GOVERNMENT OF WESTERN AUSTRALIA

Department of **Biodiversity, Conservation and Attractions**

Ashfield Flats Hydrological Study Summary

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Ashfield Flats Hydrological Study Summary Report

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Cover image: Ashfield Flats Wetland Monitoring, photograph by G. McGrath.

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Acknowledgments

I would like to acknowledge the custodians of the land and the waters of Derbarl Yerrigan (Swan River), the Whadjuk people of the Noongar nation and their Elders past and present. I acknowledge and respect their continuing culture and the contribution they make to this region. Thanks to the Department of Planning Lands and Heritage and the Australian Government’s National Landcare Program, Regional Landcare Partnerships through Perth NRM, for funding this project. Thanks also to contributions from Andrew Rate, Greg Skyrzpek, Matthias Leopold, and Carolyn Harding.

1 Ashfield Flats: Why Study the Hydrology?

This is a summary report consolidating and replicating results from the Ashfield Flats Hydrological Study (DBCA, 2021). A detailed description of methods and expanded results are described there.

Ashfield Flats Reserve is in the Perth suburb of Ashfield, on the banks of the Swan River Estuary (Figure 1). The reserve contains an occurrence of a Subtropical and Temperate Coastal Saltmarsh community, which is listed as a threatened ecological community (TEC) under the Environment Protection and Biodiversity Conservation Act 1999. This TEC is listed as vulnerable as it is considered to face a ‘high risk of extinction in the wild in the medium-term future. Temperate Coastal Saltmarsh occurs on the coastal margin, along estuaries and coastal embayments and on low wave energy coasts. They require some tidal connection, have a muddy substrate and consist of dense to patchy areas of salt-tolerant herbs, succulent shrubs or grasses, together with a smaller cover of *Melaleuca* or *Casuarina* trees. As a result of their distribution the TEC faces threats from weeds, land use change, pollution, and climate change.

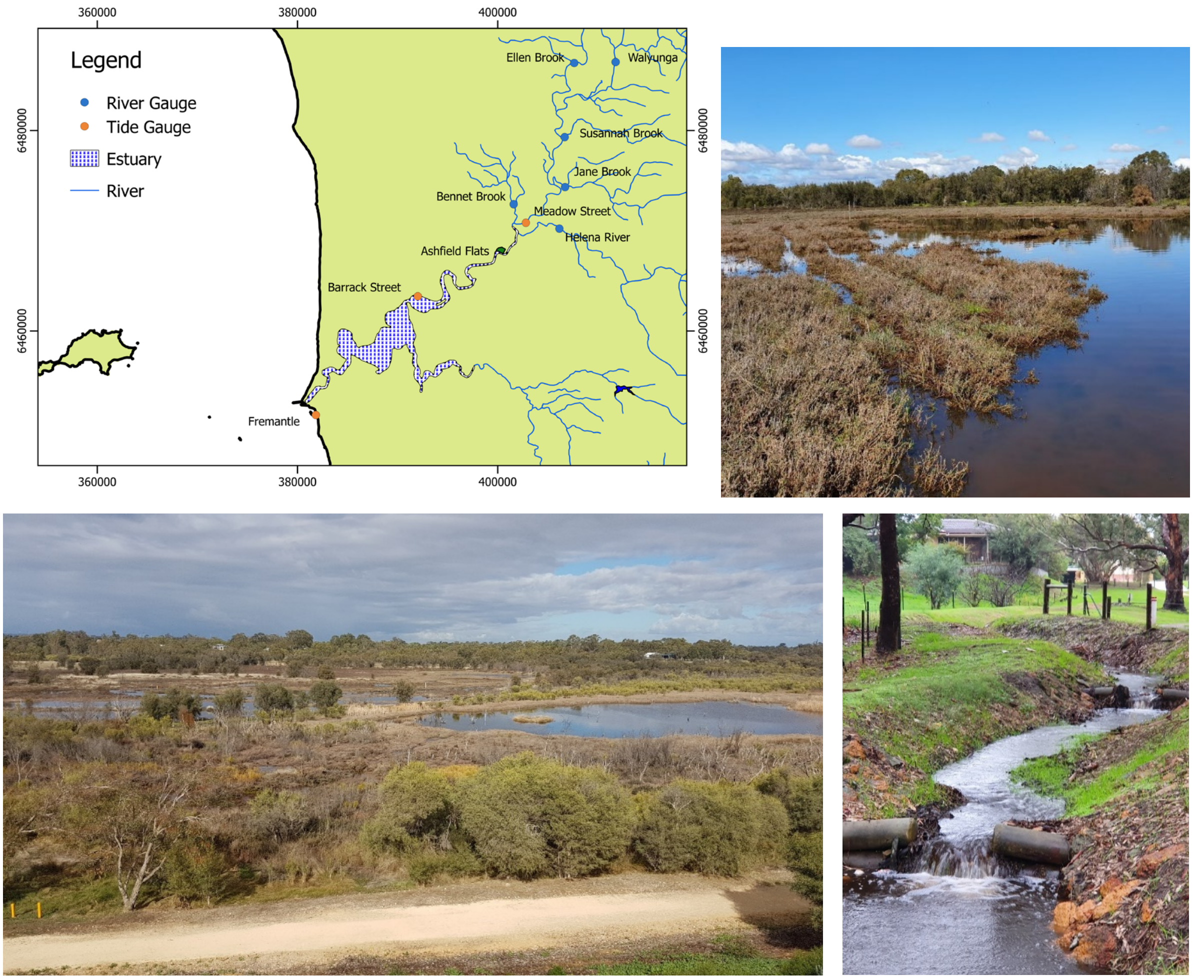


Figure 1: Site location, wetland views, and urban drainage.

