sampled. Other materials exhibiting a broad range of sulfur storage. Conversely aluminum and iron increase in abundance with depths to around two metres and exhibit less variation. Sulfur availability limits the production of pyrite in the peat and its subsequent weathering products.

4.3.3 Groundwater and surface water interactions

Groundwater level and chemistry data show that where groundwater fell below the base of the peat in summer there was an increase in groundwater sulfate, calcium, and magnesium (Rutherford 2020). Groundwater is sampled at the peat-sediment interface, where there is a marked decrease in hydraulic conductivity. This boundary appears laterally continuous and suggests there is potential for acidic water to discharge at this seepage interface when groundwater levels are low in summer.

Hydraulic parameters of these materials confirm the lateral movement of groundwater ranges from 0.05 (peat) to 0.15 (clay base beneath peat) m/day (Rutherford 2020). Therefore, over a twelve-month period acid fluxes to the southern water body could be sourced from areas ~50 to 200 metres upgradient, which generally falls within the existing desiccated peat zone (Figure 3). Understanding surface groundwater interactions in this zone is important for the management of the water body.

This work was progressed by comparing peat and sediment geochemistry results with water geochemistry. Speciation in solution and stability and solubility diagrams were constructed for desiccated peat site TGN10b (Oct 2019 & March 2020) and lagoon water TGS06 (Oct 2019) using the SpecE8 and Act2 modules in The Geochemist's Workbench v12 (Appendices 11 & 12).

Speciation modelling results are tabled in Appendix 11 and show that at the end of winter (October 2019) most minerals are stable in solution in the surface water body (TGS06), apart from quartz. Groundwater within desiccated peat is similar, with alunite, kaolinite and beidellite (high cation exchange capacity (CEC) clays stable as well as quartz. Minerals stable in desiccated peat groundwater in March 2020 expand to include feldspars, micas, gibbsite, and siderite, while alunite, anhydrite, gypsum, and magnesium sulfates increase in solubility (Appendix 11). Lagoon surface water wasn't sampled in March 2020 as the lagoon was dry.

Mineral stability diagrams for sulfur were produced to understand how the seasonal changes in pH and Eh influence mineralogy (Appendix 12). Results showing sulfate is stable in solution at sulfate in lagoon surface water (TGS06) in October 2019 and desiccated peat groundwater (TGN10b) in March 2020. In October 2019 desiccated peat groundwater shows sulfur is stable in an oxidised form, in the mineral alunite. Although a small reduction in pH would result in alunite dissolution and the formation of soluble $MgSO_4$. Similarly, jarosite is stable with a minor change in Eh in March 2020 (Appendix 12).

In March 2020, the decrease in pH in desiccated peat is associated with water that is undersaturated in carbonate and other minerals identified in the profile by XRD methods (e.g. calcite, dolomite). Undersaturation of these minerals increases in winter, becomes more negative, suggesting their dissolution is possible. While increases CO_2 gas evolution is associated with summer sampling suggesting reactions outlined in Section 4.3 occur (e.g. vegetation decay, soil respiration and methanogenesis).

The high percentage of pyrite identified within the desiccated peat, as identified by XRD analyses, suggests oxidation and mobilisation is slow (Rutherford 2020). Although it is important to note these rates will increase with the continued weathering and erosion of desiccated peat.

Groundwater and surface water gradients confirm that the southern water body forms a hydrological sink for groundwater discharging from the south and acidic groundwater from the north. The seasonal wetting and drying of the lake results in the continued dissolution and redistribution of sulfur in evaporite minerals. As horizontal gradients are low this redistribution will be upwards in the profile.

The behaviour of the lagoon as a closed basin helps constrain the calculation of potential acid stores, which in this case is total sulfur as measured by XRF. The production of potential acid storages for Tordit-Gurrup Lagoon and other peat wetlands followed a similar approach to organic carbon and salt in sections 4.1 and 4.2. Volumetric calculations for potential acid storage in the upper metre of sediments, indicating desiccated peat at Tordit-Gurrup Lagoon may store around 50% of acid producing minerals. Sulfur stored mainly as sulfate in sediments within the lagoon water body is relatively low at around 5% (Appendix 13).

5 Discussion and outcomes

Past and present hydrological investigations and monitoring data have provided an important knowledge and data base to undertake this research, as well as for future studies.

5.1 New or updated knowledge

Interpretations of geophysical and hydrological data have provided a new understanding of groundwater gradients and rates of groundwater flow. Lateral groundwater movement is now known to be slow, and as a result, aquifers are more sensitive to vertical processes.

Geological discontinuities, such as faults and basement, disrupt and sometime reverse topographically driven groundwater flow. These features are being mapped from geophysical data and will help explain complex groundwater level patterns, which builds on work completed by Chakravartula and Street (2000) and Standen et. al. (2021).

Groundwater levels mimic average rainfall trends, with decreases in rainfall since 2011 or 2016 reducing recharge, and as a result groundwater levels in most aquifers. Minimum groundwater levels generally remain within a metre from the ground surface in peat wetlands. This confirms that near-surface groundwater levels play an important role in maintaining peat soil moisture in summer months, and consequently fire risk.

The physical properties of peat soils and underlying sediments have been measured in three peat wetlands, and results show that downward leakage of surface water occurs. However, this process is slow, which promotes the evaporation and concentration of salts in open water bodies. This process, along with the dissolution of halite on wetland substrates, can explain the seasonal increase in wetland salinity. This indicates that the upward movement of stored salts in the regolith is not an important process in the wetlands studied here.

Estimates of organic carbon, salt and potential acidity have been completed for four peat wetlands. Results have been upscaled to provide storage estimates for peat wetlands within the Muir-Unicup Catchment (Appendices 8, 10 and 13). Organic carbon is estimated at around one million tonnes, salt at thirty-five thousand tonnes, and sulfur at approximately two hundred thousand tonnes. The more detailed study of Tordit-Gurrup Lagoon reveals the potential for variation within peat wetlands (Table 1).

In Tordit-Gurrup Lagoon the hydrology and landscape constrain the distribution of these storages. The southern water body and marginal desiccated peat (Zones 1 and 2 in Figure 3c) estimated to respectively store 8%, 70% and 65% of the lagoon's organic carbon, salt, and potential acidity (highlighted in red in Table 1). Zone 1 and 2 combined having a disproportionate amount of salt and acid given they comprise around 30% of the total lagoon area, and less than 10% of the lagoon volume (Appendix 5).

Zones; see Figure 3c	Material subclass	Organic carbon storage (t)	% Storage	Salt storage (t)	% Storage	Potential acid storage (S) (t)	% Storage	Alkalinity requirement as lime (t)
1	Evaporite			1316	21	2043	3	3575
2a	Fibric peat	10321	5	1307	21	13305	17	23284
2b	Hemic-Sapric peat	5879	3	1742	28	35480	45	62090
3a	Fibric peat	1695	1	215	3	2145	3	3754
3b	Hemic-Sapric peat	965	0	286	5	5720	7	10010
4&5a	Fibric peat	51559	23	653	11	13053	16	22843
4&5b	Hemic-Sapric peat	154678	69	1958	32	7832	10	13706
Total		225098	100	6160	100	79578	100	139261

Table 1: Tordit-Gurrup Lagoon organic carbon, salt, and potential acid storage (uppermost metre of peat and ten centimetres of sediments; see Figure 3c).

5.2 Resilience

Peat sampled at Poorginup Swamp contains relatively high carbohydrate relative to aromatic carbon compounds indicating a greater potential for lability and resultant mineralisation to form the greenhouse gases, carbon dioxide, methane and nitrous oxide (Verbeke et. al. 2017). This is a characteristic of higher latitude peats and is of concern as it is believed to be an indicator of reduced resilience and is a parameter that cannot be managed.

The low hydraulic properties and high-water retention of intact peat slows water and solute exchanges and deleterious chemical reactions. This can delay drying and acidification. Conversely, recharge from rainfall and groundwater is also slow and prolonged drying can alter soil physical properties and change wetland hydroperiods.

5.3 Acidity mitigation

Tordit-Gurrup Lagoon has some inherent capacity to buffer internally, but this process is slow, and the application of alkalinity, (an example is provided as lime ($CaCO_3$); see Appendix 14), or similar treatments may assist in restoring the lagoon's ecosystem utility. Although it is important to note that lagoon surface water pH returned to neutral following the drying of the lagoon in 2013 and 2020.

As the peats' resilience increases with elevated groundwater levels the lagoon's fate under a treatment, or no treatment, scenario is linked to changes in climate and shallow aquifer dynamics. How this may change conservation goals is summarised in Table 2, with expanded notes below.

			Tordit-Gurrup Lagoon - acidity management options			
			No treatment	***Alkalinity (partial)***	***Alkalinity***	***Surface Water (diversion & supplementation)***
Conservation goals (manage & protect)	**Carbon (peat)**	*Benefits*	Status quo, but continued drying and wetting relative to drying climate (rainfall & evaporation).	May address short-term acidity and maintenance of ecosystem function.	Mitigation of acidity; increase in soil and water pH and increased ecosystem utility.	Increased likelihood of Tordit-Gurrup Lagoon achieving carbon sequestration goal; due to reduced risk of drying and acidification
		Risks	Continued decline in carbon stores due to large, seasonal fires or loss via microbial activity.	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. May affect microbial function and carbon utilisation.	Increased salinity. Reduction in soil-water retention may decrease likelihood of achieving carbon sequestration goal. Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of reactive acidity.	Other peat wetlands (Poorginup Swamp or Byenup Lagoon) don't achieve carbon sequestration goal. Loss of environmental flows to other systems (water diversion) or groundwater levels and stygofauna (local aquifer abstraction).
	Bird breeding	*Benefits*	Potential for continued decline in bird populations as needs and tolerances to acidity and salinity are not yet defined.	Appropriate dosing may address short-term acidity flux associated with drying and maintenance of ecosystem function	May address longer-term acidity and maintenance of ecosystem function and stabilised habitat that facilitates successful occupation and breeding. .	Increased likelihood of achieving bird breeding goal in dry climate cycles
		Risks	Potential for continued decline in bird populations as needs and tolerances to acidity and salinity are not yet defined	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. May affect water quality, ecosystem function and associated viability of nesting or feeding birds.	Sustained large increases in ecosystem pH due to reaction/utilisation of lime in the absence of reactive acidity. May also affect water quality, ecosystem function and associated viability of nesting or feeding birds.	Other peat wetlands (Poorginup Swamp or Byenup Lagoon) don't achieve bird breeding goal. Loss of environmental flows to other systems (water diversion) or reduction in recharge and groundwater levels and invertebrates and native fish (local aquifer abstraction).
	Wetland vegetation (bird habitat)	*Benefits*	Status quo, but continued drying and terrestrialisation of vegetation due to drying climate (rainfall & evaporation).	May address short-term acidity and maintenance of ecosystem function. Potential for short-term stabilisation of wetland biomass	Vegetation requirements and tolerances to rapid and large changes in alkalinity aren't defined. Potential for stabilisation of wetland biomass.	Condition of wetland phreatophytes (sedges) improves with water level stabilisation and production of significant wetland biomass.
		Risks	Potential for continued decline in bird habitat and populations as needs and tolerances to acidity and salinity are not yet well defined.	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of reactive acidity. May affect water quality, ecosystem function.	Sustained large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. Requires detailed evaluation of system response to alkalinity addition.	Increase in wetland vegetation and terrestrialisation of vegetation composition on desiccated peat ceases (eucalypt species).
	Invertebrates and fish	*Benefits*	Status quo, loss of invertebrate and native fish species in the 2000's likely to continue due to acidification, salinisation and drying climate.	Potential recovery of invertebrate and native fish species. Requirements of biota and tolerances to changes in pH and salinity not well defined.	Potential recovery of invertebrate and native fish species. Requirements of biota and tolerances to changes in pH and salinity not well defined.	Increased likelihood of Tordit-Gurrup Lagoon achieving invertebrate and fish conservation goals; due to increased wetland hydroperiod.
		Risks	Irreversible loss of invertebrate and fish populations.	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. May affect water quality, remaining invertebrate and fish populations and ecosystem function	Sustained large increases in ecosystem pH due to reaction/utilisation of lime in the absence of reactive acidity. May affect water quality, remaining invertebrate and fish populations and ecosystem function	Changed wetland hydroperiod inhibits life cycle of some invertebrates and native fish. Requires hydrological planning to manage water levels.
	Water (lagoon)	*Benefits*	Status quo, but continued drying and wetting relative to drying climate (rainfall & evaporation). Dry periods accompanied by possible low pH soil and water and the precipitation of evaporite minerals.	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. May affect water quality, and ecosystem function	Long -term stability in water quality with to maintenance of circumneutral pH due to alkalinity addition.	Stable pH and salinity in Tordit-Gurrup Lagoon with water derived from diversion and/or augmentation of inflows or groundwater.
		Risks	Potential for decline in water quality, especially following fire or widespread drying and acidification.	Transient large increases in ecosystem pH due to reaction/utilisation of lime in the absence of acidity. May affect water quality, ecosystem function.	Irreversible change in water quality following increases in pH due to reaction/ utilisation of lime in the absence of significant, reactive acidity. Requires detailed evaluation of system response to alkalinity addition.	Other peat wetland (Poorginup Swamp or Byenup Lagoon) have less water. Little data on runoff, minimal drain infrastructure, and no information on divertible yields from drains

Table 2; Tordit-Gurrup Lagoon conservation goals versus management options

5.3.1 Acid surplus

Potential acidity is highest on the margin of Tordit-Gurrup Lagoon and it increases with depth (up to 1m below ground level). Sediment porosity and permeabilities here are low, which along with the depth makes them difficult to treat using geochemical methods that rely on recharge and mixing.

Literature reports mixed results on the treatment of peat and organic carbon through liming (e.g. Ishikura et. al 2017 and Lochon et. al. 2019). Potential threats being increased soil respiration, reductions in water retention due to increased porosity and permeability and permeability and changes to flora, fauna and microbial assemblages.

5.3.2 Water deficit

Identifying and delivering more water to drying peat wetlands would assist in mitigating acidification threats. However, Tordit-Gurrup Lagoon is large and requires considerable water to saturate the peat profile. There are also no suitable sites to divert surface water, as this could reduce recharge, and groundwater levels are in decline across most of the southern Muir-Byenup Ramsar site. For example, peat and vegetation are showing signs of drying and salinisation in Byenup Lagoon and shallow aquifers in Poorginup Swamp may now be disconnected from deeper aquifers.

The potential problem of artificial drains altering the water table and causing the rapid drying of peat in Poorginup Swamp was raised as a concern in Farrell and Cook (2009).

5.4 Limitations

Sampling and analysis of desiccated peat was carried out across one north-south trending transect and results were interpolated across the western area of this landscape unit. Uncertainty with respect to the geochemistry of the eastern desiccated area could be reduced through further sampling and analysis.

The Tordit-Gurrup Lagoon water body dries infrequently. Sampling of the lagoon substrate in March 2020 was limited due to time and budget constraints. Further sampling would verify acid stores on the lagoon floor.

Application of treatments using on ground methods would be difficult due to limited access to the lagoon, and the instability of sediments on the lagoon floor. Treatment using airborne methods is likely to cause less on-ground physical disturbance but introduces the risk that areas not requiring treatment are affected.

Information on biodiversity tolerances within the Muir-Byenup Ramsar site is limited. A comparison of waterbird and shorebird numbers in 1980's and 2009 found that bird numbers in the northern Muir-Unicup Catchment wetlands had declined in number and this was likely attributed to a loss of habitat (Hearn et. al. 2013). This observation was supported by a decline in invertebrate fauna richness in Noobijub Swamp, which was correlated with reductions in pH and linked to increases in salinity and reed bed habitat senescence (Cale and Pinder 2018). Treatment of the lagoon would therefore need to be underpinned by an improved understanding of Tordit-Gurrup Lagoon's flora and fauna salinity and pH tolerances, as well as the cost-benefit achieved through treatment.

5.5 Further work

Undertake work to reduce interpretation uncertainty, refine and verify resilience indicators and understand the likelihood of acidification events in Tordit-Gurrup Lagoon and other peat wetlands in the Muir-Byenup Ramsar site.

The volume and composition of sediments in the peat profile displays variation that complicates calculations of average organic carbon storage in g/kg. The work on organic and inorganic carbon mass balances should continue to be carried out and refined.

In situ mesocosm tests to evaluate the various alkalinity amendments would be best developed following the work detailed above to understand outcomes of acidity mitigation (Section 5.3.1).

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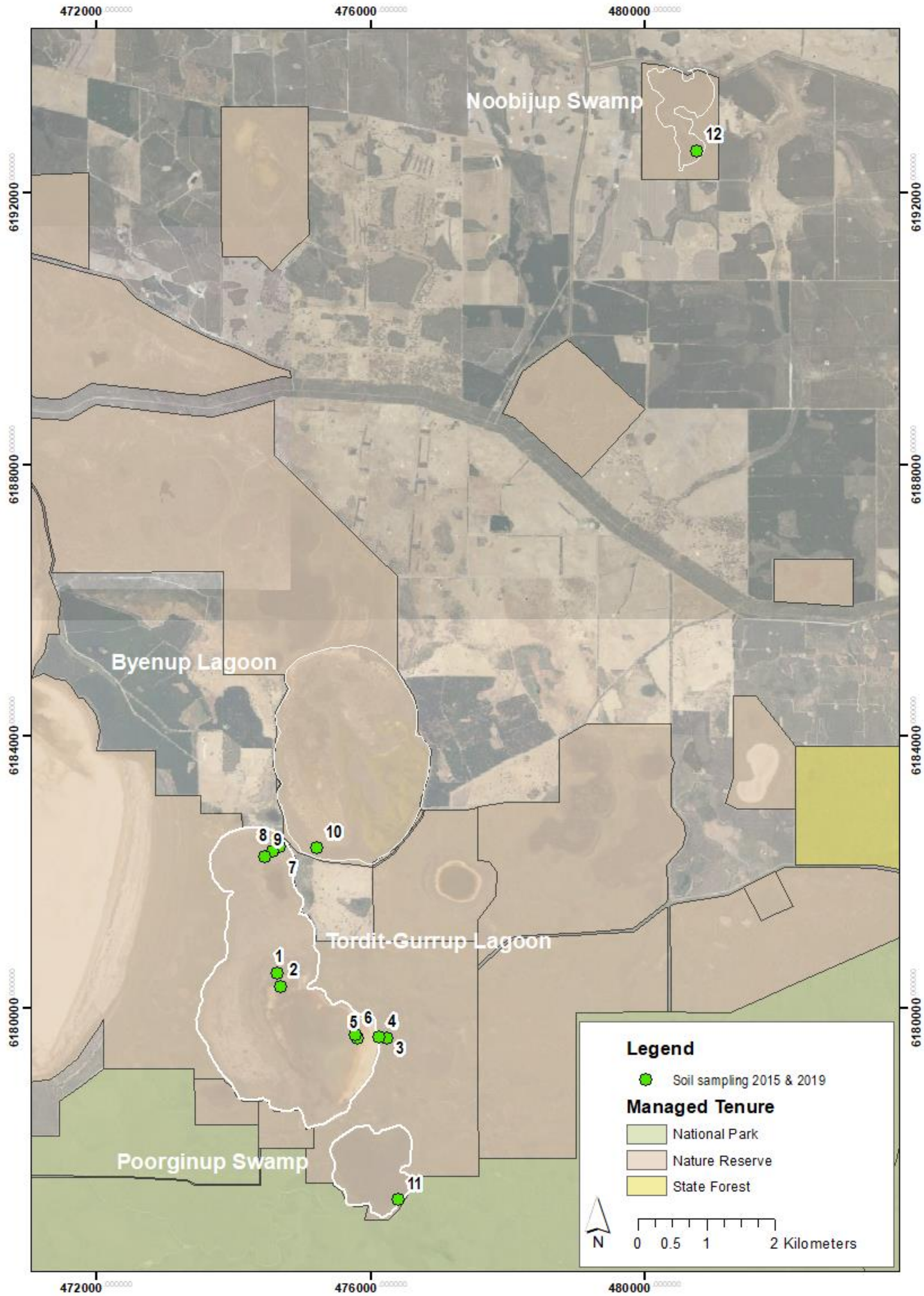
Appendices