Figure 2: Distribution of vegetation units. Vegetation unit codes are described in DBCA (2019).

A vegetation survey at Ashfield Flats identified 47 native and 65 introduced taxa from 34 families (DBCA, 2019). Ten species of salt-tolerant samphire, several sedges, and wetland trees were mapped (see Figure 2). The halophytes, Tecticornia and Salicornia, are significant components that define the TEC. They are known to be drought and salinity tolerant (Marchesini et al., 2014) with a conservative water use strategy. Growth rates decrease at low salinity and very high salinity, while extreme salinity impedes growth and can induced mortality (Equinox, 2013). Seedling survival is enhanced by the duration of reduced salinity after germination and growth rates of species seem to differ with varying salinity (English and Colmer, 2013). Tecticornia species also appear to show a wide variation in tolerance to inundation and submergence (Colmer and Flowers, 2008; Colmer et al., 2009; English and Colmer, 2011). Prolonged submergence is potentially a selective stress preventing some species from occupying low-lying habitats (Equinox, 2013). Changes to the duration, frequency and depth of inundation and to salinity are therefore expected to have significant impacts on the occurrence and distribution of halophytes at Ashfield Flats.

The study of water flow (hydrology) through these systems is challenging as, by definition, the TEC experiences influence from ocean processes, tides, river flows, urban drainage, and shallow groundwater. They are also intermittently wet and dry. The hydrology also influences the geochemistry of sediments and conveys pollution in urban drainage and groundwater. Finally, as is evident from the sensitivity of halophytes to salinity and submergence, hydrology also plays a key role in determining the health of the TEC. This report summarises the results of a hydrological study that aimed to characterise the hydrology of the site, and specifically to identify key processes regulating water flow, water levels, salinity and known historical pollution of groundwater near the Ashfield Reserve (DBCA, 2021). This knowledge will be used to protect the TEC and better manage the site.

2 Approach

2.1 Aim and Objectives

This study aimed to identify the dominant hydrological processes at the Reserve. The objectives were to:

- undertake a monitoring program to measure aspects of the hydrology;
- assess and model water levels, flows and water quality with a view to estimating components of the water balance; and
- investigate the occurrence of pollutants in soil and groundwater and their potential sources.

2.2 Methods

2.2.1 Monitoring Program

The Woolcock Ct Drain was gauged, and a stage discharge relationship developed to monitor the flow rate at a 10-minute interval for 18 months. In addition, water quality in the Chapman St Drain was measured during four rainfall events between 5th August - 31st October 2019, with samples collected at 15-minute intervals to characterise water sources and pollutant loads. Monitoring of surface water levels in wetland pools was conducted using a network of staff gauges and capacitance probes, from August 2018 to November 2020.

A groundwater monitoring program was initiated in March 2019 and consisted of the installation of 16 monitoring wells across the site, including shallow (~3 m depth) and deep (~12 m depth) screened wells. The objectives were to collect data on groundwater levels and water quality for the purpose of quantifying aquifer hydraulic properties, water flow directions and water fluxes.

Groundwater sampling was conducted in July and September 2019. Surface water samples were collected on four dates, two of which were coincident with groundwater sampling (16/07/2019, 24/09/2019, 29/10/2019, 20/12/2019) to assess spatial and temporal variation in water chemistry across eight distinct open pools and from the three drains, namely Chapman St, Woolcock Ct, and Kitchener St drains. Spatial sampling of water and sediment was conducted on two occasions (March 2019 and March 2020) by students from the University of Western Australia, under the supervision of Prof. Andrew Rate. Samples were variously analysed for water isotopes, major cations and anions, nutrients and metals.

2.2.2 Analyses

Estuary water levels were analysed using harmonic and wavelet methods (Grinsted et al., 2004; Veleda et al., 2012; Stephenson, 2016; Gouhier et al., 2019). To identify mechanisms causing flooding at Ashfield Flats a disaggregation approach was adopted to disentangle various processes contributing to river water levels. The approach used, proposed by Matte et al., (2013), is a modified harmonic analysis, which includes, in its basis functions, contributions from ocean tides, barometric effects, river flow and their non-linear interactions as derived from a theory of river-tides (Jay, 1991; Kukulka and Jay 2003).

Aquifer properties were inferred from tidal analysis of groundwater levels and response to changes in atmospheric pressure (Trefry and Bekele, 2004; Jiao and Tang, 1999, Turnadge et al., 2019).

Hydrograph separation can use chemical tracers carried with the water flow to disentangle the various contributions. The fractional contributions of groundwater and rainfall to runoff were separated using the results of the chemical analysis of water samples collected during the runoff events in the Chapman St Drain and the methods described by McGlynn and McDonnel, 2003 and Klaus and McDonnell, 2013.

2.2.3 Modelling

A stormwater model was developed to simulate the hydrodynamics of flow in the urban stormwater system. The Storm Water Management Model was developed using infrastructure data supplied by the Town of Bassendean and calibrated on three catchments where flow data was collected. Model simulations were then conducted on 30 years of weather data to estimate long-term discharge characteristics.

The hydroperiod is a fundamental metric of relevance to ecological processes in salt-marsh ecosystems (Pechmann et al., 1989; Crase et al., 2013; Estrelles et al., 2018). Sea levels near Perth are presently rising due to anthropogenic climate change at a rate of ~1.5 mm/year, consistent with global observations (Pattiaratchi, 2011). In addition to rising sea levels, climate change is expected to decrease annual rainfall and increase potential evaporation rates (IPCC, 2013). A hydrological model was developed to simulate surface water levels in the wetland pools. The model, driven by rainfall, evaporation and river water levels, assumed minimal interaction with groundwater. Bayesian methods were applied to model calibration. This model was used to simulate water levels at 30-minute time steps for 30 years of weather and river data to characterise wetland hydroperiods and water depths. Next the model was used to simulate IPCC climate change scenarios by including projected impacts on mean sea level, evapotranspiration and rainfall. Simulations were applied to repeat the estimation of water levels and hydroperiods for 2030, 2050 and 2090 for a range climate change scenarios (Wainwright and Verdon-Kidd, 2016).

Figure 3: Installation of groundwater monitoring wells MW04D (top left); MW04S (top right) and locations of drains, groundwater monitoring wells and surface water monitoring sites.

3 Key Findings

3.1 Urban Drainage

A total of 11 stormwater catchments of relevance to Ashfield Flats were identified (Figure 4). Of the catchments discharging directly into the Reserve the Woolcock Ct Drain is the largest, at 16.6 ha. The Chapman St and Kitchener St Drains bisect the wetlands however they discharge directly to the Swan River and do not interact significantly with the wetlands. Groundwater is a significant contributor to flow in the Woolcock Ct and Chapman St drains, at ~65% of annual discharge (Table 1). As a result of the groundwater contribution these drains flow perennially. Even during rainfall events groundwater is a significant contributor to discharge (Figure 4).

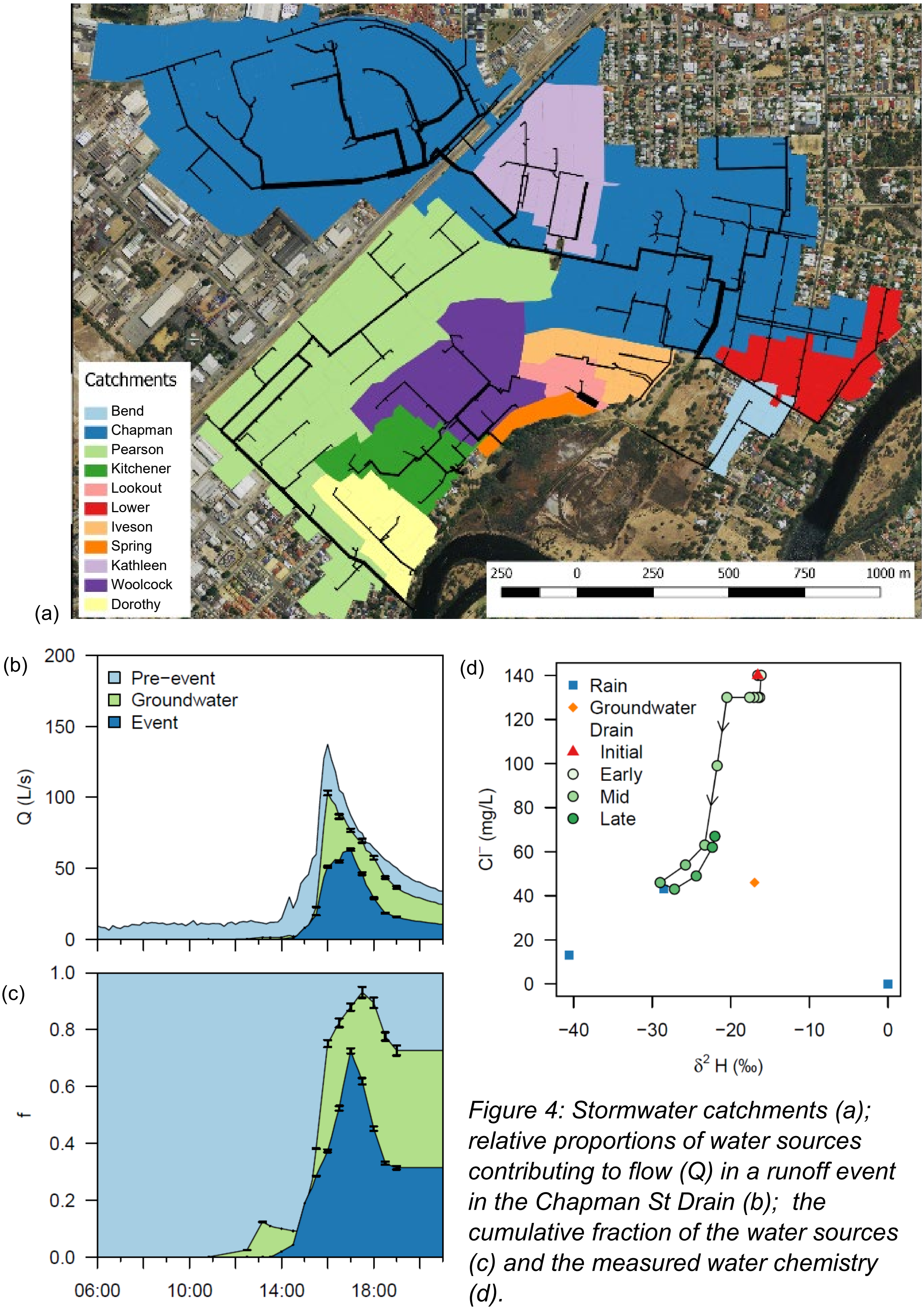


Figure 4: Stormwater catchments (a); relative proportions of water sources contributing to flow (Q) in a runoff event in the Chapman St Drain (b); the cumulative fraction of the water sources (c) and the measured water chemistry (d).

Table 1: Observed stormwater runoff characteristics.