Appendix 1 Infrastructure and data collection sites



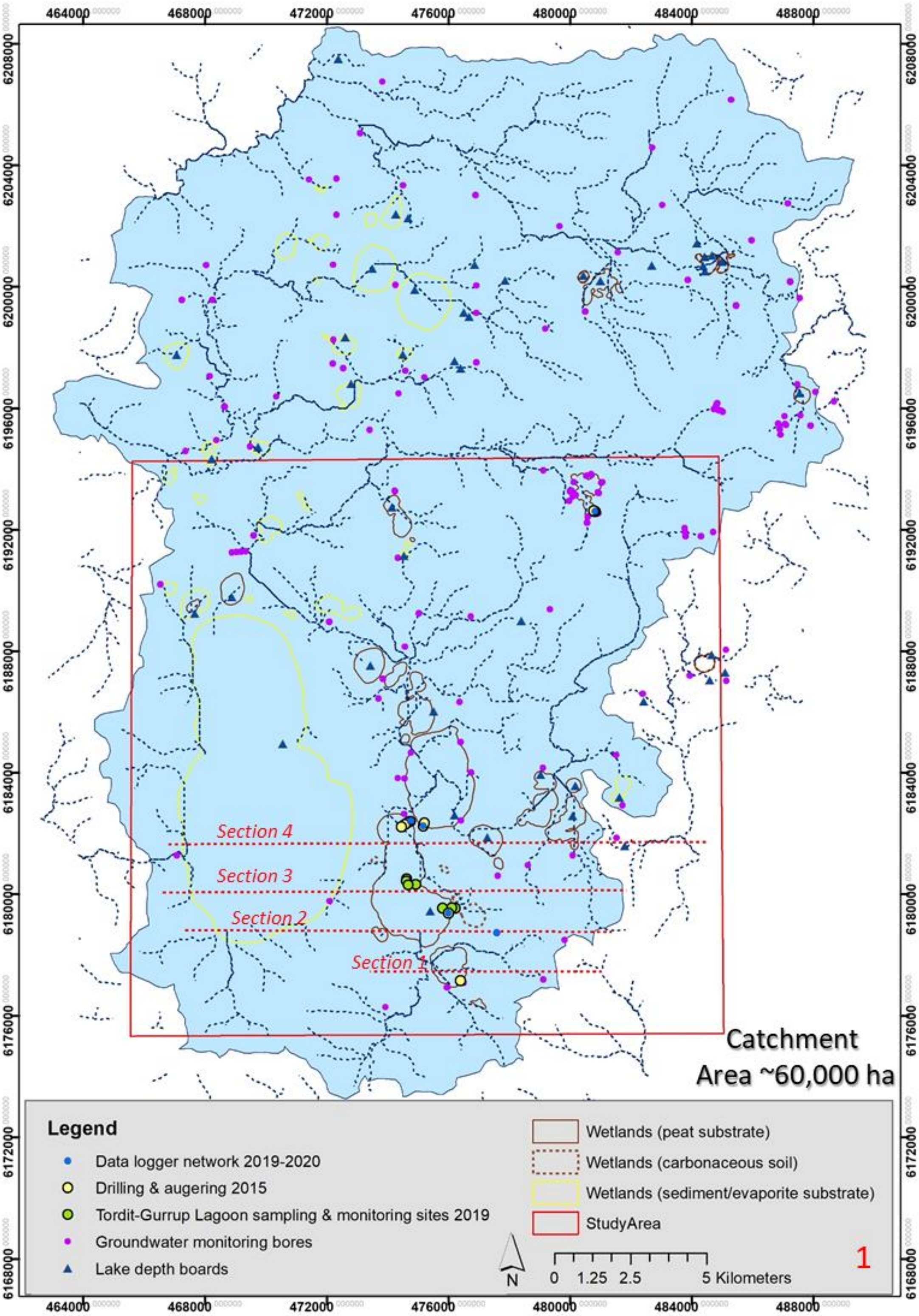
Location of soil sampling and analysis sites; see monitoring program table for site names

Site ID	Location Monitoring Sites		Excavation Depth & Construction									
	Easting_MGA50	Northing_MGA50	Aprox Depth (mbgl)	ToS_mbgl	BoS_mbgl	Completion; see map for numbered location - brackets ()	Field water quality analyses	*Volume sample required - lab analyses	Data logger	On-going monitoring post 9/2019 (Aprox dates/frequency)	Installation & monitoring Program
TGN08	474627	6180509	0.6			2019 soil core (1)					
TGN09	474614	6180436	0.95	0	0.95	filter sock; no backfill	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 3/20; 5/20; 7/20; 9/20	Data logger
TGN10	474922	6180311	1.0	0	1	filter sock; no backfill	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 3/20; 5/20; 7/20; 9/20	Data logger
TGN11_12	474687	6180305	0.1			2019 soil core (2)				3/20	Soil/lake water grap sample
TGS03	476234	6179540	0.31			2019 soil core (3)					
TGS04	476116	6179556	0.56			2019 soil core (4)					
TGS07	475808	6179541	0.1			2019 soil core (5)				3/20	Soil/lake water grap sample
TGS05	475771	6179598	0.1			2020 soil core (6)				3/20	Soil/lake water grap sample
TGS01	476005	6179371	6	0.5	6	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
TGN01	474754	6182394	6	0.5	6	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
TGN04	474670	6182361	1.9			2015 soil core (7)					
TGN05	474572	6182293	1.9			2015 soil core (8)					
TGN06	474458	6182218	1.8			2015 soil core (9)					
BY04	475217	6182343	1.8			2015 soil core (10)					
Poor01	476399	6177160	1.05			2015 soil core (11)					
NB04	480766	6192629	1.35			2015 soil core (12)					
BY01	475170	6182247	6	0.5	6	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
EMU27D	474773	6182424	20	14	20	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
EMU27S	474773	6182426	2	1	2	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD & Baro Diver)	1/20; 5/20; 9/20	Data logger
MU51	477584	6178735	20	17.8	19.8	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
MU46S	476500	6177082	27	20	26	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger
NB01	480825	6192604	6	0.5	6	Existing bore	Field pH,Temp, EC & alkalinity (as CaCO3)	~1100mL	Y (CTD Diver)	1/20; 5/20; 9/20	Data logger

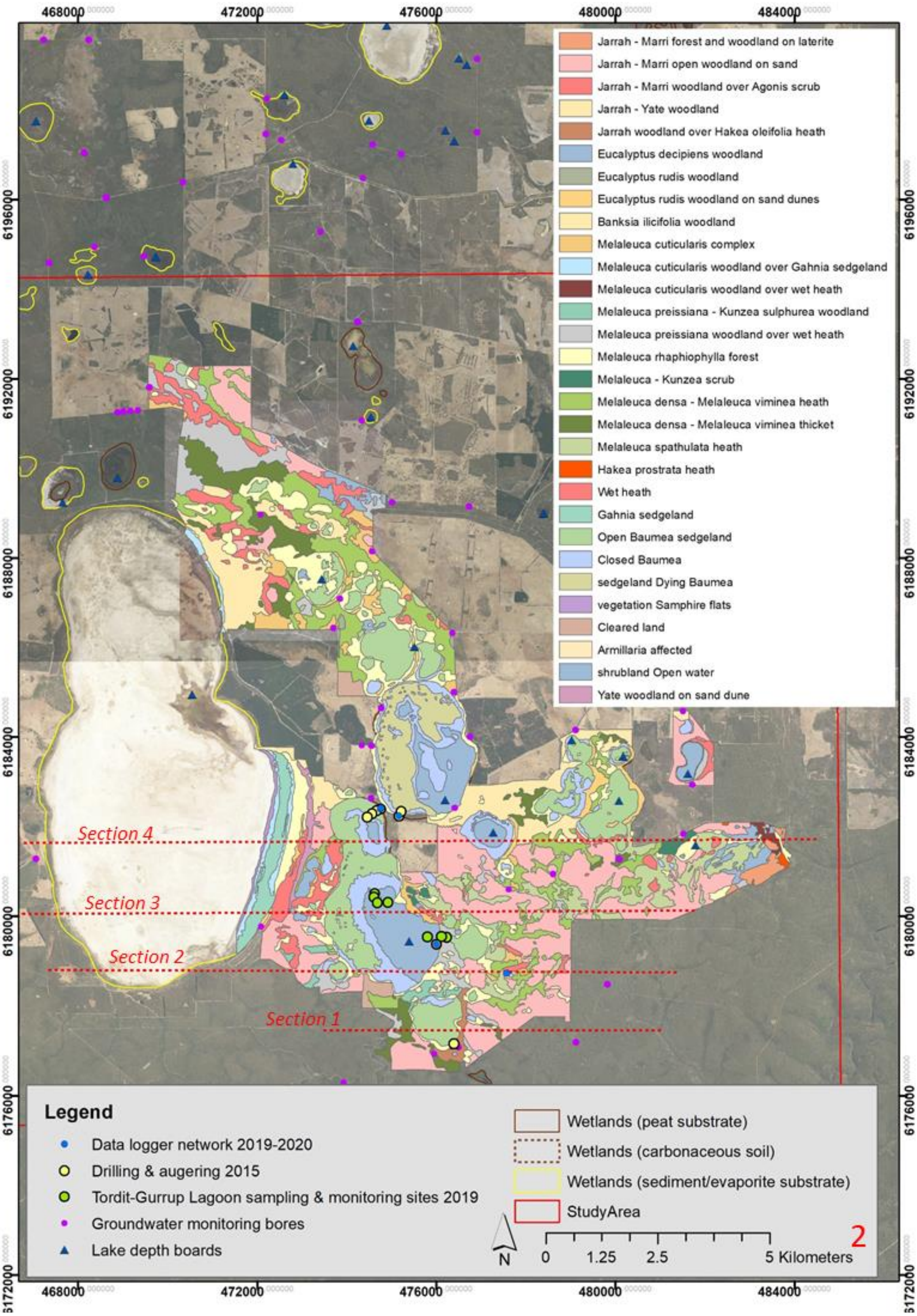
*major ions (500 mL, unfiltered); minor ions and REE (125mL, filtered & pre-acidified); nutrients (125mL, unfiltered); nutrients (125mL, filtered); ferrous iron (60ml; unfiltered); reactive silica (125 mL, filtered); stable water isotopes (20ml, unfiltered (clear glass or HDPE))

Monitoring program table

Appendix 2 Catchment, wetland & vegetation maps

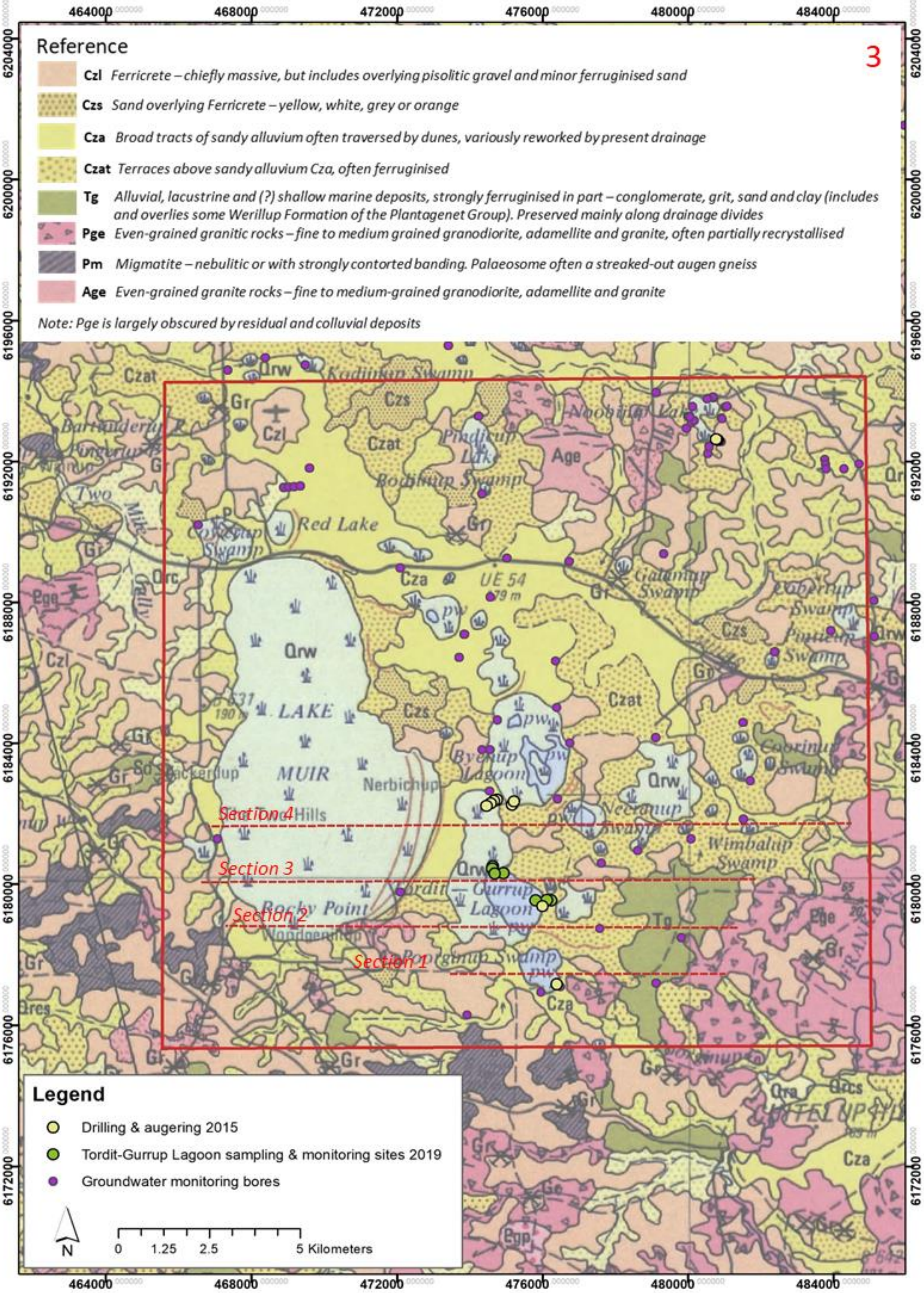


Muir-Unicup Catchment (Smith 2003), showing wetlands, drainage (mainly seasonal) interpreted from LiDAR data and the location of cross sections 1 to 4 shown in Appendix 3 Map 7.

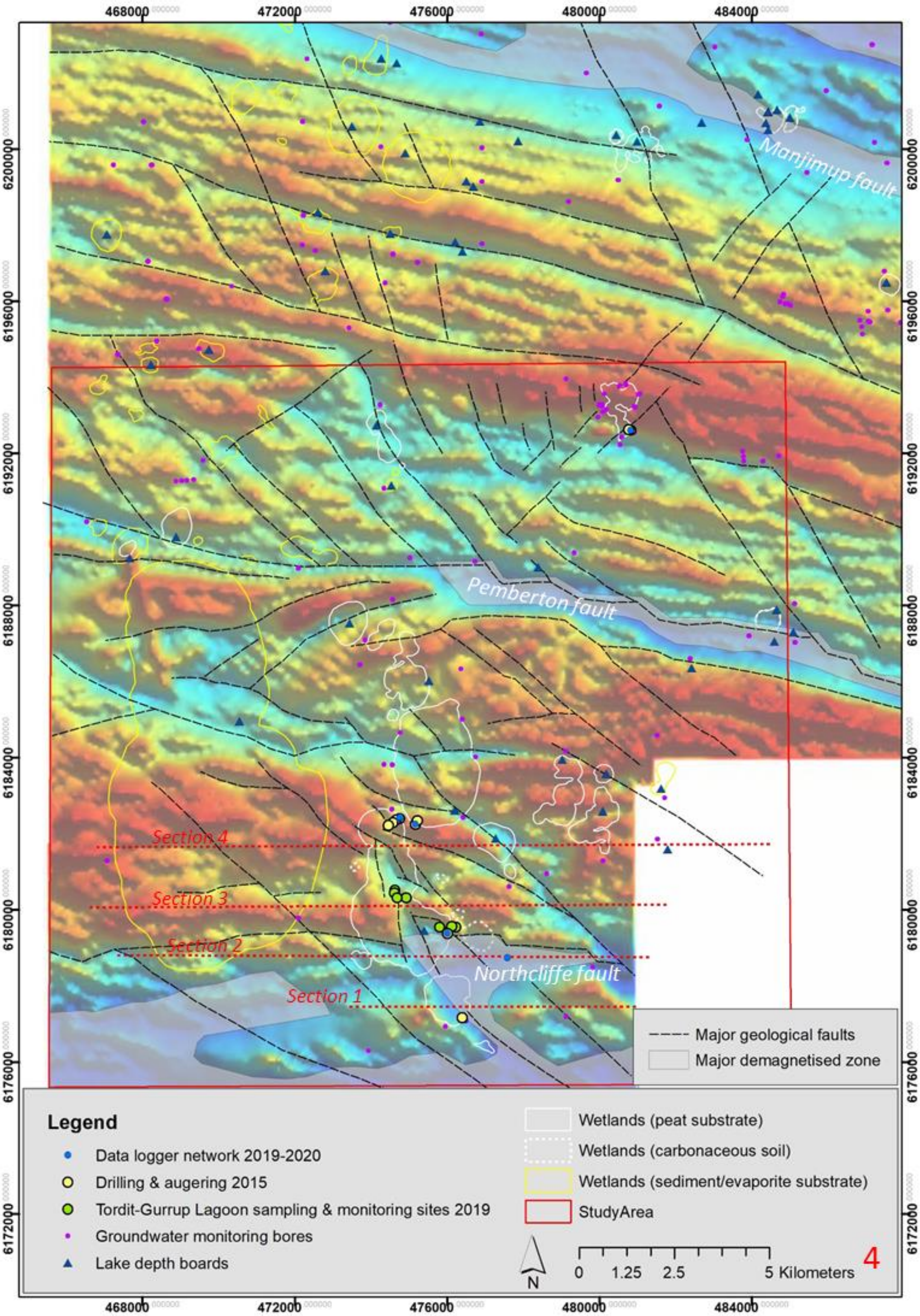


Vegetation map (Gibson and Keighery 1999) superimposed on aerial photography.

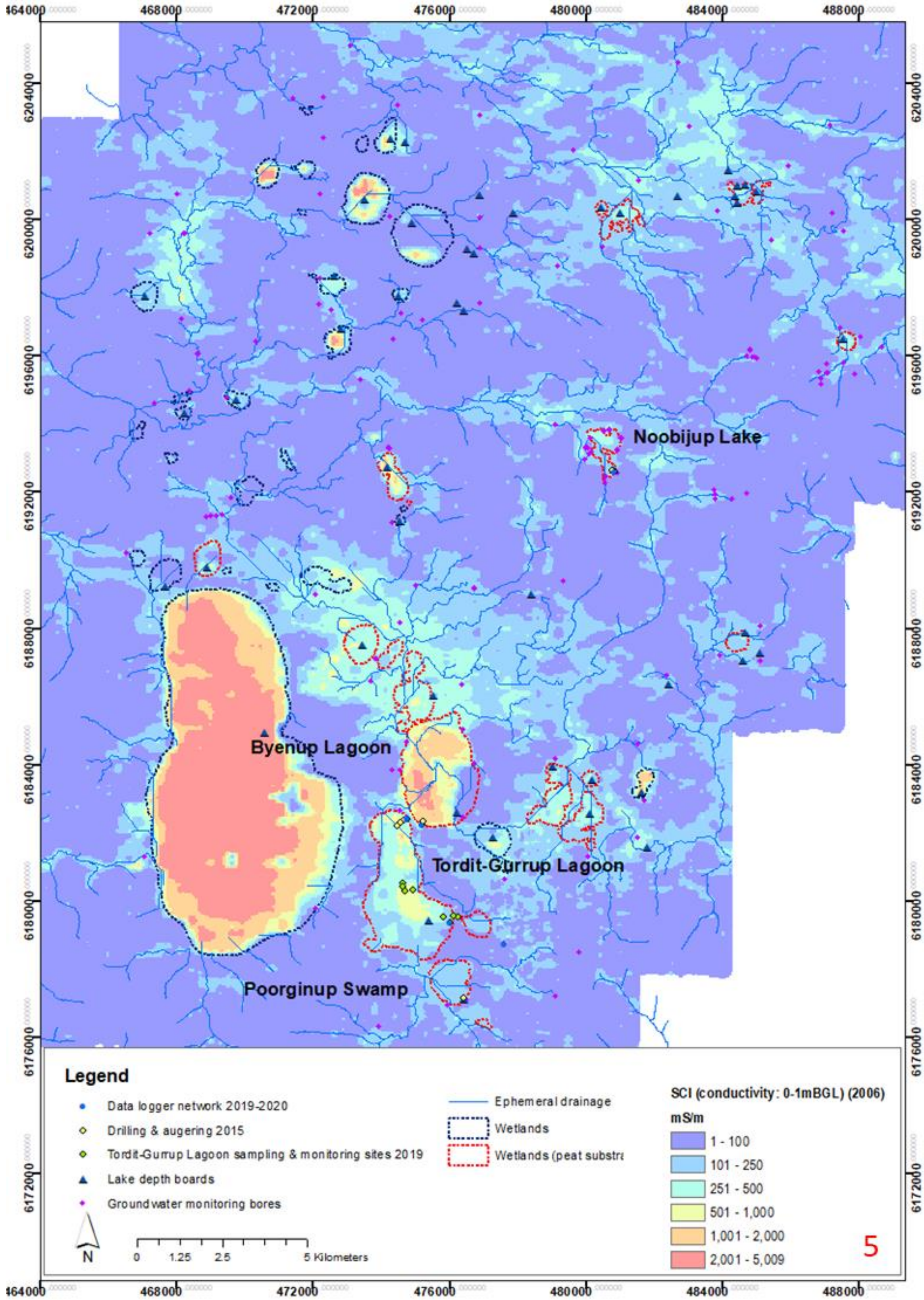
Appendix 3 Coarse scale contaminant sources & mobilization