Catchment	Annual Flow ML	Runoff Coefficient[c] mm mm^{-1}	Base flow Index mm mm^{-1}
Chapman St[a]	377.5	0.11±0.06	0.65
Woolcock Ct[b]	55.7	0.15±0.11	0.65
Lower[1]	5.2	0.33±0.33	0

a. For the year September– 2018 – September 2019; b. For the year August – 2019 – August 2020; c. Mean ± the standard deviation

The construction of the Woolcock Ct Drain has likely led to a freshening of the wetland water pools on the western side of the TEC as well as contributed to a more perennially inundated state. This drain may have already impacted fringing salt-marsh species and favoured the proliferation of sedges and melaleuca in this western half of the Reserve. The Chapman St and Kitchener St drains appear to have a minimal interaction with the wetlands at present, however with projected sea level rise these drains may start to flow directly into the area inhabited by halophytes. As a result, the lower salinity may reduce the competitive advantage currently available to the Salicornia and Tecticornia species.

3.2 Surface Waters and the Influence of the Estuary

Ashfield Flats is located 33 km upriver from the coast towards the upper extent of the Swan River Estuary (Figure 1). Water levels in the river adjacent the wetland are therefore influenced by a variety of processes affecting coastal water levels as well as river runoff from several tributaries which converge upstream of the site. At Fremantle the tides are classified as micro-tidal diurnal, with a range of 0.6 m (Pattiarachi, 2011). Due to its microtidal nature, a variety of processes significantly influence water levels at a range of timescales from minutes to decades. Processes that have been quantified include: wind set up (3 – 6 hr, 0.2 m), pressure systems (1–10 days, ~0.8 m), continental shelf waves forced by remote tropical cyclones (3–10 days, ~0.6 m; O'Callaghan et al., 2007; Eliot and Pattiaratchi, 2010), Leeuwin Current (seasonal, ~0.3 m), inter-annual climate variability such as the El Niño Southern Oscillation (10 yrs, ~0.2 m), nodal tides (18.6 yr, ~0.2 m; Haig et al., 2011), and climate change (Swan River Trust, 2007).

The southwest of Western Australia has also experienced significant and prolonged decrease in rainfall since the 1970's of the order of 15 – 20%, which has in turn led to a 70% decline of inflows to Perth's water supply dams (Petrone et al., 2010) as well as sediments delivered with seasonal flows. River runoff is shown here to dampen tides at Guildford and therefore despite reduced flows in the river there has been some compensation to flooding at Ashfield from the increased amplitude of tides (Figure 5).

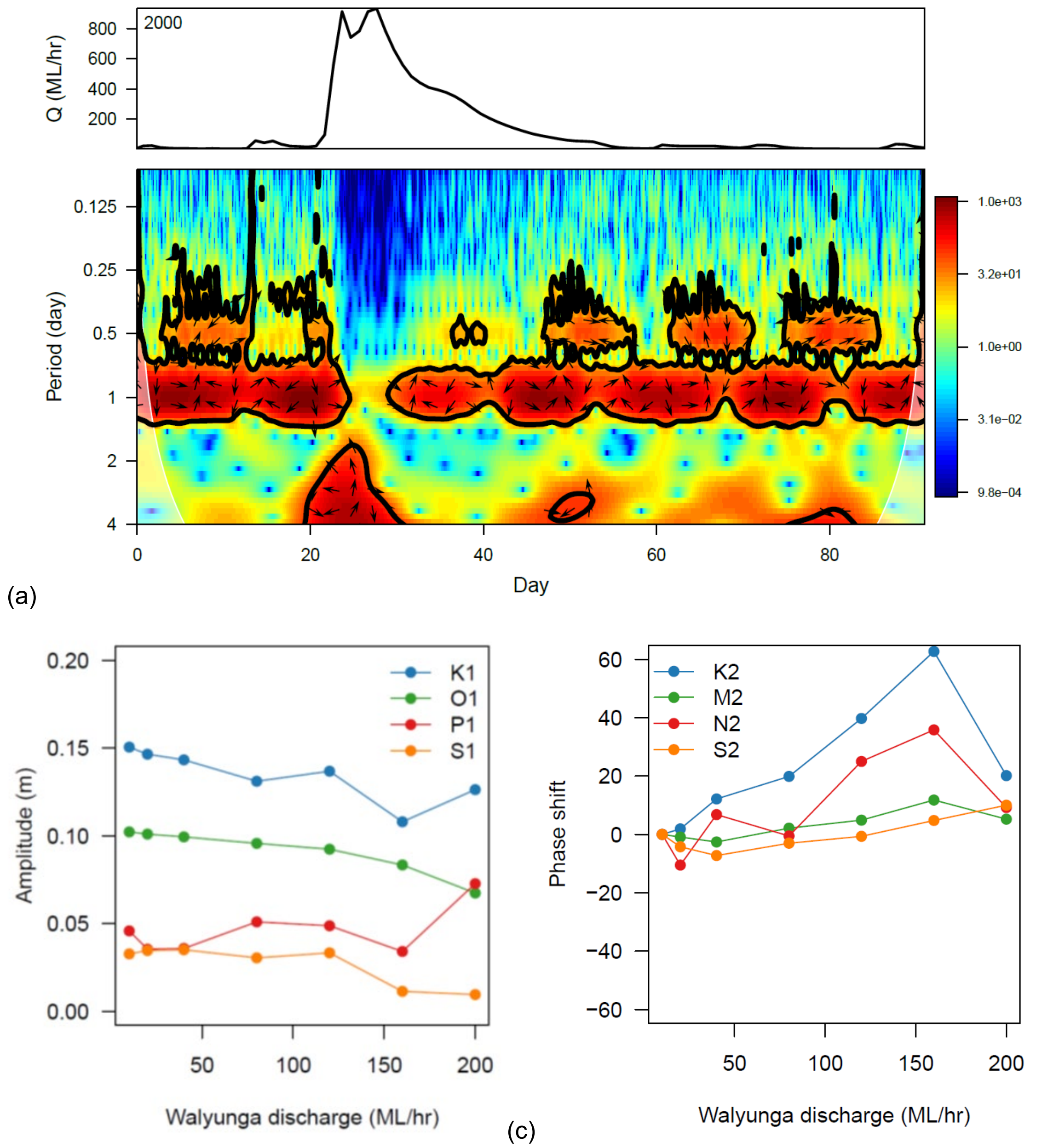


Figure 5: Effect of river flow rates at Walyunga (Q) on the tidal energy as shown by the wavelet power spectra (a) and tidal constituent amplitude (b) and phase (c) from harmonic analysis.

Water level monitoring of the wetland pools showed that the wetland floods at a threshold river level of ~0.55 m AHD. After flooding water levels recede to the approximate flood level and remain stable for several months, albeit interspersed with the occasional flood. Some pools on the western side of the site remain wet throughout the year, while those on the east tend to dry by mid spring and are completely dry by the end of summer.

The hydrological model accurately reproduces various aspects of the water level dynamics observed at the site (Figure 7). These include: the sudden transition from dry to flooded in response to river tides; the rapid recession of a flood event; the maintenance of near-stable water levels for prolonged periods; the convex shape of the drying during spring, and the extended period of dry conditions over summer.

From the model, measurements of surface water quality and an analysis of the surface topography, a simple conceptual model of the seasonal cycle of surface waters helps explain the presence of the TEC (Figure 7).

The topography of the wetland is bowl-shaped. The Reserve floods from either side of the outlet of the Chapman St Drain, and spills over at a few low points of the drain embankments near the river (Figure 8). As river levels fall there is rapid drainage by shallow overland flow which is slowed by friction. Once this water has drained, the remaining water is then lost only partially to groundwater recharge but mostly to evapotranspiration. This bowl-shaped morphology is consistent with theories of salt-marsh morphodynamics (Friedrichs and Perry, 2001). River waters are brackish and during drying the pool water evaporates, leading to a rise in the salinity until a salt efflorescence remains on the surface by the end of summer.

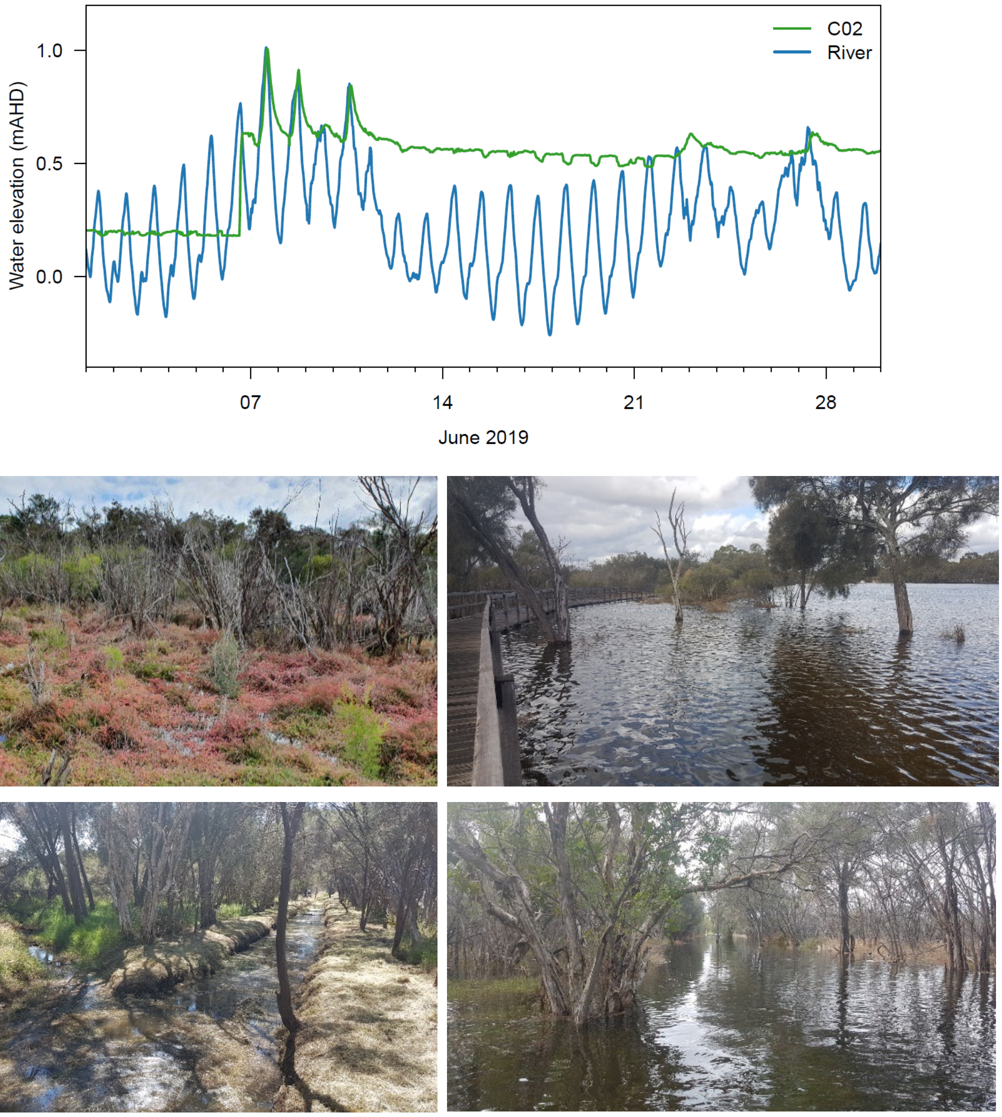


Figure 6: Measured surface water levels (at site C02) in comparison to river levels at the Meadow St Bridge gauge. The levels before 7th June reflect the elevation of the dry ground surface. Images show the before and after flooding state. Photos show pre and post-flooding states near the Swan River.