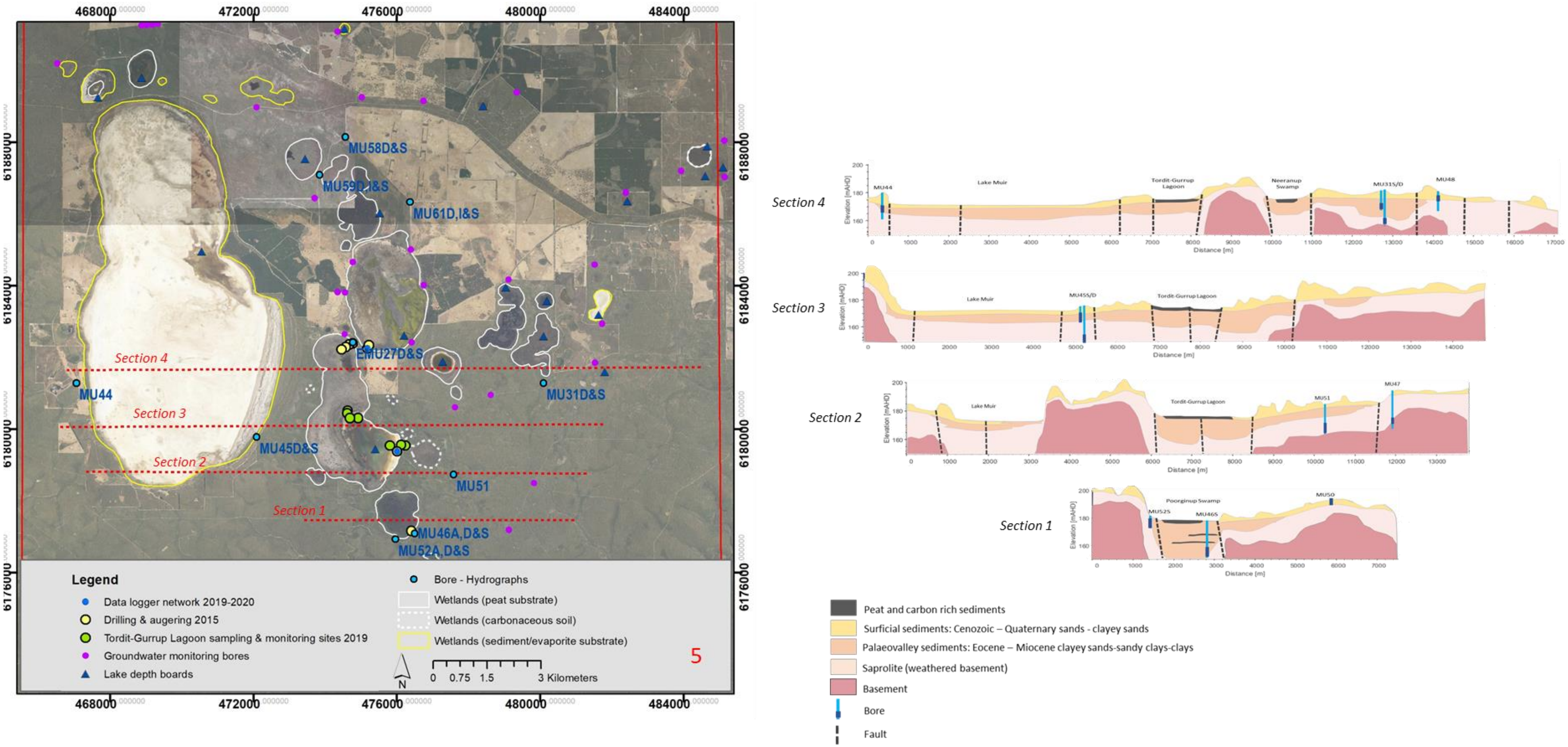
1:250k scale geology map (Wilde and Walker 1984) showing the location of the study area and cross sections 1 to 4 (see Map 7). Map reference modified from Wilde and Walker (1984).



Structural interpretation of imaged Total Magnetic Intensity (TMI) data acquired in 2013 (GPX Job Number 2435); note approx. location of major fault zones in white text.



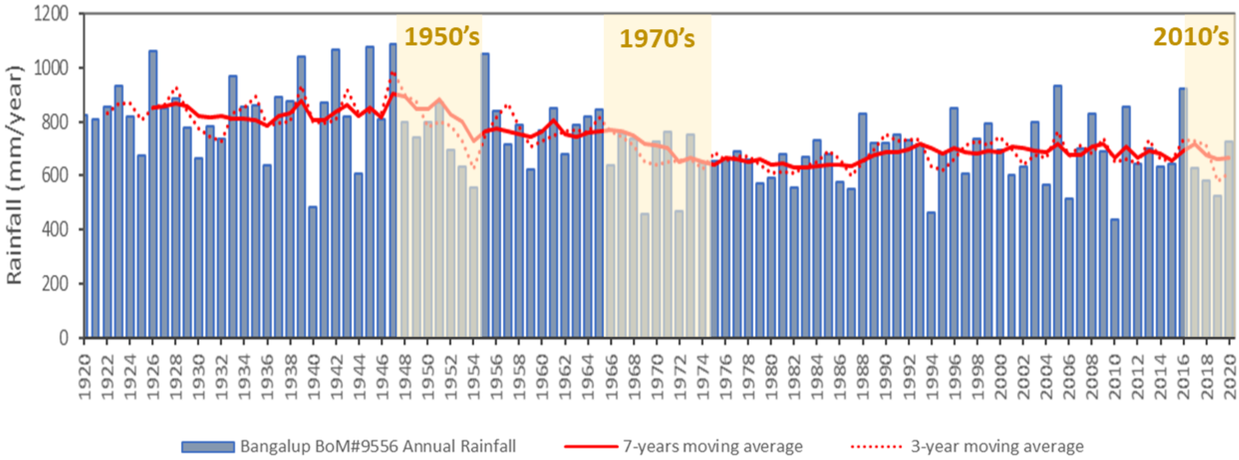
Airborne electromagnetic (AEM) conductivity depth image for (0 to 1 metre below ground level) (Søerensen et. al. 2019).



Map shows the location of sections and monitoring bores. Cross sections 1 to 4 produced from an interpretation of drillhole and airborne electromagnetic (AEM) data.

Appendix 4 Study area rainfall, groundwater levels and gradients

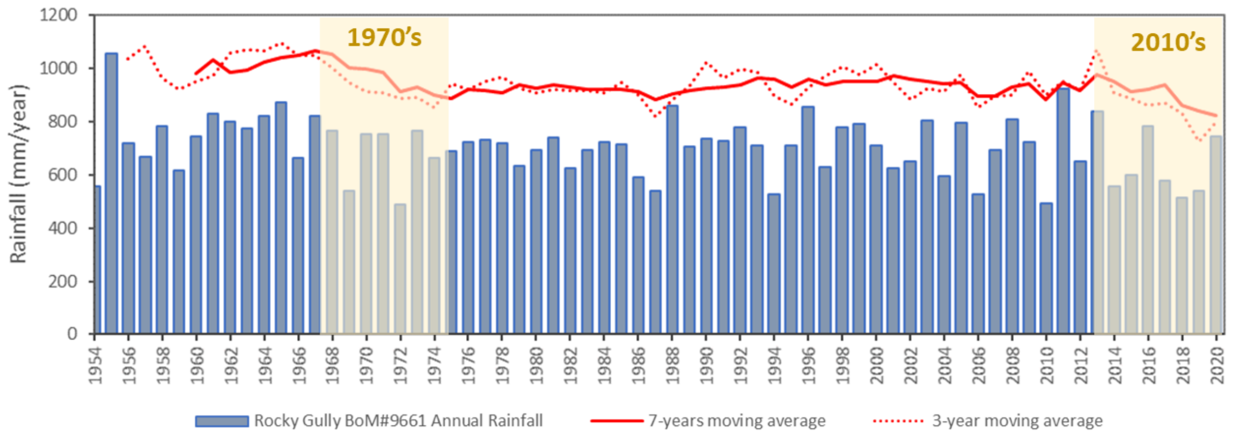
Annual Rainfall – Bangalup BoM Station #9556



1920 to 1950	837	831
1951 to 1954	687	759
1955 to 1965	796	765
1966 to 1974	662	654
1975 to 2016	682	670
2017 to 2020	615	661

Median monthly rainfall substituted for missing data: April-Sept 1949; Jan 1977; May 1994 & Nov 1999

Annual Rainfall – Rocky Gully BoM Station #9661



Period	Ave annual rainfall (mm)	Median annual rainfall (mm)
1954 to 1968	767	775
1969 to 1974	661	708
1975 to 2010	696	711
2011 to 2020	673	624

NB: median monthly rainfall substituted for missing data: July 2002; Oct & Nov 2004; April 2005; Dec 2008 & Nov 2012


BoM #9556
BoM #9661
Lake Muir
Tordit-Gurrup Lagoon
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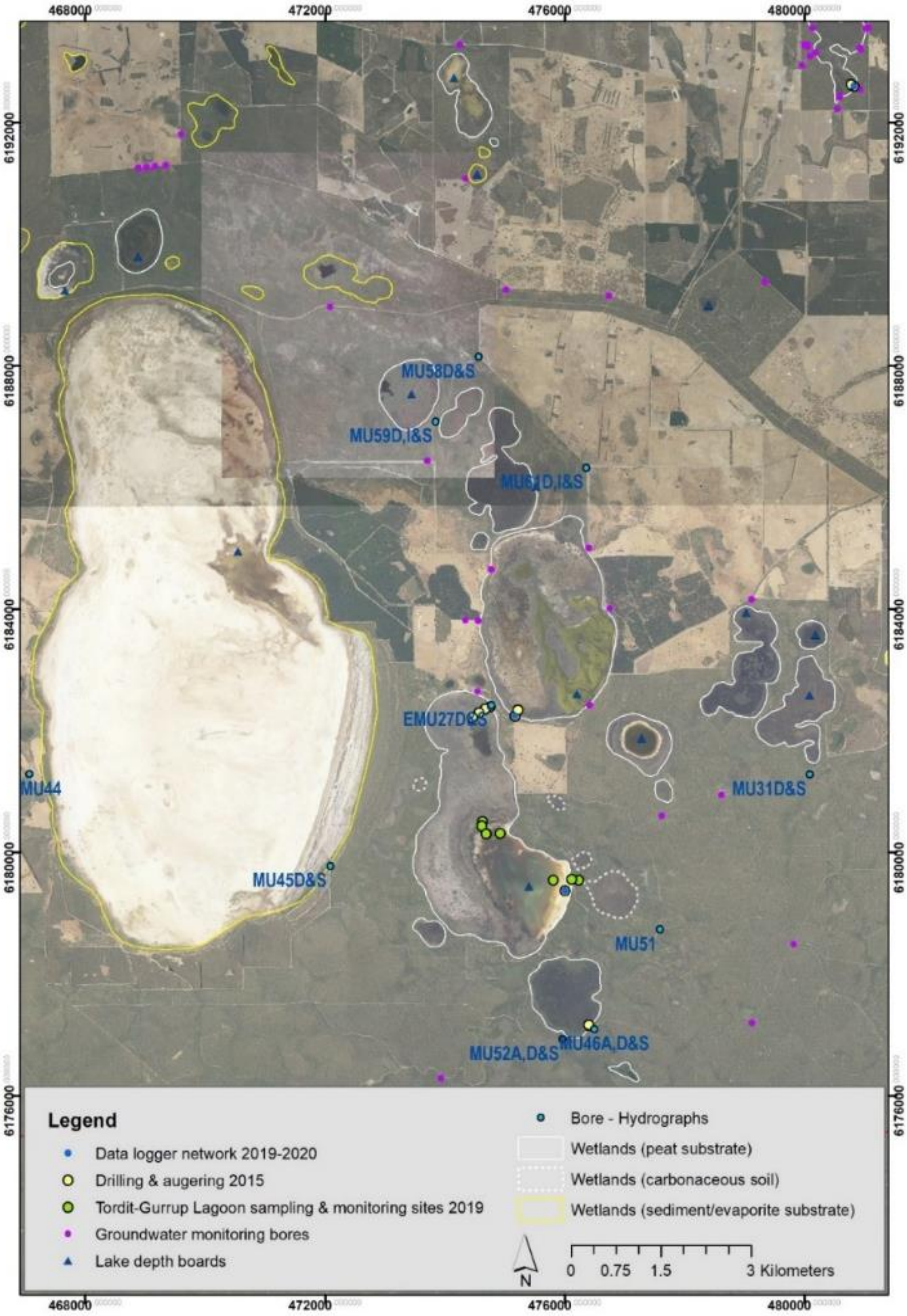
2.5
5 Kilometers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6188000
6184000
6180000
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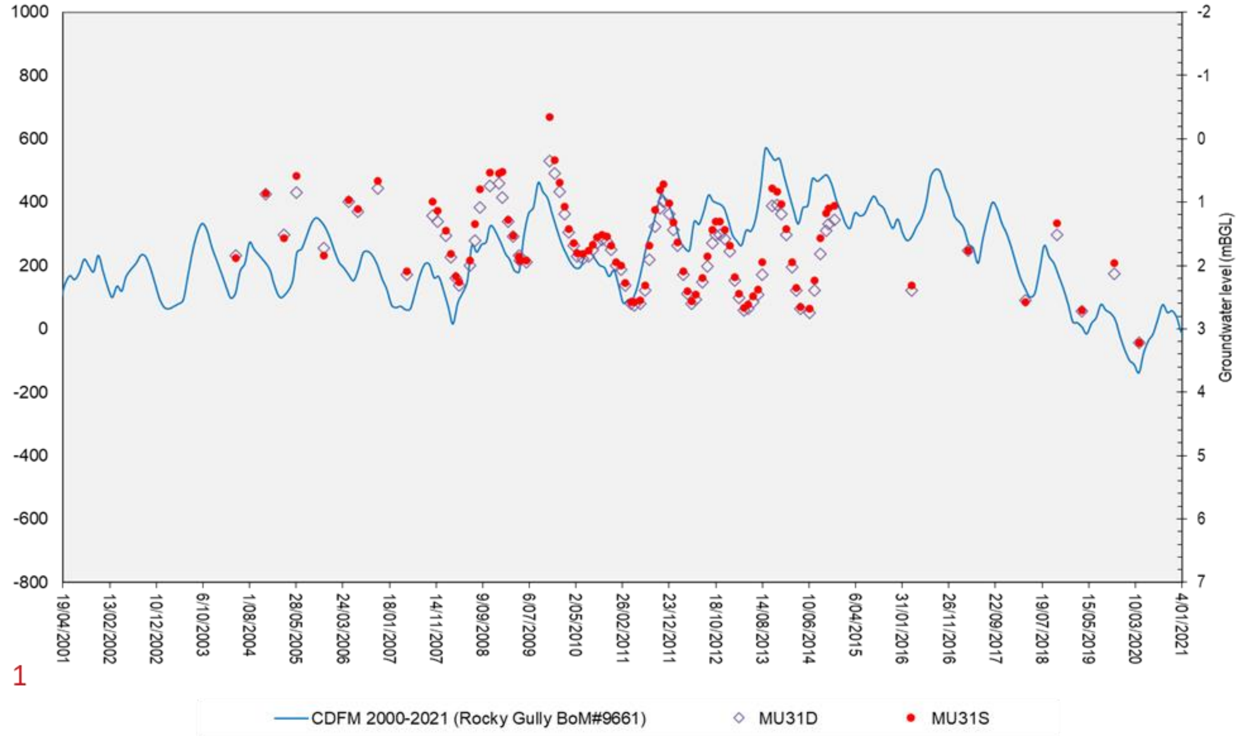
MU58D&S
MU59D,I&S
MU61D,I&S
EMU27D&S
MU44
MU45D&S
MU31D&S
MU51
MU52A,D&S
MU46A,D&S
Legend
Data logger network 2019-2020
Drilling & augering 2015
Tordit-Gurrup Lagoon sampling & monitoring sites 2019
Groundwater monitoring bores
Lake depth boards
Bore - Hydrographs
Wetlands (peat substrate)
Wetlands (carbonaceous soil)
Wetlands (sediment/evaporite substrate)
N
0 0.75 1.5 3 Kilometers

Bore ID	Drill date	Easting MGA50	Northing MGA50	Ground elevation (mAHD)	Standpipe ht (m)	Depth drilled (m)	Bore screen base (mBGL)	Bore screen top (mBGL)	Aquifer trends	Minimum (min) groundwater level (GWL) response drill date to 2021
MU31D	10/04/2003	480088.0	6181283.0	176.91	0.65	32.0	29.0	32.0	connected	Min GWL 2020 - min decreasing since ~2016
MU31S	11/04/2003	480089.0	6181283.6	176.92	0.62	16.5	10.5	16.5		
MU44	29/03/2004	467064.0	6181284.5	174.16	0.57	19.5	10.5	16.5		Min GWL 2007 - monitoring ceased 2015
MU45D	25/03/2004	472087.9	6179776.8	174.28	0.76	33.0	24.0	30.0	downward head	Min GWL 2012 - min MU45S GWL decreasing - monitoring ceased 2015 (no access)
MU45S	26/03/2004	472087.9	6179774.9	174.27	0.71	9.0	6.0	9.0		
MU46A	2/05/2006	476491.1	6177091.7	175.10	0.78	80.0	41.0	47.0	MU46A & D connected; downward head	Min GWL 2020 - min decreasing since ~2016
MU46D	22/03/2004	476501.5	6177083.8	176.63	0.66	72.0	65.0	71.0		
MU46S	24/03/2004	476500.2	6177082.0	176.70	0.62	27.0	20.0	26.0		
MU51	29/03/2004	477583.6	6178734.6	180.38	1.02	20.0	14.0	20.0		Min GWL 2020 - min slow decrease since ~2011
MU52A	1/05/2006	475961.0	6176929.4	175.94	0.70	5.5	2.0	5.0	connected	Min GWL 2020 - min decreasing since ~2016
MU52D	30/03/2004	475955.6	6176928.3	176.17	0.54	28.5	20.5	26.5		
MU52S	30/03/2004	475957.5	6176927.8	176.01	0.68	12.0	5.0	11.0		
MU58D	19/04/2005	474567.0	6188153.1	175.12	0.54	14.0	12.0	14.0	connected	Min GWL 2014 - no signifcant change min GWL - insensitive to rainfall CDFM
MU58S	19/04/2005	474567.4	6188153.7	175.04	0.60	3.0	1.0	3.0		
MU59D	16/02/2006	473848.7	6187090.6	174.50	0.61	58.0	39.0	42.0	MU59I & S connected; downward head	Min GWL 2014 - no signifcant change min GWL - insensitive to rainfall CDFM
MU59I	16/02/2006	473849.2	6187091.9	174.48	0.63	22.5	19.5	22.5		
MU59S	16/02/2006	473849.7	6187093.3	174.53	0.61	7.2	4.2	7.2		
MU61D	22/02/2006	476364.3	6186328.6	174.70	0.62	54.0	47.8	53.8	MU61D & S connected; upward head MU61I?	Min GWL 2011 - min decreasing since ~2016
MU61I	22/02/2006	476365.5	6186329.7	174.89	0.46	33.0	26.0	32.0		
MU61S	22/02/2006	476366.2	6186330.5	174.83	0.47	12.0	9.0	12.0		
EMU27D	24/05/2000	474772.9	6182424.5	176.10	0.61	20.0	17.8	19.8	downward head	Min GWL 2020 - min decreasing since ~2016
EMU27S	24/05/2000	474772.5	6182425.9	176.15	0.54	2.0	1.0	2.0		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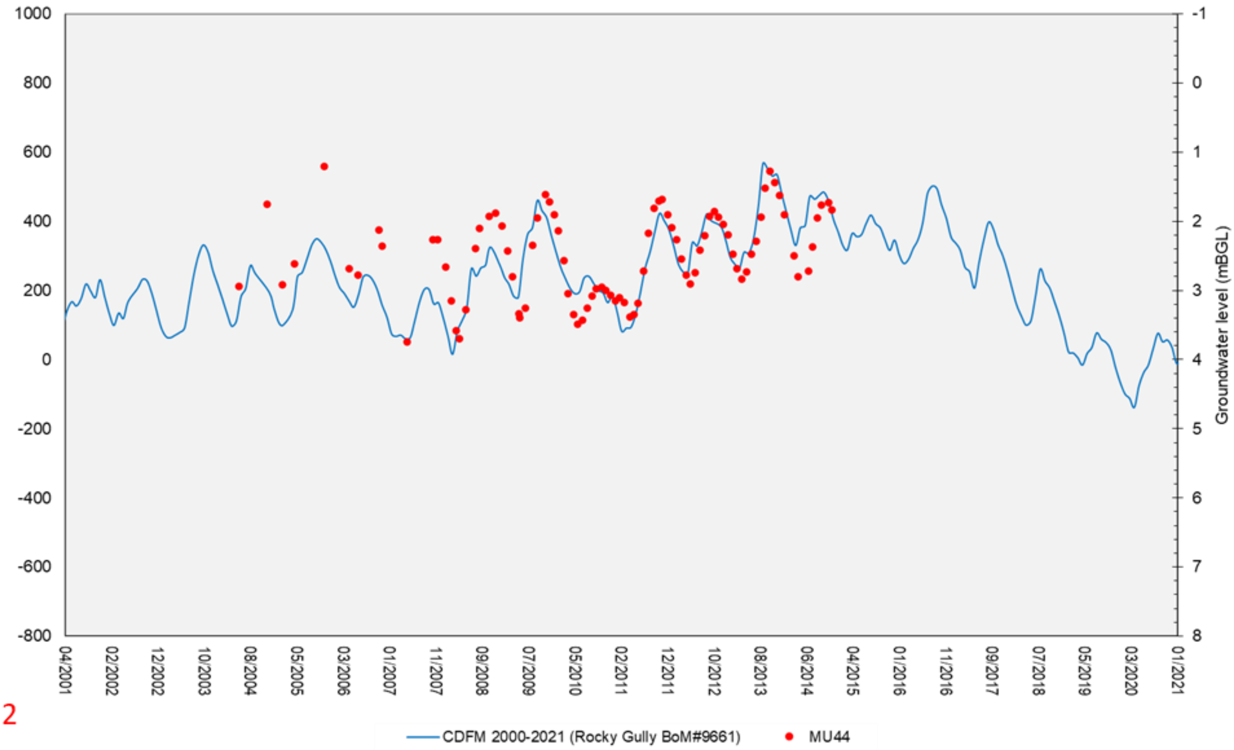
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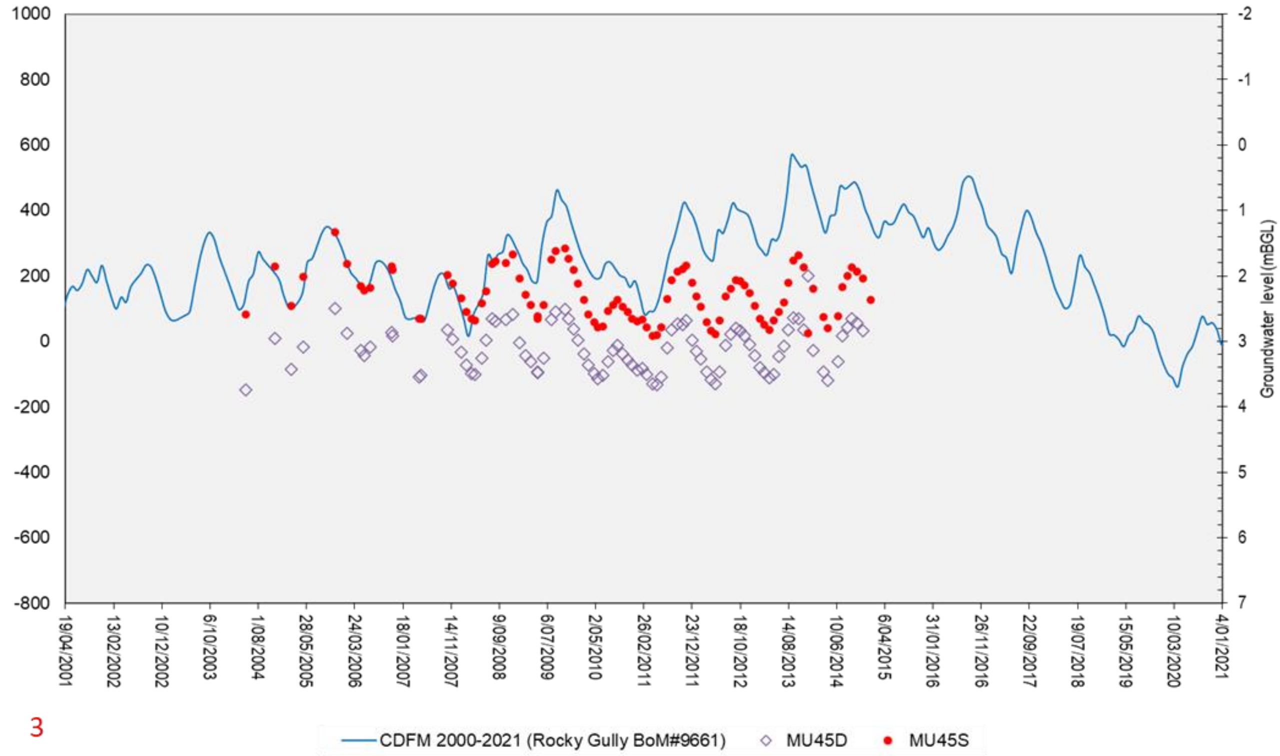
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26/11/2016
22/09/2017
19/07/2018
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4/01/2021
CDFM 2000-2021 (Rocky Gully BoM#9661)
MU45D
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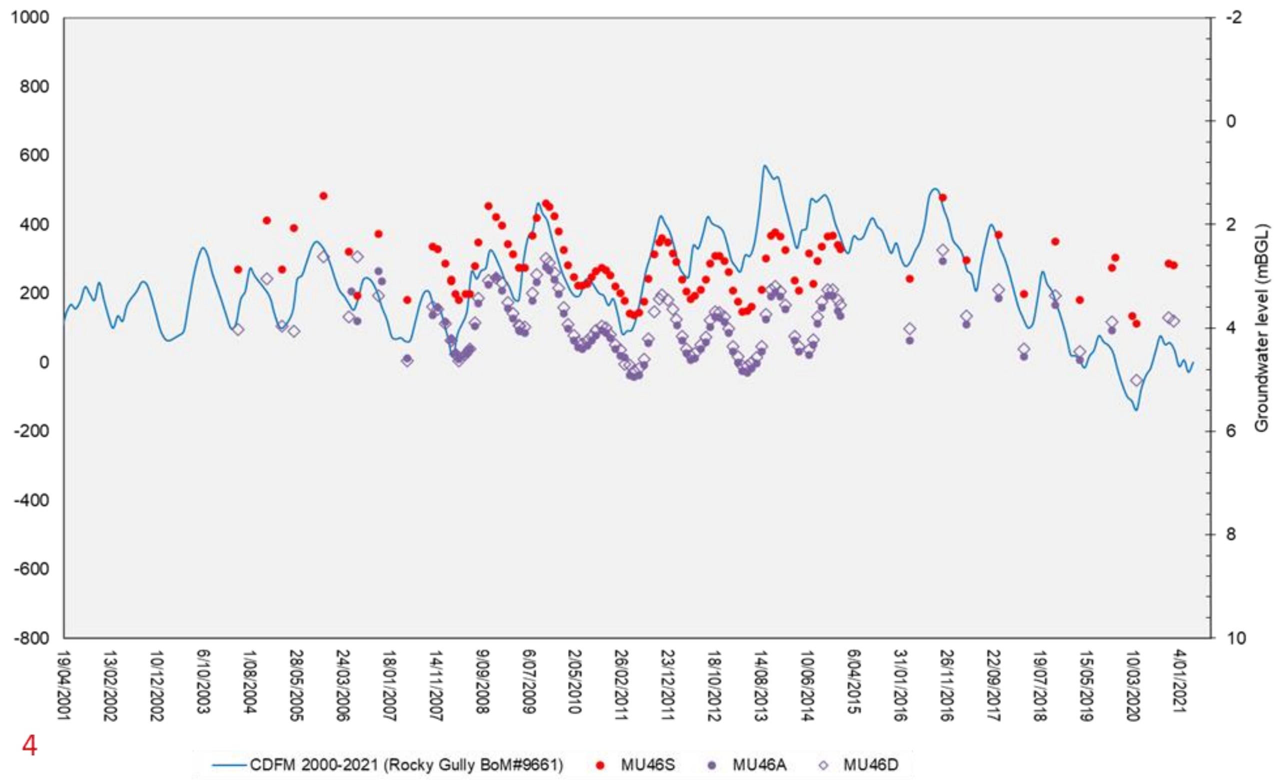
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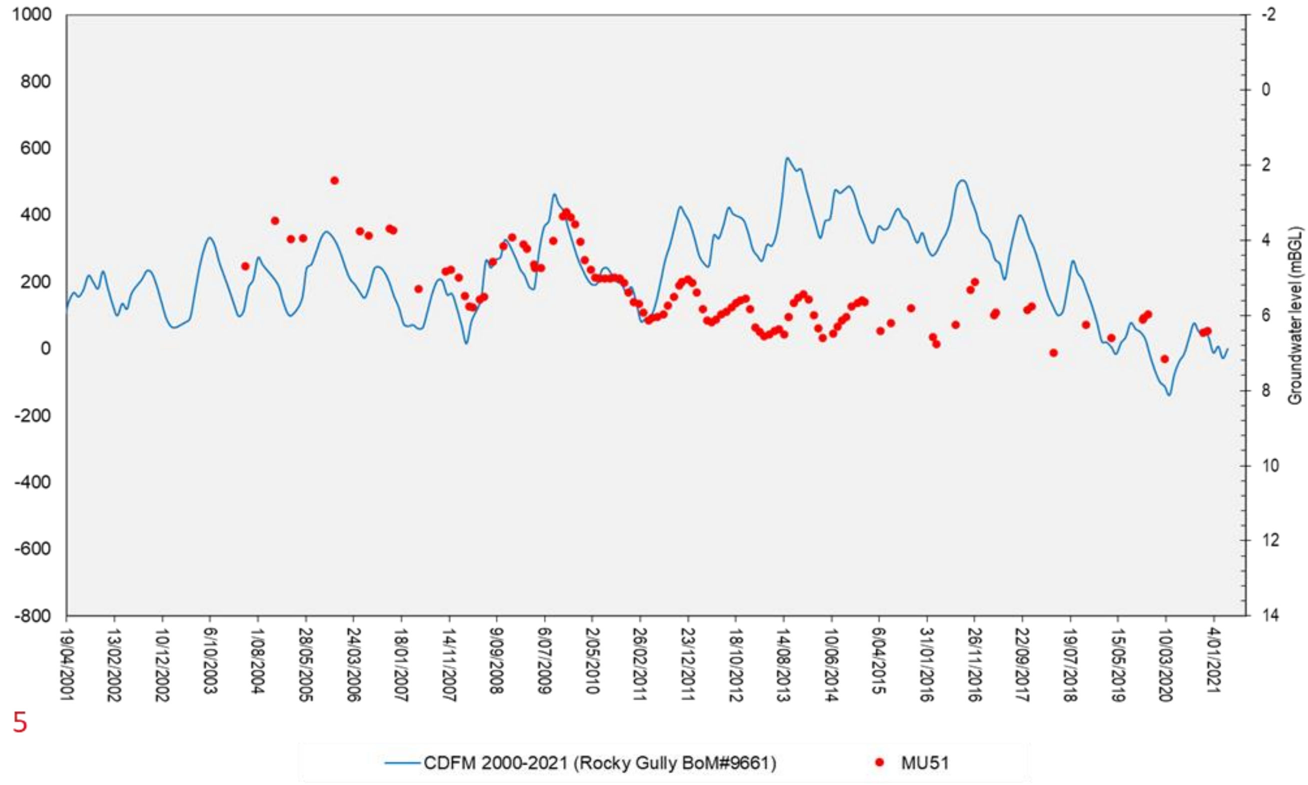
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MU51

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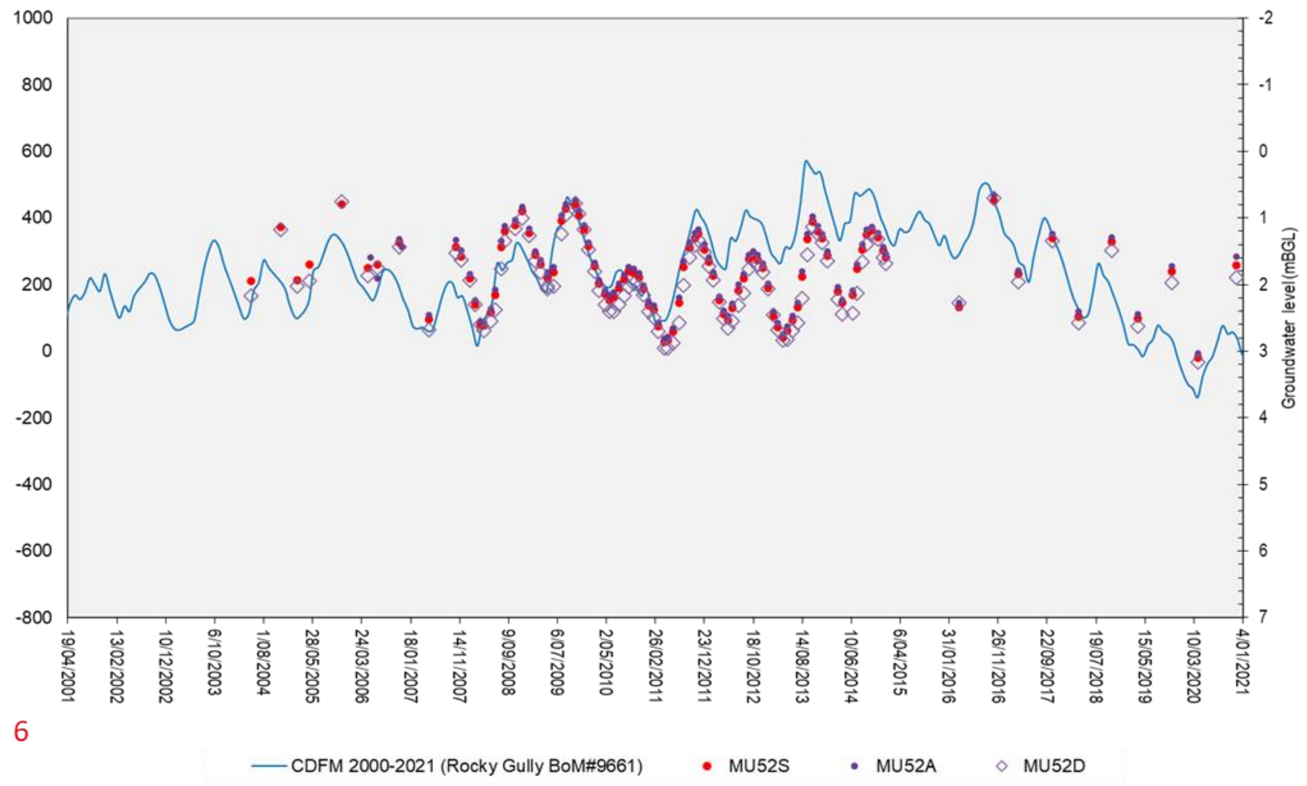
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CDFM 2000-2021 (Rocky Gully BoM#9661)
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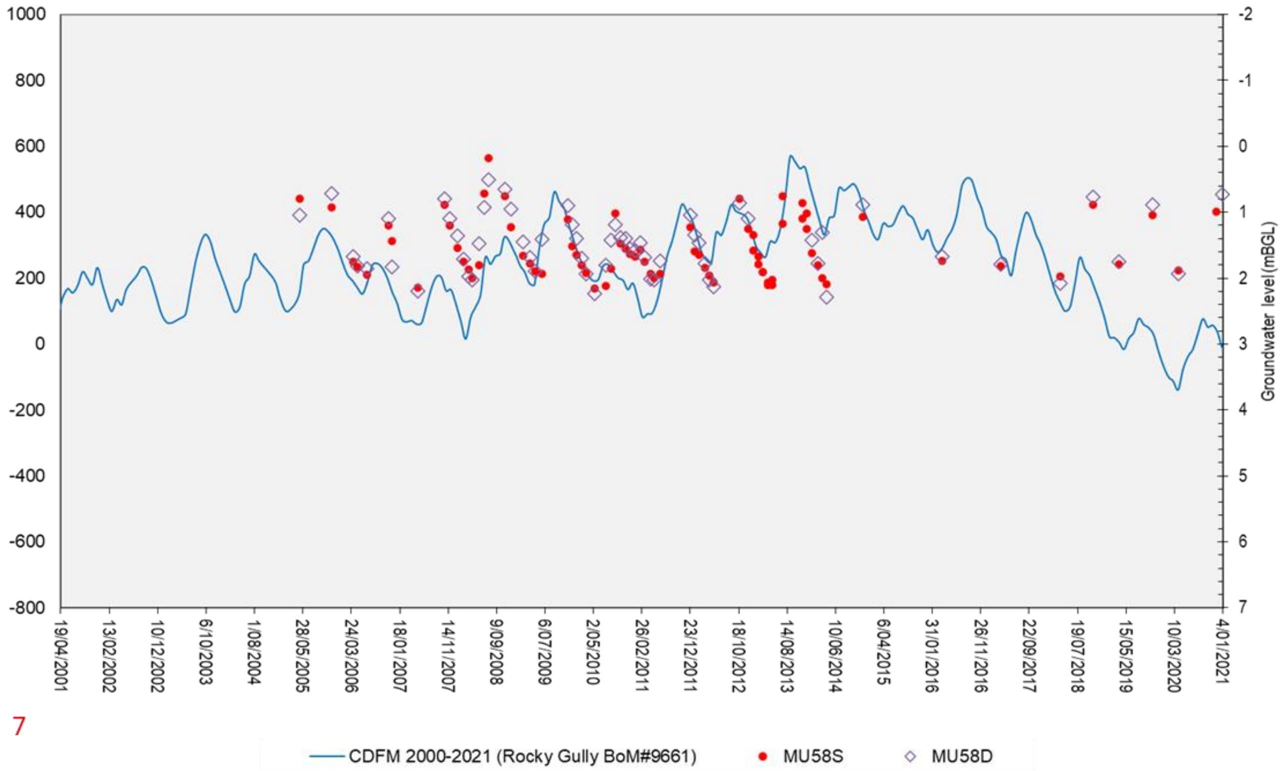
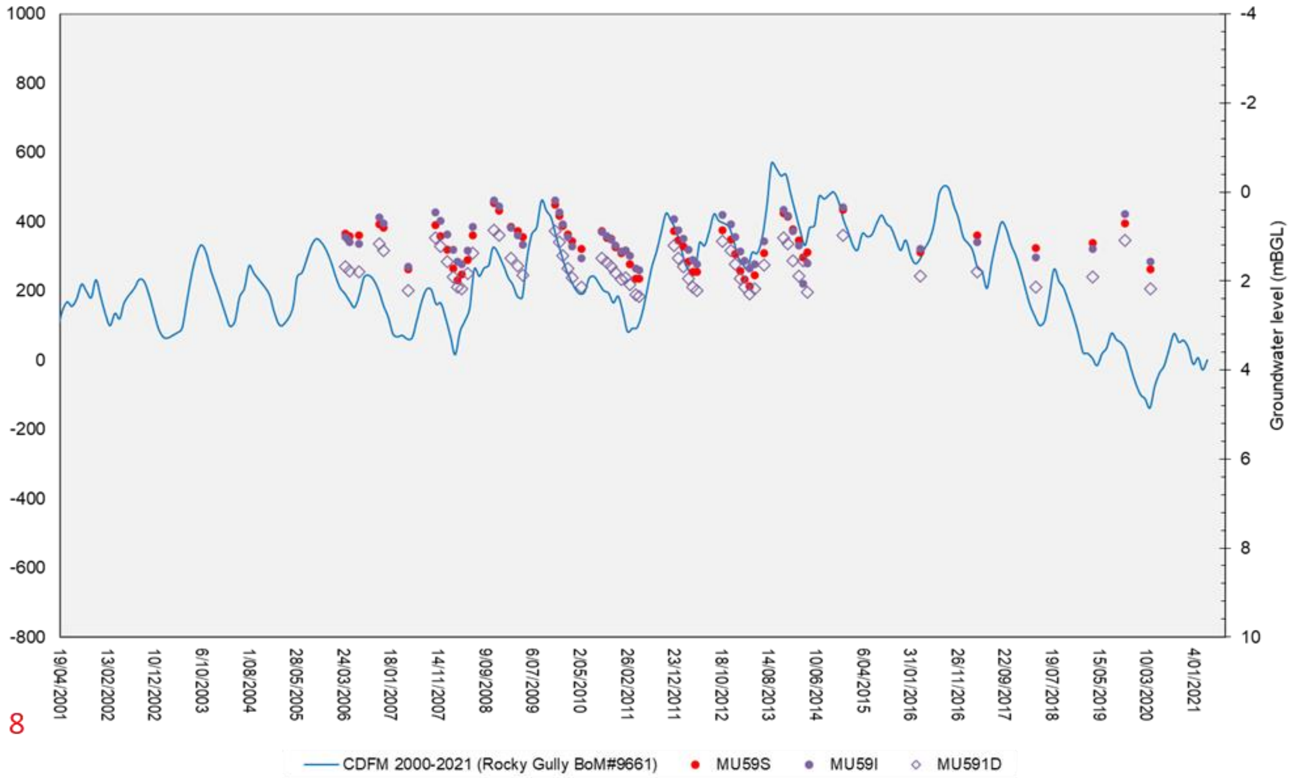