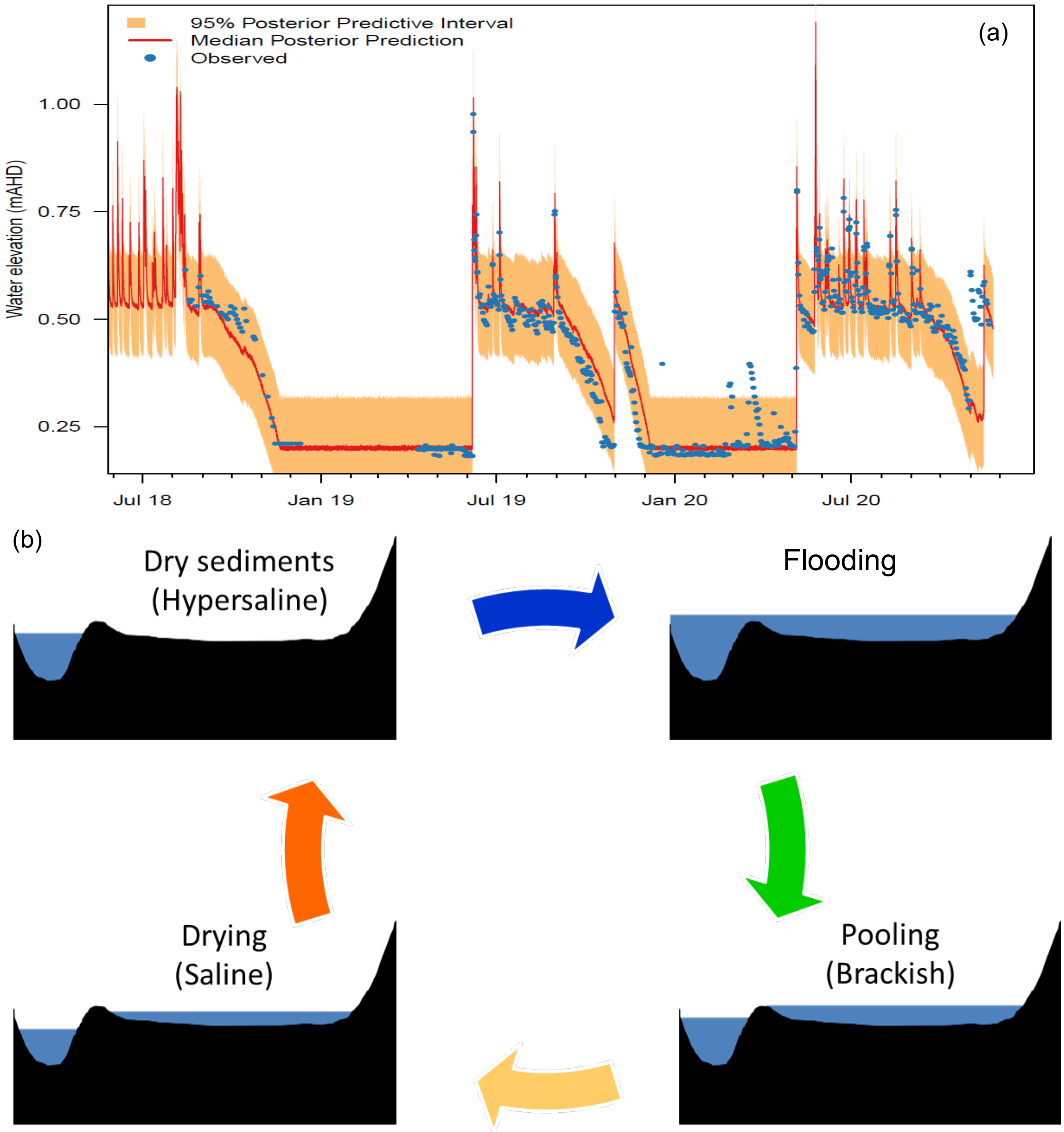


Figure 7: Modelled and observed wetland water levels (a) and a conceptual model for river-wetland interactions (b).

Using water levels disaggregated by several estuary processes it was shown that tides are the dominant flooding mechanism, and they contribute the most to flooding where the TEC occurs (Figure 9). Next important is low pressure systems producing storm surges, while river flows have only a small contribution on the average, although they are important for generating the largest floods.

Modelling suggests that in a short period of time (2030) climate change impacts will be observable, with the average hydroperiod at pool SW05 (Figure 3) expected to increase by 59 days/year from a present mean value of 266 days/year (

Table 2 and Figure 10). At SW06 the increase in hydroperiod is predicted to average 70 days/year. By 2090 both emissions scenarios suggest these wetland pools will be permanently inundated. Furthermore, river levels will rise above the threshold at which the river presently floods the Reserve.