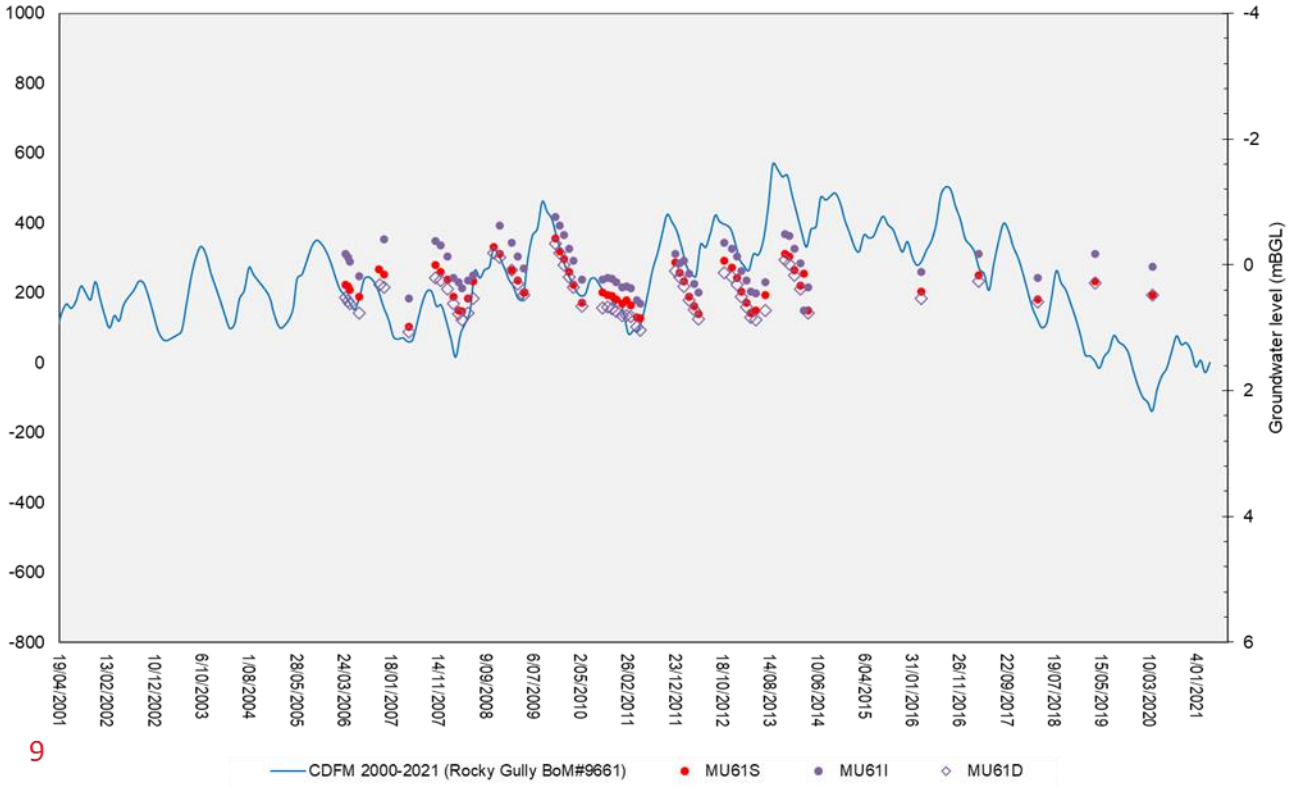
Groundwater level(mBGL)
CDFM 2000-2021 (Rocky Gully BoM#9661)
MU58S
MU58D

7



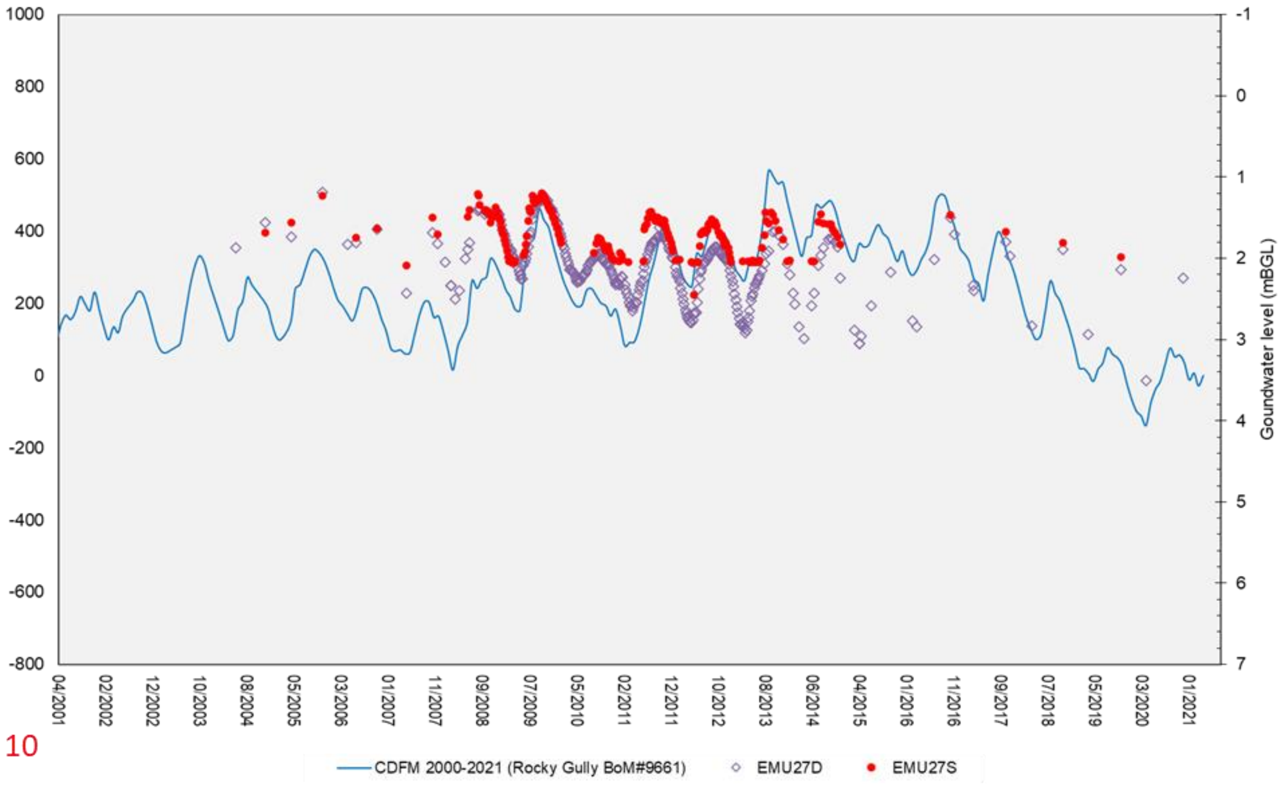
Groundwater level (mBGL)
CDFM 2000-2021 (Rocky Gully BoM#9661)
MU59S
MU59I
MU591D

8



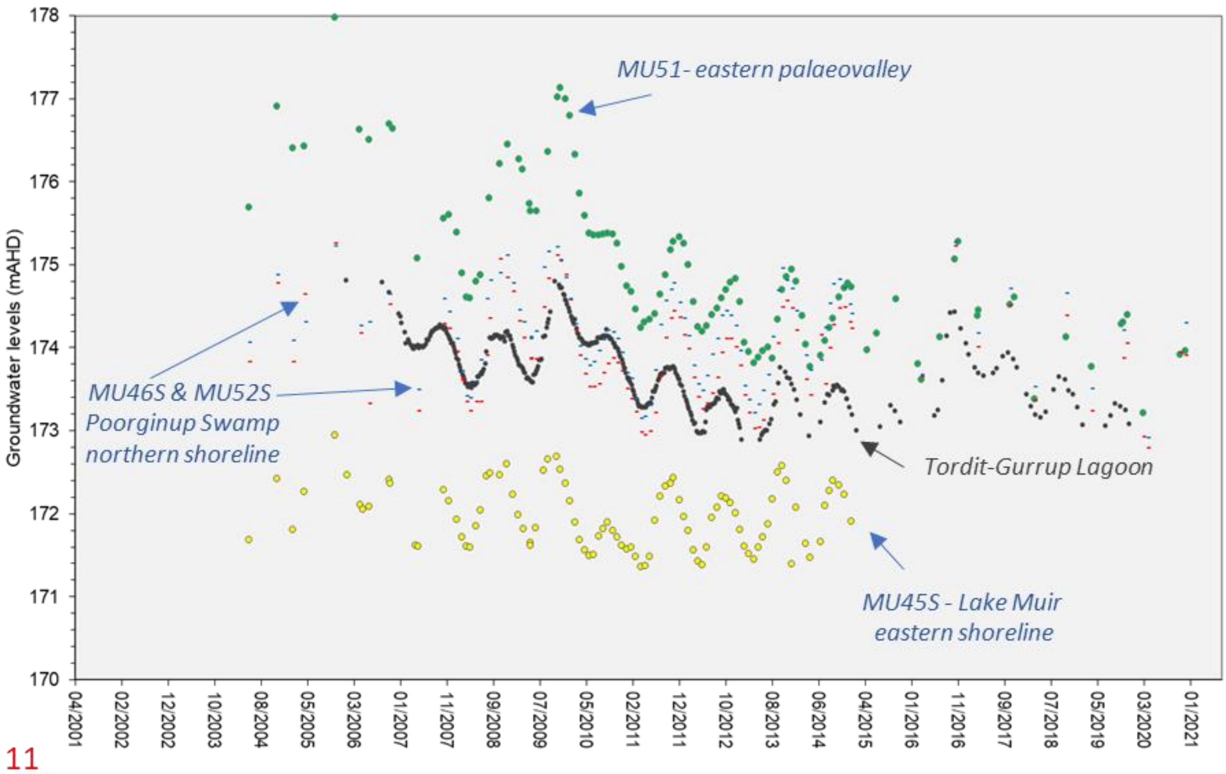
1000
800
600
400
200
0
-200
-400
-600
-800
-4
-2
0
2
4
6
Groundwater level (mBGL)
19/04/2001
13/02/2002
10/12/2002
6/10/2003
1/08/2004
28/05/2005
24/03/2006
18/01/2007
14/11/2007
9/09/2008
6/07/2009
2/05/2010
26/02/2011
23/12/2011
18/10/2012
14/08/2013
10/06/2014
6/04/2015
31/01/2016
26/11/2016
22/09/2017
19/07/2018
15/05/2019
10/03/2020
4/01/2021
CDFM 2000-2021 (Rocky Gully BoM#9661)
MU61S
MU61I
MU61D

9



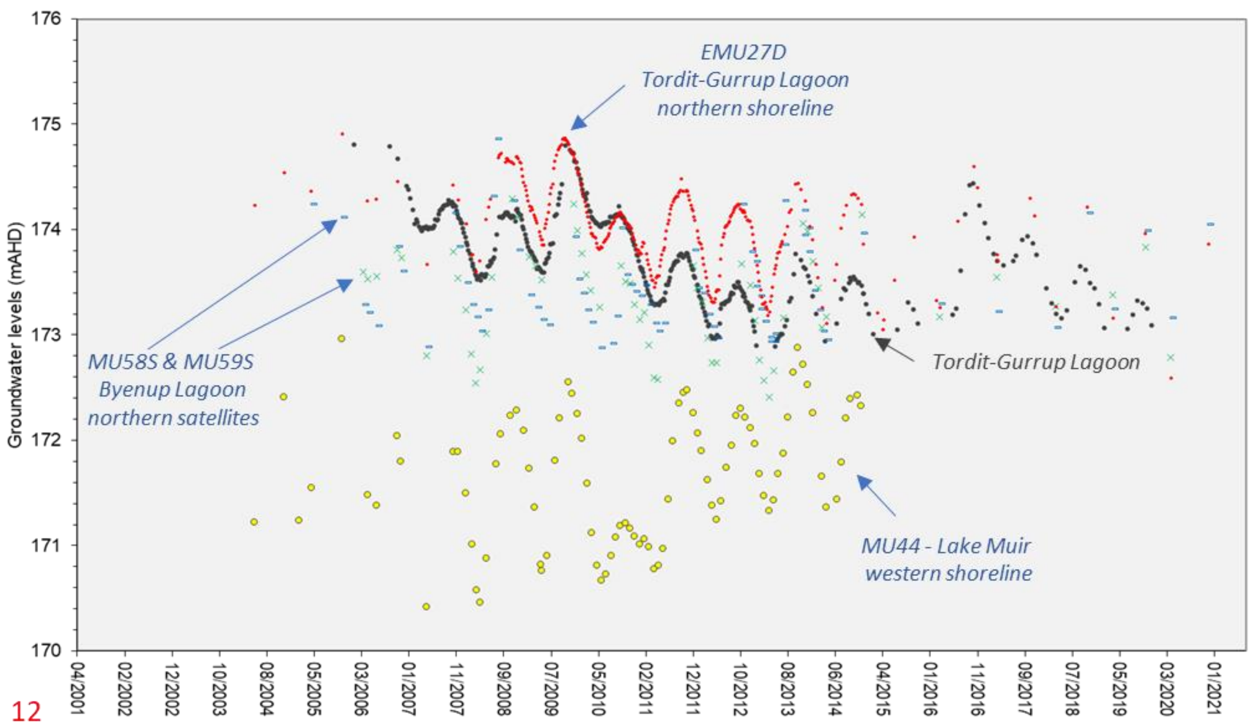
1000
800
600
400
200
0
-200
-400
-600
-800
-1
0
1
2
3
4
5
6
7
Goundwater level (mBGL)
04/2001
02/2002
12/2002
10/2003
08/2004
05/2005
03/2006
01/2007
11/2007
09/2008
07/2009
05/2010
02/2011
12/2011
10/2012
08/2013
06/2014
04/2015
01/2016
11/2016
09/2017
07/2018
05/2019
03/2020
01/2021
CDFM 2000-2021 (Rocky Gully BoM#9661)
EMU27D
EMU27S

10



MU51- eastern palaeovalley
MU46S & MU52S
Poorginup Swamp
northern shoreline
Tordit-Gurrup Lagoon
MU45S - Lake Muir
eastern shoreline
Groundwater levels (mAHD)

11

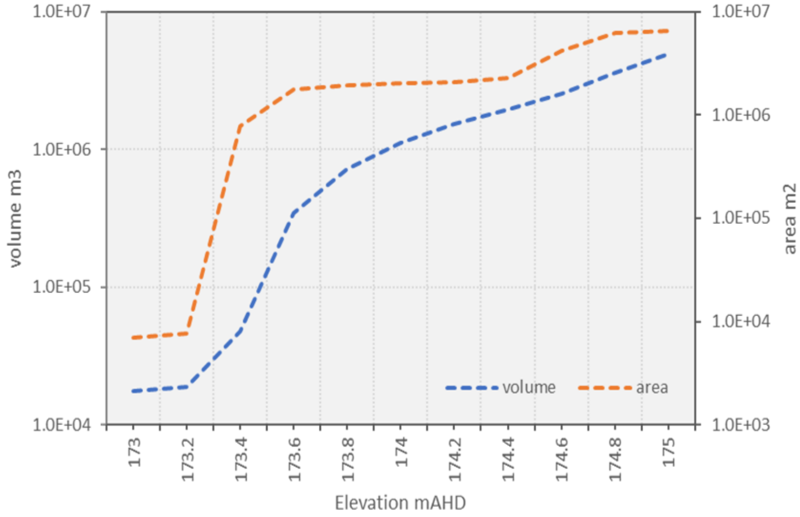


EMU27D
Tordit-Gurrup Lagoon
northern shoreline
MU58S & MU59S
Byenup Lagoon
northern satellites
Tordit-Gurrup Lagoon
MU44 - Lake Muir
western shoreline
Groundwater levels (mAHD)

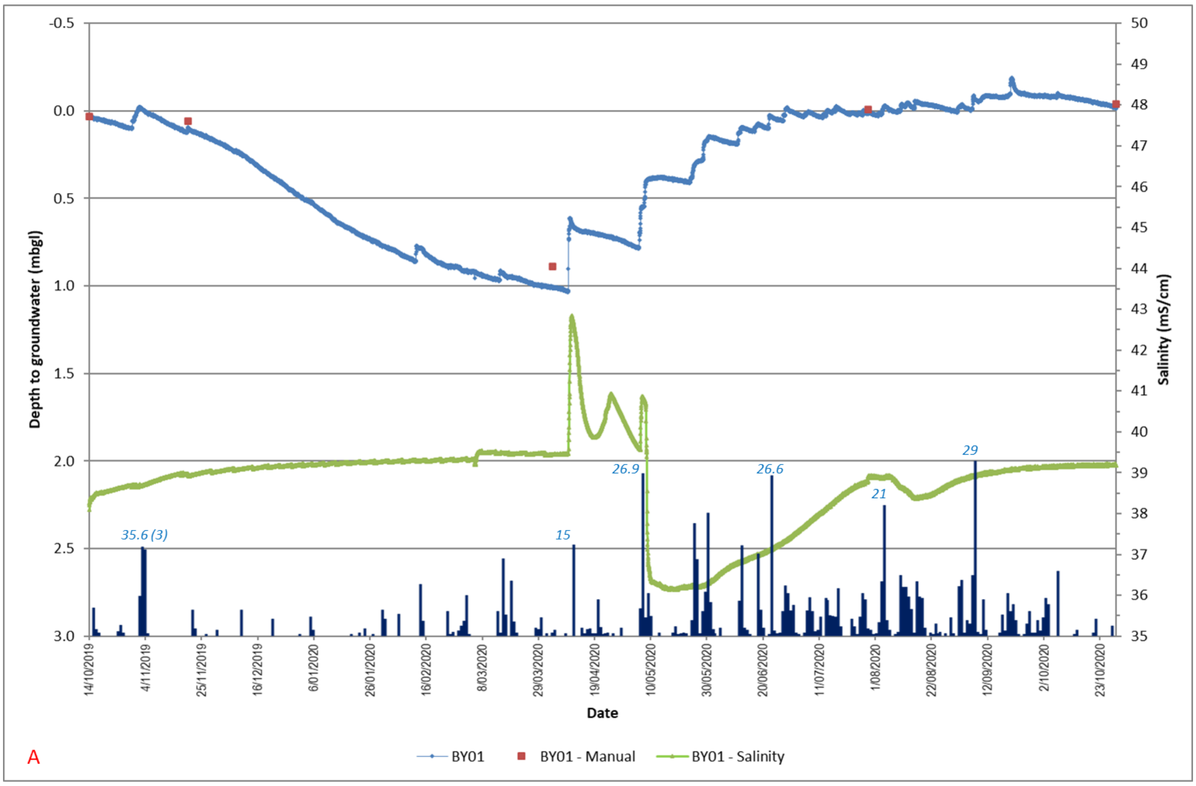
12

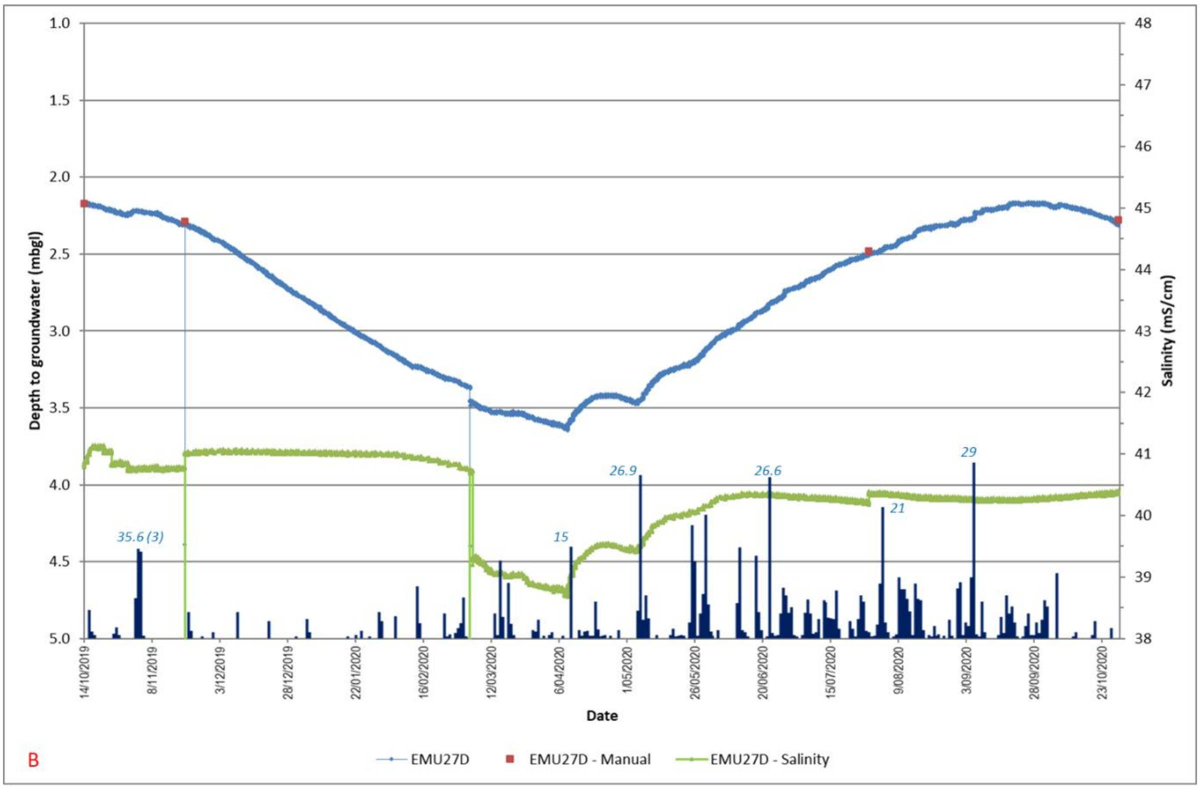
Appendix 5 Tordit-Gurrup Lagoon water storage

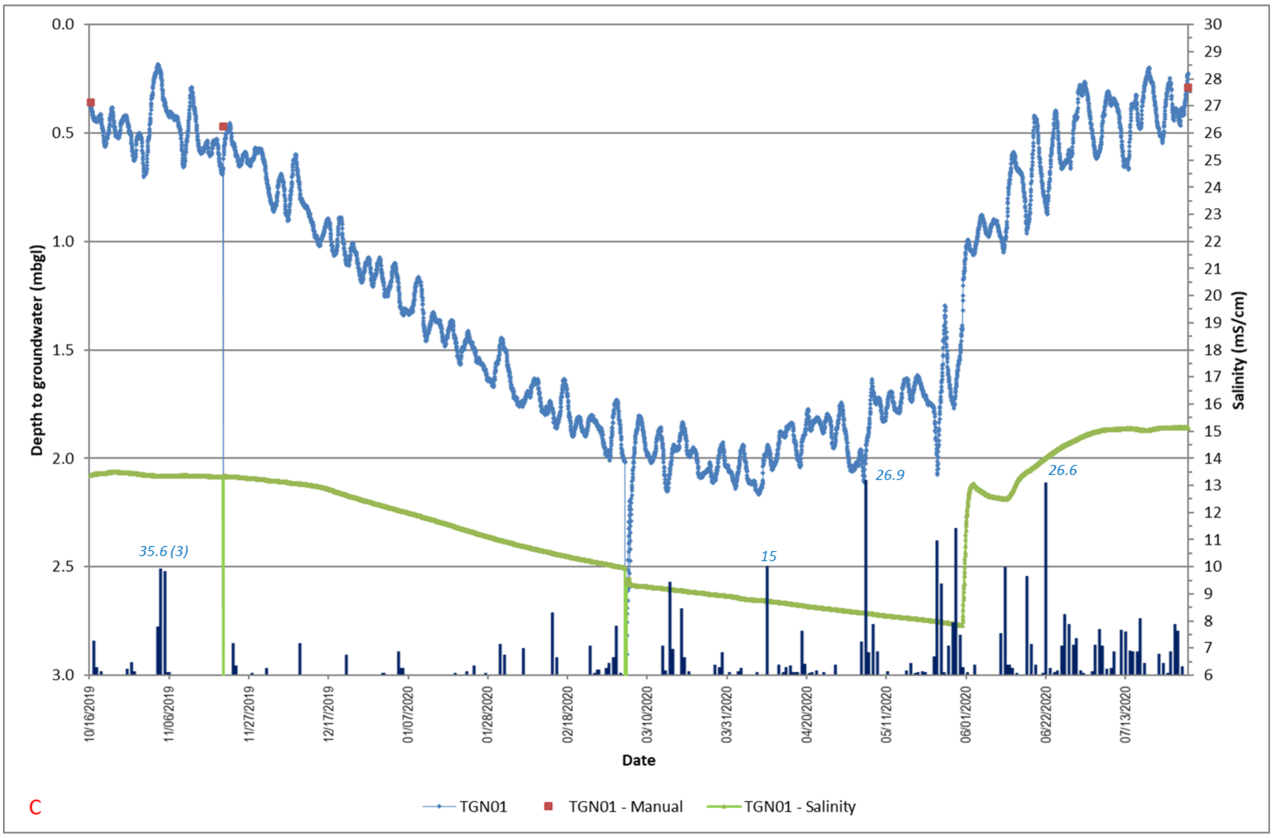
*Elevation (mAHD)	Area (2D)	Area (3D)	Area (ha)	Volume (m3)	From	To	Change volume	Change area (3D)	Comments (Map Zone in bracket)	Fill Volume	Fill Area (3D)	% total volume	% total Area (3D)
							0	0					
173	6259	7044	0.7	17459		173	17459	7044					
173.2	6913	7719	0.8	18768	173	173.2	1309	675	(1) southern water body				
173.4	776109	776940	77.7	47702	173.2	173.4	28934	769221					
173.6	1769141	1770000	177.0	345389	173.4	173.6	297687	993060		345389	1770000	7	27
173.8	1915121	1916016	191.6	713361	173.6	173.8	367972	146016					
174	2024219	2025177	202.5	1108101	173.8	174	394740	109161	(2) highly dessicated peat/southern beach				
174.2	2087611	2088654	208.9	1519654	174	174.2	411553	63477		1174265	318654	24	5
174.4	2270336	2270337	227.0	1950701	174.2	174.4	431047	181683	(3) northern water body/peat	431047	181683	9	3
174.6	4167160	4168627	416.9	2527056	174.4	174.6	576355	1898290					
174.8	6155276	6157286	615.7	3627393	174.6	174.8	1100337	1988659	(4) variable competency peat/southern beach				
175	**6499935**	**6502237**	**650.2**	**4901801**	174.8	175	1274408	344951		2951100	4231900	60	65
180	6731700	6734416	673.4	38767625	175	180	33865824	232179	fringing vegetation				
NB: fringing vegetation is not included in % volume and area calculations									**Total**	**4901801**	**6502237**	**100**	**100**
*Elevation calculations (<173 mAHD) from ground survey data & (173-180 mAHD) from LiDAR (Jan 2012) data when lagoon water levels were @ ~173.1 mAHD; vegetation generally sparce & low lying - not removed from LiDAR.													

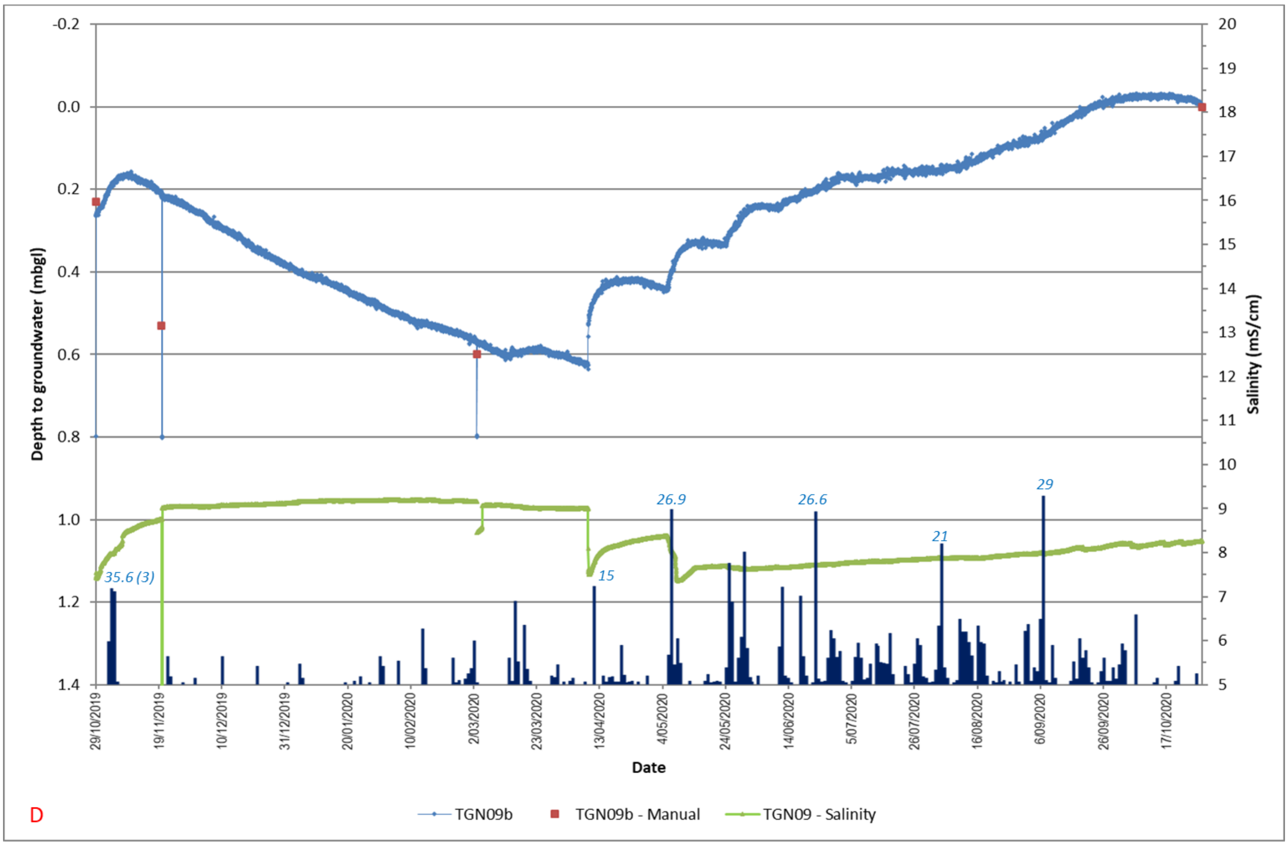


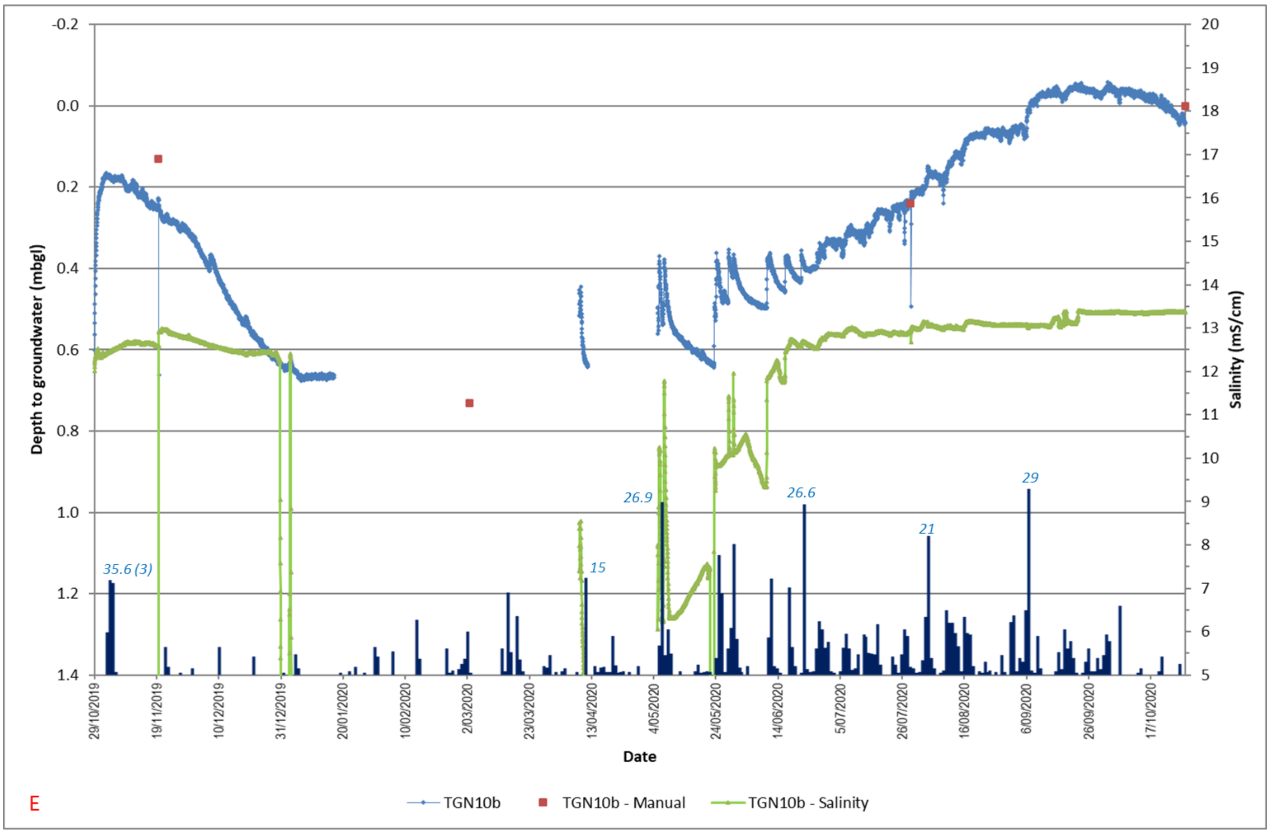
Appendix 6 Wetland scale groundwater and salinity



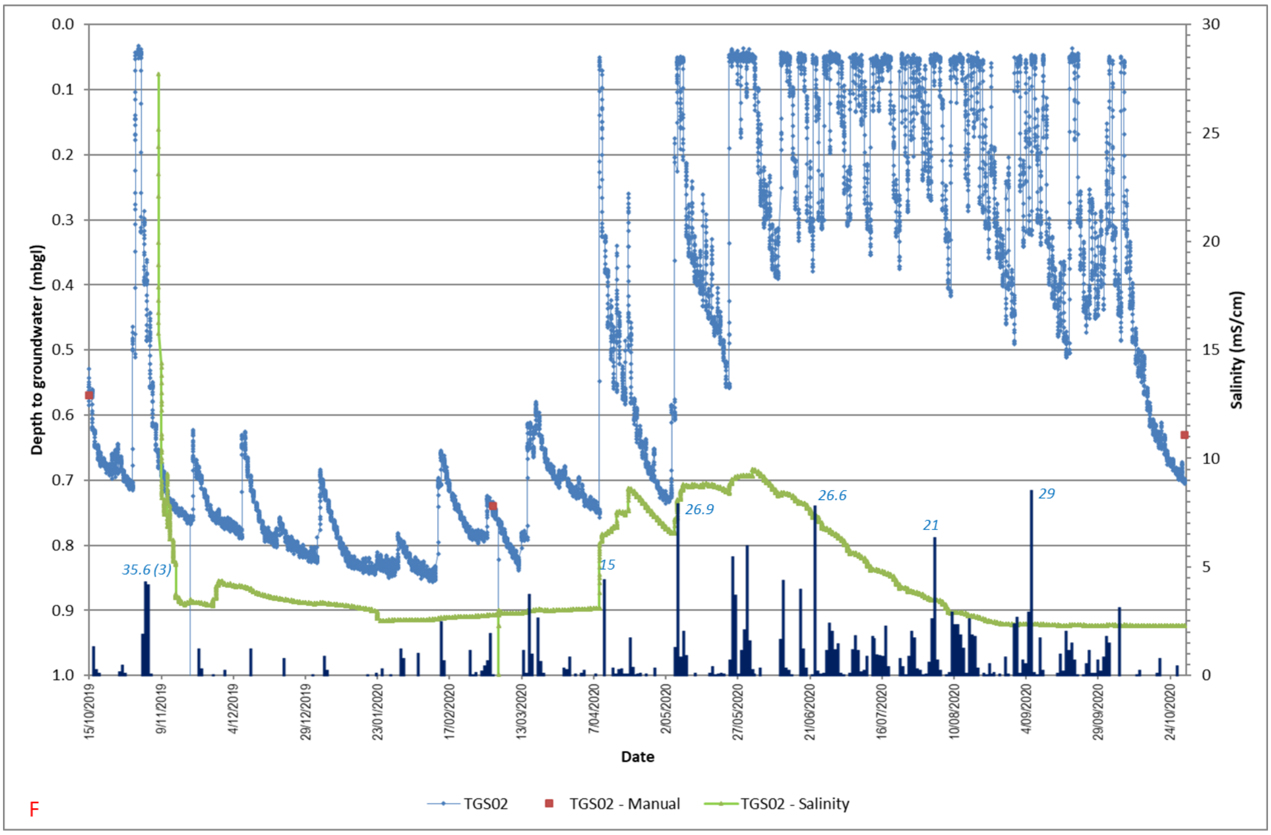



Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
C
TGN01
TGN01 - Manual
TGN01 - Salinity

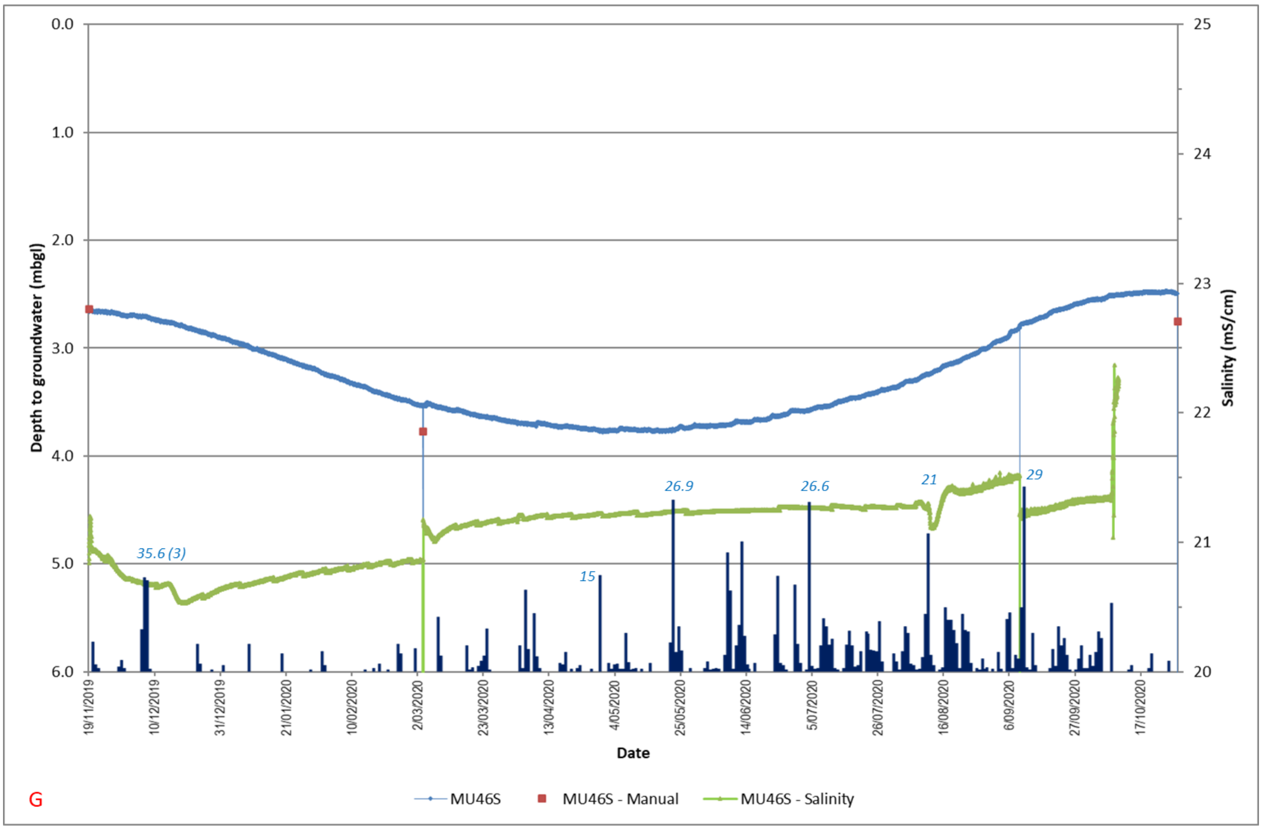

Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
21
29
D
TGN09b
TGN09b - Manual
TGN09 - Salinity