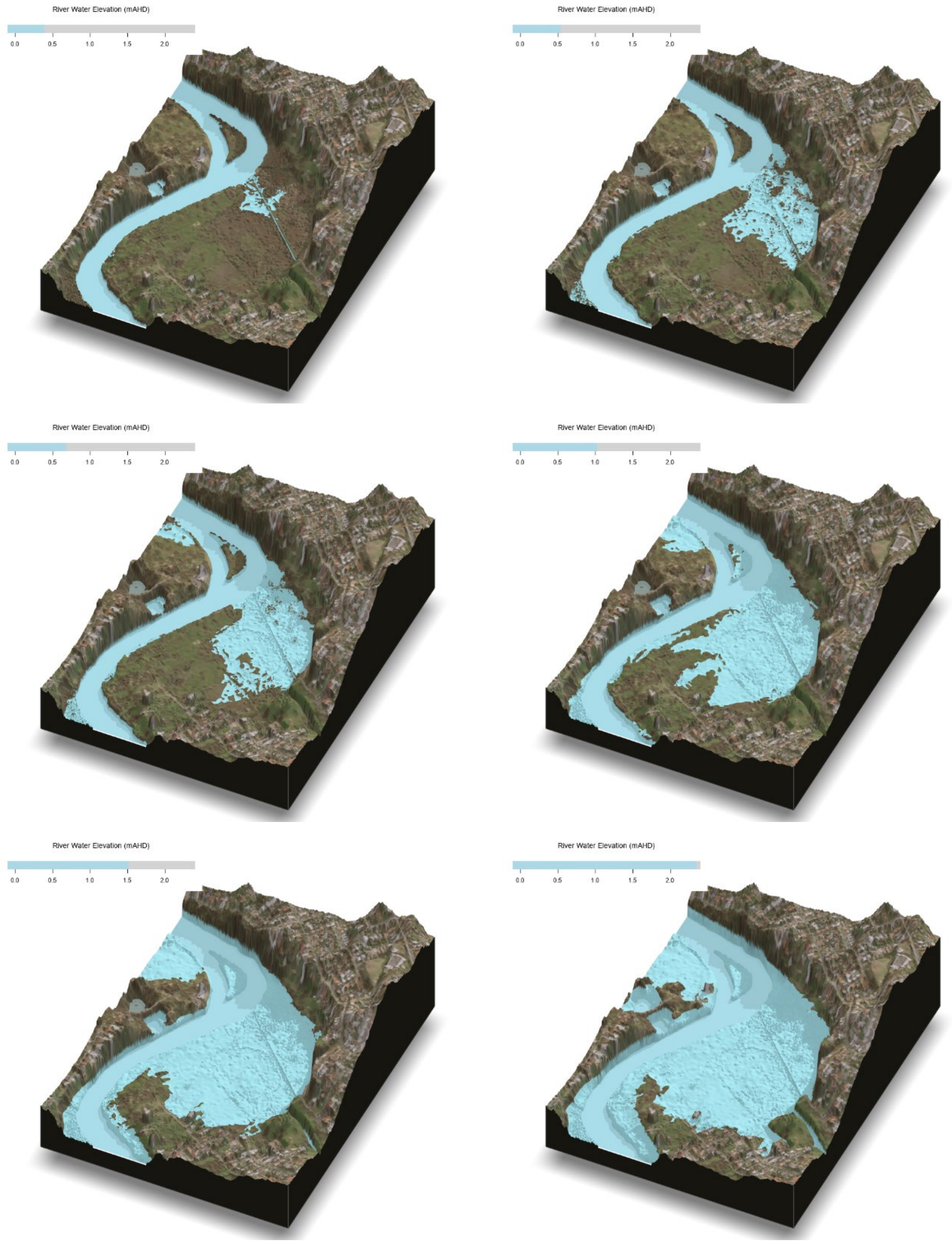


Figure 8: Extent of flooding at selected river levels.