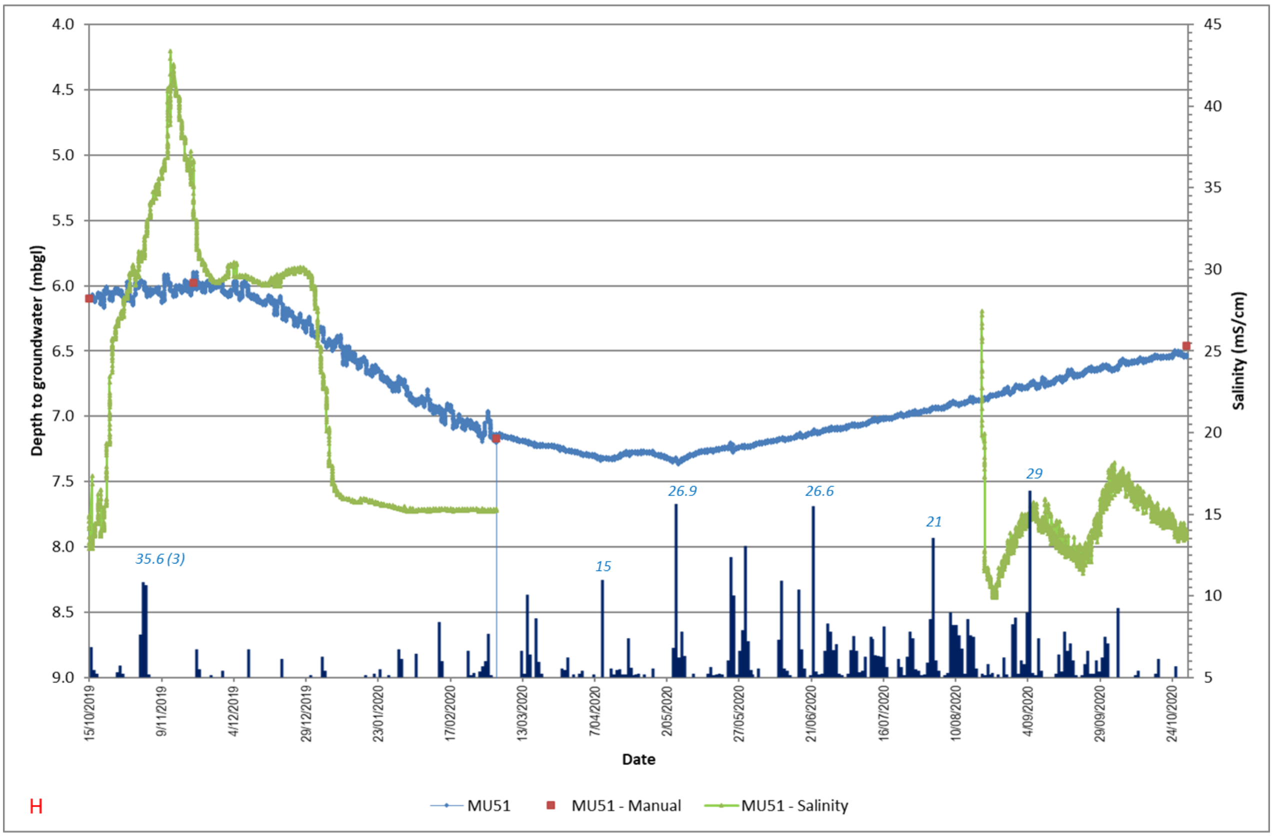


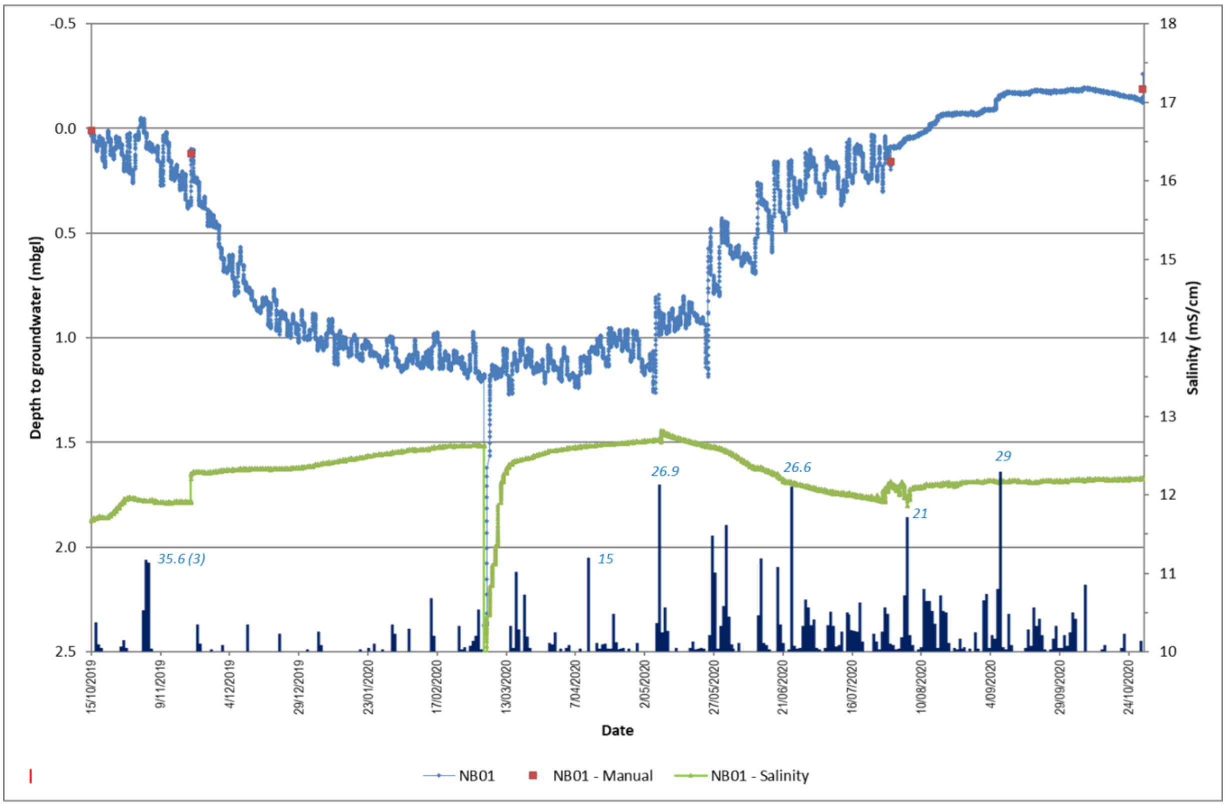
Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
21
29
TGN10b
TGN10b - Manual
TGN10b - Salinity
E



Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
21
29
TGS02
TGS02 - Manual
TGS02 - Salinity
F


Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
21
29
G
MU46S
MU46S - Manual
MU46S - Salinity


Depth to groundwater (mbgl)
Salinity (mS/cm)
Date
35.6 (3)
15
26.9
26.6
21
29
H
MU51
MU51 - Manual
MU51 - Salinity



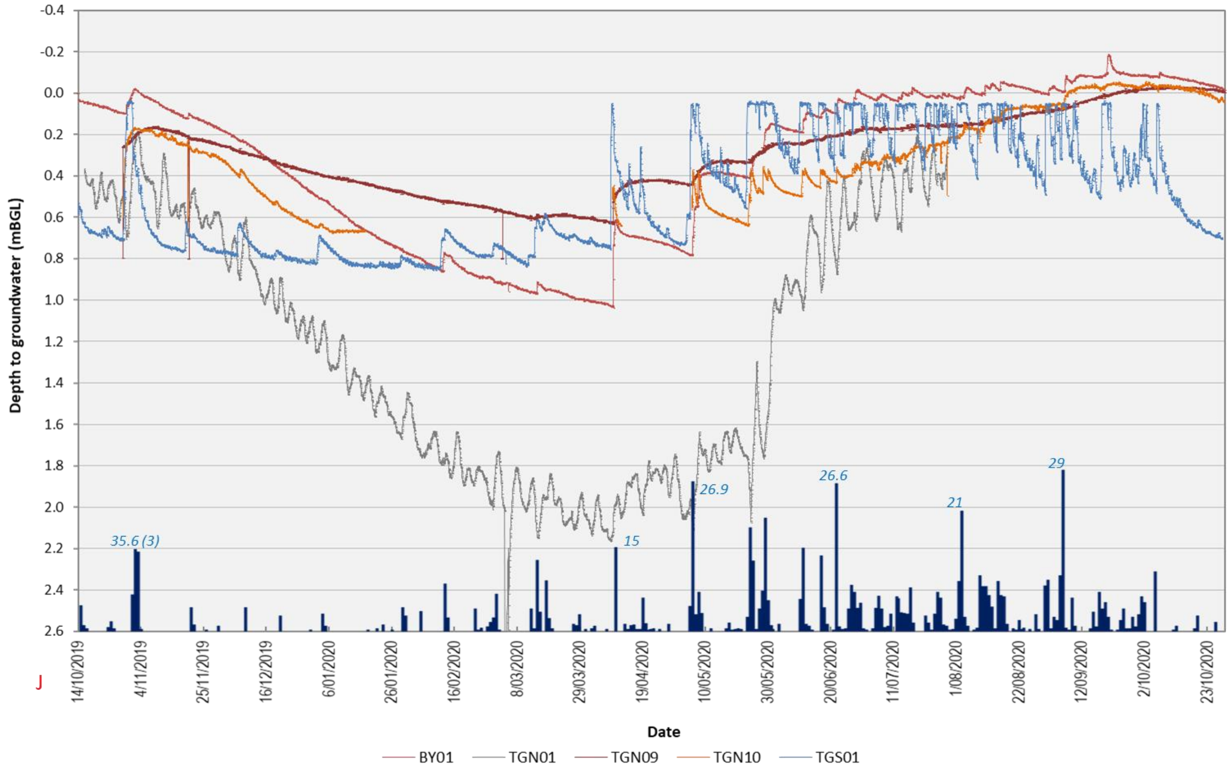
Graphed groundwater level and salinity data acquired from Diver CTD data loggers, across sites, for the period Oct 2019 to Oct 2020.

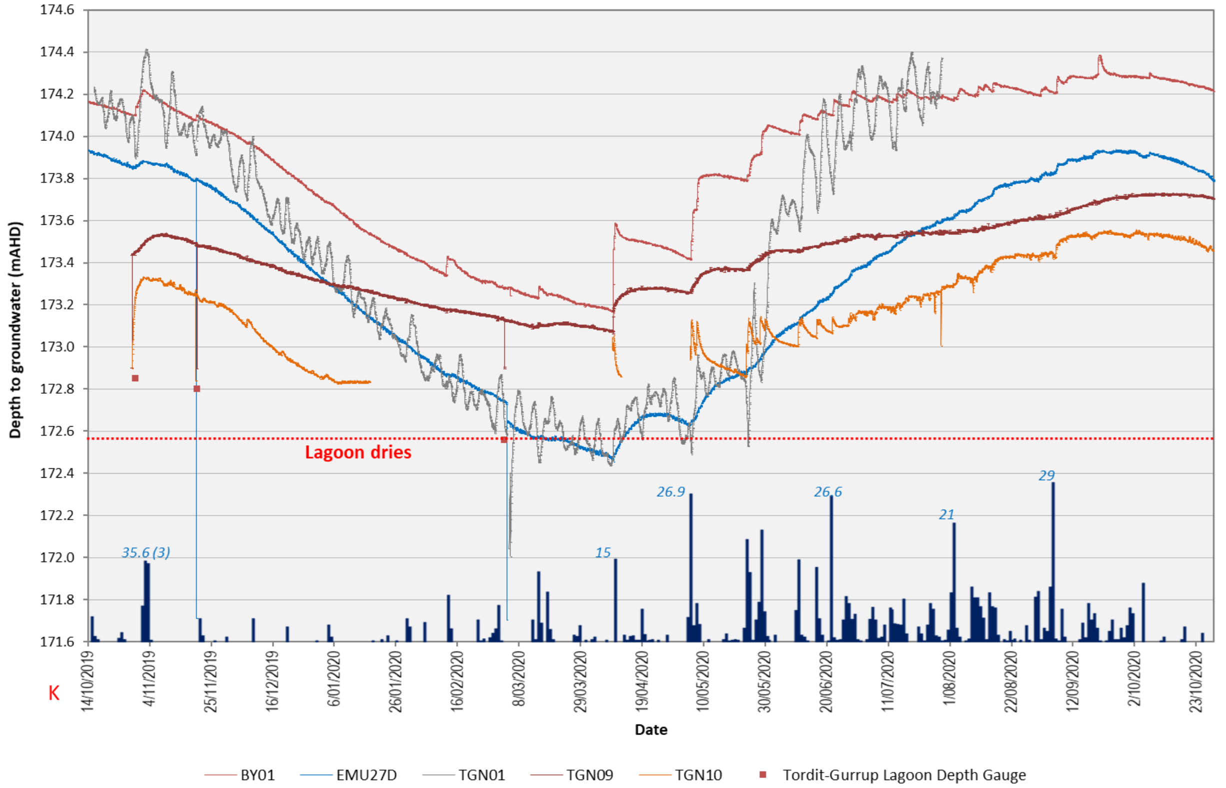
Note the data logger from TGN01 covers the period Oct 2019 to July 2020 as the logger was missing from the bore when dataloggers were collected in Oct 2020.

Problems with groundwater level data are noted where bores are leaking; TGS01/02 and TGN10b.

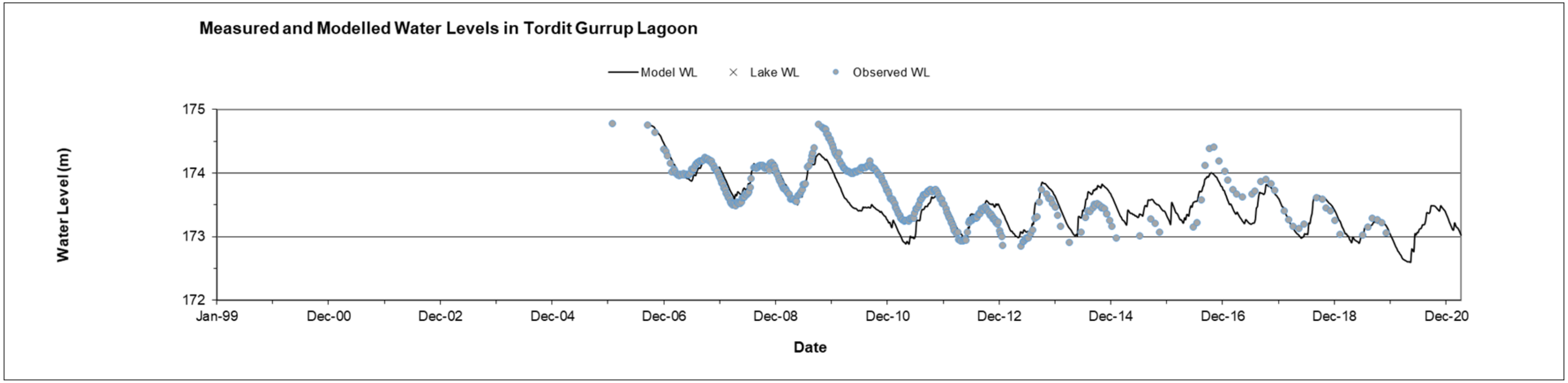
Diver data logger salinity data are erroneous (exceeded logger max; 120mS/cm) for periods of the data acquired for older, deeper bores constructed in saprolite aquifers; MU46s and MU51. Erroneous salinity data were removed from graphs presented here and salinity data for MU46s and MU51 should be treated with caution.

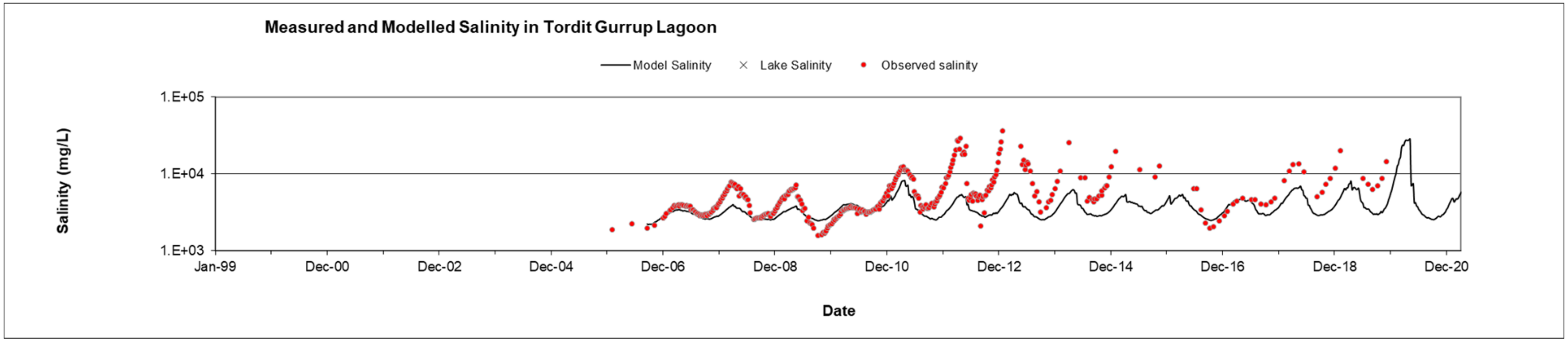
Superimposed bar graph of daily rainfall from BOM station Rocky Gully (#9661); note blue text represents rainfall events (mm); bracketed numbers are included if rainfall total is across more than one day


Depth to groundwater (mBGL)
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
35.6 (3)
15
26.9
26.6
21
29
14/10/2019
4/11/2019
25/11/2019
16/12/2019
6/01/2020
26/01/2020
16/02/2020
8/03/2020
29/03/2020
19/04/2020
10/05/2020
30/05/2020
20/06/2020
11/07/2020
1/08/2020
22/08/2020
12/09/2020
2/10/2020
23/10/2020
J
Date
BY01
TGN01
TGN09
TGN10
TGS01


Depth to groundwater (mAHD)
174.6
174.4
174.2
174.0
173.8
173.6
173.4
173.2
173.0
172.8
172.6
172.4
172.2
172.0
171.8
171.6
Lagoon dries
35.6 (3)
15
26.9
26.6
21
29
14/10/2019
4/11/2019
25/11/2019
16/12/2019
6/01/2020
26/01/2020
16/02/2020
8/03/2020
29/03/2020
19/04/2020
10/05/2020
30/05/2020
20/06/2020
11/07/2020
1/08/2020
22/08/2020
12/09/2020
2/10/2020
23/10/2020
K
Date
BY01
EMU27D
TGN01
TGN09
TGN10
Tordit-Gurrup Lagoon Depth Gauge

Appendix 7 Tordit-Gurrup Lagoon water and solute balance model





Appendix 8 Organic carbon storage (wetland scale)

Tordit-Gurrup

Figure 3c	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)	% storage
1	Evaporite	0.1						
2a	Fibric peat	0.3	395	0.0395	118.5	87.1	10321	5
2b	Hemic-Sapric peat	0.5	135	0.0135	67.5	87.1	5879	3
3a	Fibric peat	0.3	395	0.0395	118.5	14.3	1695	1
3b	Hemic-Sapric peat	0.5	135	0.0135	67.5	14.3	965	0
4&5a	Fibric peat	0.3	395	0.0395	118.5	435.1	51559	23
4&5b	Hemic-Sapric peat	0.9	395	0.0395	355.5	435.1	154678	69
							225098	100

Poorginup

ID	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.2	395	0.0395	79	123.7	9772
	Hemic-Sapric peat	0.6	395	0.0395	237	123.7	29317
							39089

Poorginup south

ID	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.2	395	0.0395	79	7	553
	Hemic-Sapric peat	0.6	395	0.0395	237	7	1659
							2212

Byenup

ID	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	395	0.0395	118.5	585.5	69382
	Hemic-Sapric peat	0.9	395	0.0395	355.5	585.5	208145
							277527

Byenup satellites

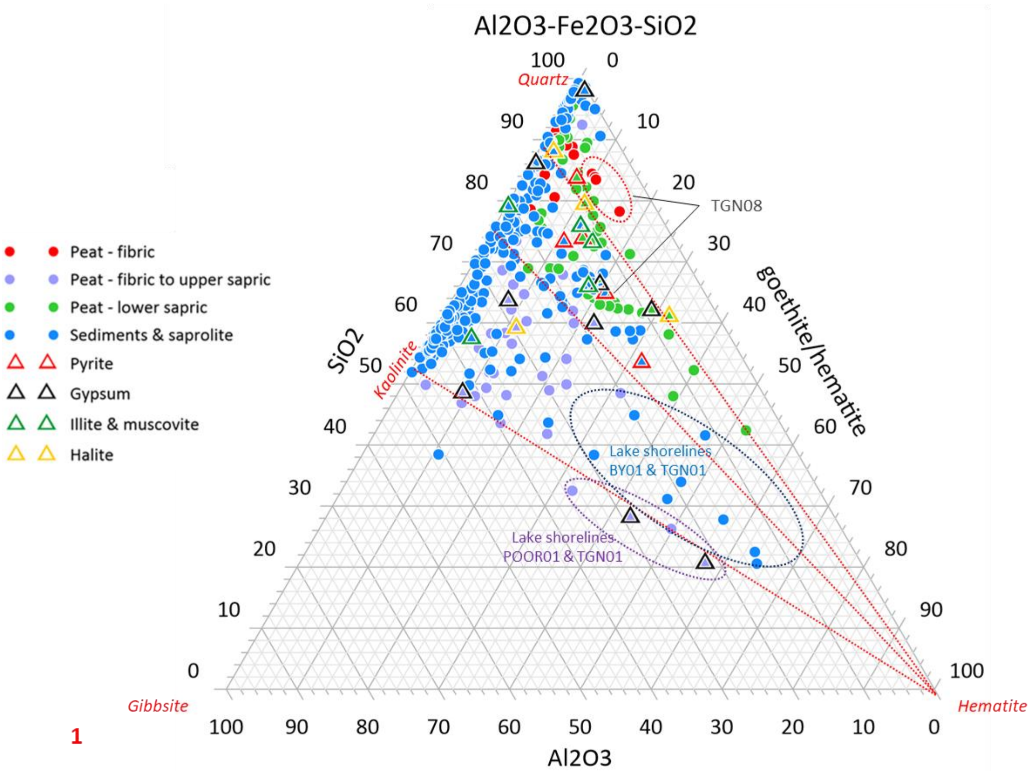
ID	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	395	0.0395	118.5	263	31166
	Hemic-Sapric peat	0.9	395	0.0395	355.5	263	93497
							124662

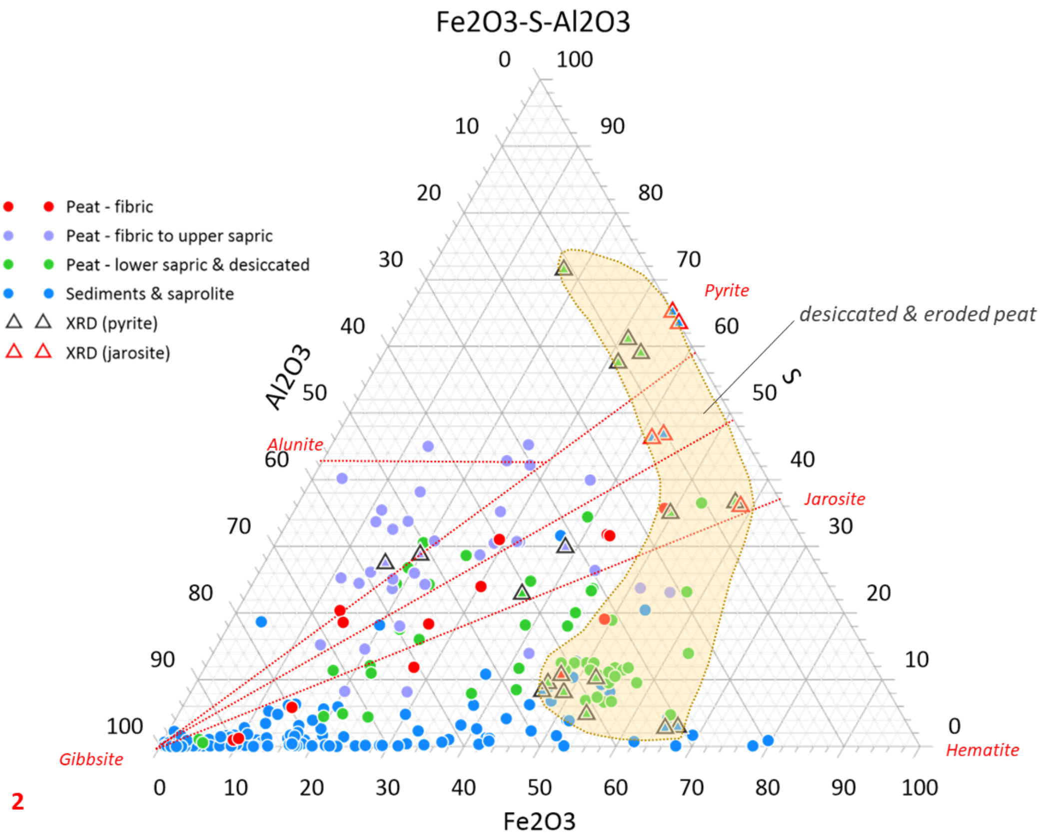
Noobijup

ID	Material subclass	Ave Layer Thickness (m)	Ave Carbon organic (g/kg)	Ave Carbon t/m3	Ave Carbon t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	395	0.0395	118.5	74.6	8840
	Hemic-Sapric peat	0.3	395	0.0395	118.5	74.6	8840
							17680

Name	Area (ha)	"Condition	Ave Carbon t/ha	Storage tonnes
Bokerup Swamp	49	G	474	23401
Kulunilup Swamp	77	G	474	36541
Noobijup Swamp	75	S		17680
Yarnup Swamp	23	P	122	2753
Geordinup Swamp	255	G	474	120821
Byenup Lagoon	586	S		277527
Byenup satellites	263	G		124662
Tordit-Gurrup Lagoon	661	S-P		225098
Tordit-Gurrup Lagoon satellite	17	S	474	8244
Poorginup Swamp	124	G		39089
Poorginup Swamp sth	7	G		2212
Red Lake	63	P	68	4224
Pindicup	66	S	356	23593
Neeranup Swamp	86	G	474	40631
Cowerup Lake (unmined)	12	S	122	1447
*provided by R.Hearn	2362 (~4% catchment)			947923

Appendix 9 Peat inorganic geochemistry





Material	Zone	Max depth sampled (mBGL)	Ave thickness (m)	Al2O3-Fe2O3-SiO2 ternary diagram (1)	Al2O3-Fe2O3-S ternary diagram (2)
Fibric peat	FP	0 to 0.3	0.2	Trends relative to SP zone; lower Fe2O3; quartz dominant	Trends relative to HP zone; lower S; precipitation jarosite
Fibric-upper sapric (hemic) peat	HP	0.8	0.5	Trends relative to SP zone; lower SiO2 & Fe2O3; clay (kaolinite) dominant	Trends relative to SP zone; higher S; precipitation jarosite & alunite
Lower sapric peat	SP	1.4	0.5	Trends relative to S zone; reduced Al2O3 & higher Fe2O3; precipitation Fe oxyhydroxides	Trends relative to S zone; reduced Al2O3 & higher S; precipitation jarosite
Desiccated peat	DP	1.0	0.8	Trends relative to SP zone; reduced SiO2; precipitation Fe oxyhydroxides	Trends relative to S zone; reduced Al2O3 & higher Fe2O3 & S; precipitation pyrite
Sediments / saprolite	S	Below lower sapric peat	NA	Overall trends; high/moderate Al2O3-moderate Fe2O3-high SiO2; Quartz & clay minerals are relatively stable	Overall trends; high Al2O3-moderate Fe2O3-low S; Al and Fe oxyhydroxide minerals are relatively stable - lower Al2O3 associated with high Fe2O3 (diagenetic changes)

Appendix 10 Salt storage (wetland scale)

Tordit-Gurrup

Figure 3c	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*	*% storage*
1	Evaporite-sediments	0.5	5000	2000	2	0.002	10	131.6	1316	21
2a	Fibric peat	0.3	3000	5000	5	0.005	15	87.1	1307	21
2b	Hemic-Sapric peat	0.5	5000	4000	4	0.004	20	87.1	1742	28
3a	Fibric peat	0.3	3000	5000	5	0.005	15	14.3	215	3
3b	Hemic-Sapric peat	0.5	5000	4000	4	0.004	20	14.3	286	5
4&5a	Fibric peat	0.3	3000	500	0.5	0.0005	1.5	435.1	653	11
4&5b	Hemic-Sapric peat	0.9	9000	500	0.5	0.0005	4.5	435.1	1958	32
									6160	100

Poorginup

ID	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*
	Fibric peat	0.2	2000	500	0.5	0.0005	1	123.7	124
	Hemic-Sapric peat	0.6	6000	500	0.5	0.0005	3	123.7	371
									495

Poorginup south

ID	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*
	Fibric peat	0.2	2000	500	0.5	0.0005	1	7	7
	Hemic-Sapric peat	0.6	6000	500	0.5	0.0005	3	7	21
									28

Byenup

ID	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*
	Fibric peat	0.3	3000	3000	3	0.003	9	585.5	5270
	Hemic-Sapric peat	0.9	9000	2500	2.5	0.0025	22.5	585.5	13174
									18443

Byenup satellites

ID	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*
	Fibric peat	0.3	3000	2000	2	0.002	6	263	1578
	Hemic-Sapric peat	0.9	9000	2000	2	0.002	18	263	4734
									6312

Noobijup

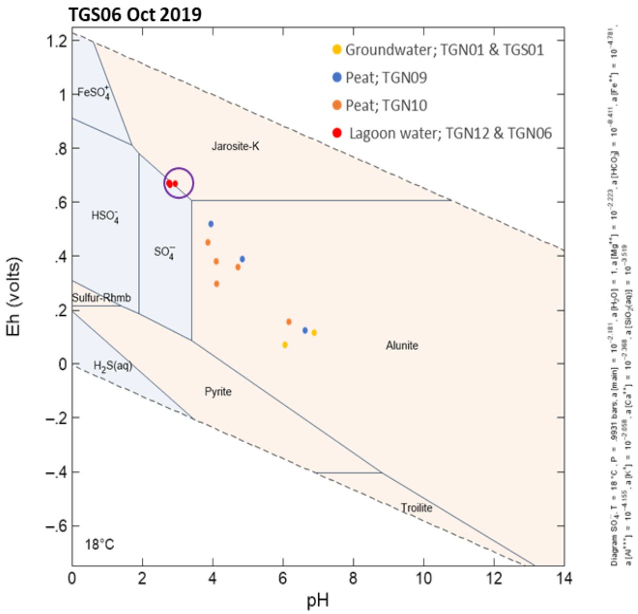
ID	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave salt mg/L*	*Ave salt kg/m3*	*Ave salt t/m3*	*Ave salt t/ha*	*Area (ha)*	*Storage (tonnes)*
	Fibric peat	0.3	3000	500	0.5	0.0005	1.5	74.6	112
	Hemic-Sapric peat	0.3	3000	500	0.5	0.0005	1.5	74.6	112
									224

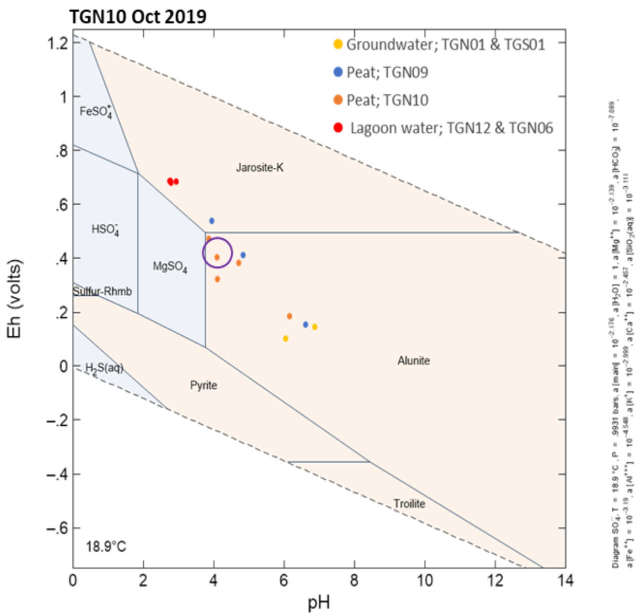
Name	Area (ha)	"Condition	Ave Salt t/ha (within peat)	Storage tonnes (within peat)
Bokerup Swamp	49	G	2.0	98
Kulunilup Swamp	77	G	2.0	154
Noobijup Swamp	75	S		224
Yarnup Swamp	23	P	20.0	453
Geordinup Swamp	255	G	2.0	510
Byenup Lagoon	586	S		18443
Byenup satellites	263	G		6312
Tordit-Gurrup Lagoon	661	S-P		6160
Tordit-Gurrup Lagoon satellite	17	S	3.0	52
Poorginup Swamp	124	G		495
Poorginup Swamp sth	7	G		28
Red Lake	63	P	20.0	1251
Pindicup	66	S	5.0	330
Neeranup Swamp	86	G	6.0	516
Cowerup Lake (unmined)	12	S	2.0	24
*provided by R.Hearn	2362 (~4% catchment)			35051

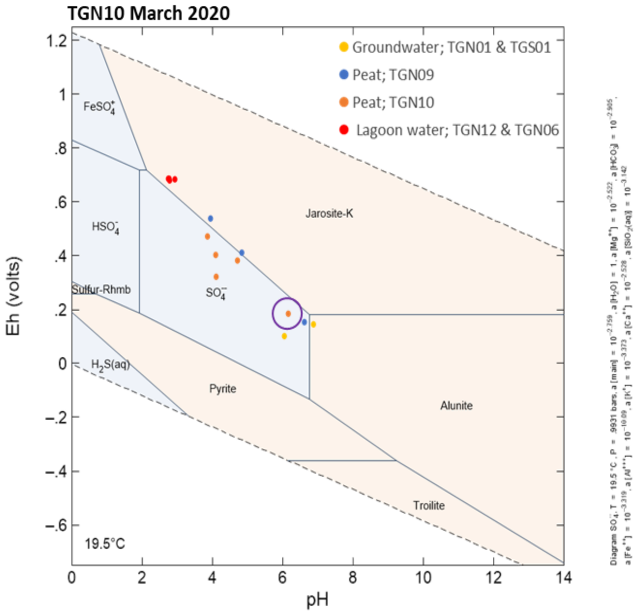
Appendix 11 Geochemical modelling – mineral saturation indices

Mineral / gas	Formula	Mineral group	TGS06 Oct 2019 saturation Q/K/bar	TGN10 Oct 2019 saturation Q/K/bar	TGN10 March 2020 saturation Q/K/bar	Season - max solubility / dissolution / conc
Albite	Na(AlSi3O8)	Feldspar	-8.04	-1.82	0.60	winter
Alunite	KAl3(SO4)2(OH)6	Sulfate-K	-4.71	2.21	-3.32	summer
Anhydrite	CaSO4	Sulfate-Ca	-0.34	-0.42	-1.07	summer
Aragonite	CaCO3	Carbonate-Ca	-9.97	-7.40	-1.19	winter
Beidellit-Ca	(Na,Ca0.5)0.3Al2((Si,Al)4O10)(OH)2 · nH2O	High CEC clay - Ca	-9.55	0.77	3.09	winter
Beidellit-H	derivative of Beidellite-Ca	High CEC clay - H	-9.09	0.80	2.45	winter
Beidellit-K	derivative of Beidellite-Ca	High CEC clay - K	-9.85	0.50	2.71	winter
Beidellit-Mg	derivative of Beidellite-Ca	High CEC clay - Mg	-9.52	0.83	3.10	winter
Beidellit-Na	derivative of Beidellite-Ca	High CEC clay - Na	-9.58	0.78	3.00	winter
Boehmite	AlO(OH)	Al-oxy-hydroxide	-5.90	-2.27	-1.49	winter
Calcite	CaCO3	Carbonate-Ca	-9.80	-7.23	-1.02	winter
Chalcedony	SiO2	Cryptocrystalline silica	0.34	0.73	0.69	mix lagoon water
Chamosite-7A	(Fe2+,Mg,Al,Fe3+)6(Si,Al)4O10(OH,O)8	Mica-Fe-Mg	-28.41	-12.21	-2.54	winter
CO2(g)	CO2 gas		0.0004	0.0004	0.05	summer
Dolomite	CaMg(CO3)2	Carbonate-Ca-Mg	-18.59	-13.28	-1.17	winter
Epsomite	MgSO4 · 7H2O	Sulfate-Mg	-2.56	-2.48	-3.44	no significant change
Gibbsite	Al(OH)3	Al-oxy-hydroxide	-4.17	-0.55	0.22	winter (minor change)
Gypsum	CaSO4 · 2H2O	Sulfate-Ca	-0.10	-0.19	-0.84	summer (minor change)
Halite	NaCl	Chloride-Na	-3.85	-3.66	-4.29	summer (minor change)
Illite	K0.65Al2.0[Al0.65Si3.35O10](OH)2	Mica-K	-12.45	-1.22	2.39	winter
Kaolinite	Al2(Si2O5)(OH)4	Low CEC clay	-6.66	1.37	2.83	winter (minor change)
K-feldspar	K(AlSi3O8)	Feldspar	-6.79	-0.61	1.76	winter
Magnesite	MgCO3	Carbonate-Mg	-10.46	-7.71	-1.81	winter
Maximum Microcline	K(AlSi3O8)	Feldspar	-6.79	-0.61	1.76	winter
MgSO4(c)	MgSO4	Sulfate-Mg	-9.80	-9.66	-10.59	summer (minor change)
Muscovite	KAl2(AlSi3O10)(OH)2	Mica-K	-13.74	-0.31	3.60	winter
Paragonite	NaAl2(AlSi3O10)(OH)2	Mica-Na	-15.90	-2.43	1.53	winter
Quartz	SiO2	Silica	0.62	1.01	0.96	no significant change
Saponite-Ca	Ca0.25(Mg,Fe)3((Si,Al)4O10)(OH)2 · nH2O	High CEC clay - Ca	-28.65	-17.26	-4.98	winter
Saponite-H	derivative of Saponite-Ca	High CEC clay - H	-28.18	-17.22	-5.62	winter
Saponite-K	derivative of Saponite-Ca	High CEC clay - K	-28.95	-17.53	-5.37	winter
Saponite-Mg	derivative of Saponite-Ca	High CEC clay - Mg	-28.62	-17.20	-4.97	winter
Saponite-Na	derivative of Saponite-Ca	High CEC clay - Na	-28.68	-17.25	-5.07	winter
Siderite	FeCO3	Carbonate-Fe	-10.31	-6.06	0.10	winter

Appendix 12 Geochemical modelling – mineral stability diagrams







Appendix 13 Potential acid storage (wetland scale)

Tordit-Gurrup

Figure 3c	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)	% storage
1	Evaporite	0.1	1000	0.015	15	136.2	2043	3
2a	Fibric peat	0.3	3000	0.05	150	88.7	13305	17
2b	Hemic-Sapric peat	0.5	5000	0.08	400	88.7	35480	45
3a	Fibric peat	0.3	3000	0.05	150	14.3	2145	3
3b	Hemic-Sapric peat	0.5	5000	0.08	400	14.3	5720	7
4&5a	Fibric peat	0.3	3000	0.01	30	435.1	13053	16
4&5b	Hemic-Sapric peat	0.9	9000	0.002	18	435.1	7832	10
							79578	100

Poorginup

ID	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.2	2000	0.01	20	123.7	2474
	Hemic-Sapric peat	0.6	6000	0.002	12	123.7	1484
							3958

Poorginup south

ID	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.2	2000	0.01	20	7	140
	Hemic-Sapric peat	0.6	6000	0.002	12	7	84
							224

Byenup

ID	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	3000	0.01	30	585.5	17565
	Hemic-Sapric peat	0.9	9000	0.002	18	585.5	10539
							28104

Byenup satellites

ID	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	3000	0.01	30	263	7890
	Hemic-Sapric peat	0.9	9000	0.002	18	263	4734
							12624

Noobijup

ID	Material subclass	Ave Layer Thickness (m)	Volume m3/ha	Ave Sulfur t/m3	Ave Sulfur t/ha	Area (ha)	Storage (tonnes)
	Fibric peat	0.3	3000	0.01	30	74.6	2238
	Hemic-Sapric peat	0.3	3000	0.002	6	74.6	448
							2686

Name	Area (ha)	"Condition	Ave Sulfur t/ha	Storage tonnes
Bokerup Swamp	49	G	48	2352
Kulunilup Swamp	77	G	48	3696
Noobijup Swamp	75	S		2686
Yarnup Swamp	23	P	380	8610
Geordinup Swamp	255	G	48	12240
Byenup Lagoon	586	S		28104
Byenup satellites	263	G		12624
Tordit-Gurrup Lagoon	661	S-P		79578
Tordit-Gurrup Lagoon satellite	17	S	48	835
Poorginup Swamp	124	G		3958
Poorginup Swamp sth	7	G		224
Red Lake	63	P	380	23778
Pindicup	66	S	48	3168
Neeranup Swamp	86	G	48	4128
Cowerup Lake (unmined)	12	S	380	4527
*provided by R.Hearn	2362 (~4% catchment)			190508

Appendix 14 Alkalinity estimates as lime

Tordit-Gurrup									
Zones; see Figure 3c	*Material subclass*	*Ave Layer Thickness (m)*	*Volume m3/ha*	*Ave Sulfur t/m3*	Ave lime (CaCO3) (x1.75) t/m3	*Volume lime t/m3*	*Area (ha)*	*Lime requirement (tonnes)*	*Cost estimate @ $50/t*
1	Evaporite	0.1	1000	0.015	0.026	0.0026	136.2	3575	$179k
2a	Fibric peat	0.3	3000	0.05	0.088	0.0263	88.7	23284	$1,165k
2b	Hemic-Sapric peat	0.5	5000	0.08	0.140	0.0700	88.7	62090	$3,105k
3a	Fibric peat	0.3	3000	0.05	0.088	0.0263	14.3	3754	
3b	Hemic-Sapric peat	0.5	5000	0.08	0.140	0.0700	14.3	10010	
4&5a	Fibric peat	0.3	3000	0.01	0.018	0.0053	435.1	22843	
4&5b	Hemic-Sapric peat	0.9	9000	0.002	0.004	0.0032	435.1	13706	
								139261	