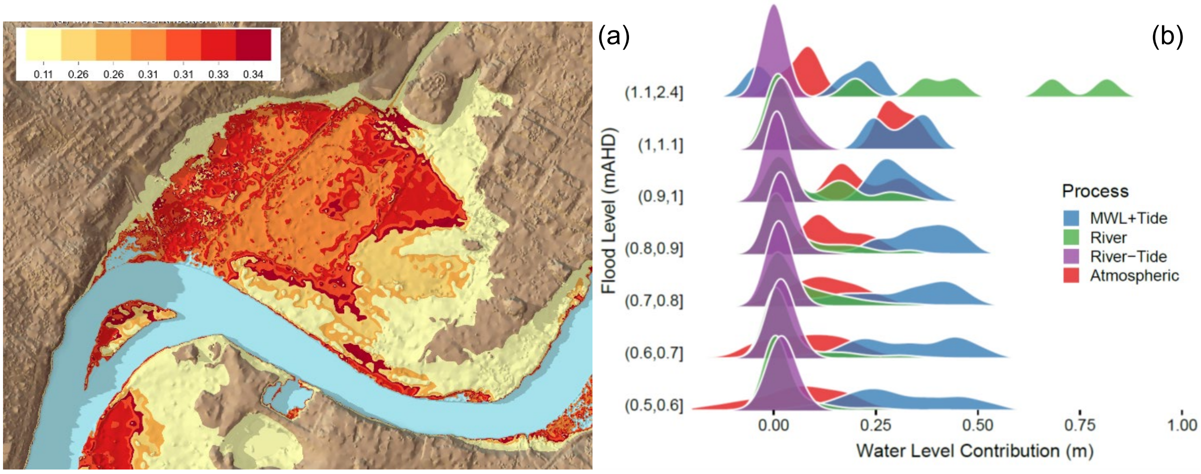


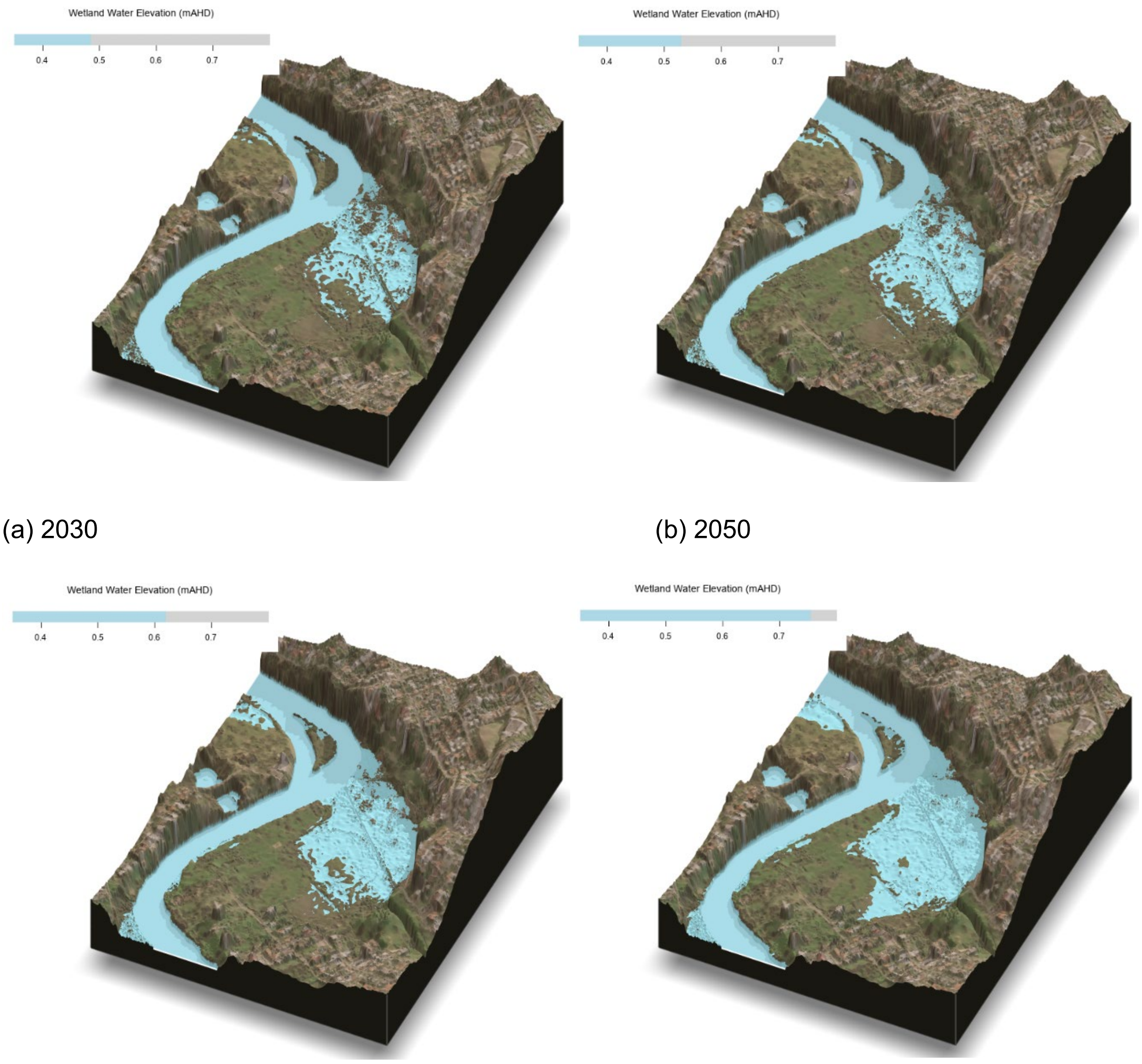
Figure 9: Spatial distribution of the average contribution peak water level (m) during flood events by tides (left) and histograms showing contributions to various flood levels from tides, river flows, river-tide interactions, and atmospheric pressure (right).

Table 2: Modelled climate change impacts on mean wetland water depths and hydroperiod.

		SW05		SW06	
Scenario	Year	Mean Water Depth (m)	Mean Hydroperiod[1] (days/year)	Mean Water Depth (m)	Mean Hydroperiod[1] (days/year)
Present	1990-2020	0.20	266	0.19	216
RCP4.5	2030	0.25	325	0.26	286
	2050	0.29	351	0.32	332
	2070	0.33	361	0.40	357
	2090	0.39	362	0.48	362
RCP8.5	2030	0.25	324	0.26	284
	2050	0.30	356	0.35	341
	2070	0.36	362	0.45	361
	2090	0.48	364	0.59	364

1. Hydroperiod defined as proportion of time water depth greater than 0.1 m.

This wetland has formed via scour by a meander of the Swan River and subsequent accretion of wetland sediments. With declining river flows, reduced frequency of river flooding and lower sediment load in the river the contribution from the river to accretion is presently diminished. The future hydrology and morphology of the site will depend to a large degree on the rate of sedimentation and consolidation processes and therefore these need careful consideration to evaluate the susceptibility of the site to sea-level rise.



(a) 2030

(b) 2050

(c) 2070

(d) 2090

Figure 10: Spatial extent of inundation at mean annual wetland water levels for emissions Scenario RCP8.5 for the periods 2030 to 2090 (a – b above, c – d below).

3.3 Groundwater

The drilling and the environmental geophysics show the wetland comprises a thin layer (~2 – 5 m thick) of silty/clayey wetland sediments overlying interbedded layers of grey/green plastic clays, likely Guildford Clay, medium – coarse grained sands, likely Bassendean Sand, as well as coarse sandy alluvial deposits with shell grit and charcoal. The groundwater monitoring program and interpretation of that data showed water is within 1 m of the surface and generally flows from the west and north across the site to the southeast to the river. The aquifer beneath the wetland sediments is weakly confined with groundwater flowing upwards and evaporating during summer and then switching to flow downwards during winter.

Using the trends in amplitudes and the phase lag of tides in the aquifer, the hydraulic properties were estimated. The estimated aquifer diffusivity was in the range 0.34 to

1.93 $m^2 s^{-1}$ with vertical hydraulic conductivities in the range between 3.0×10^{-8} and 1.1×10^{-6} m s^{-1} and storativities between 1.2×10^{-4} and 6.8×10^{-3}. These values are within expected values for the silty and sandy – clay materials identified in the drilling. A similar estimate of the stativity was estimated from aquifer response to atmospheric pressure.

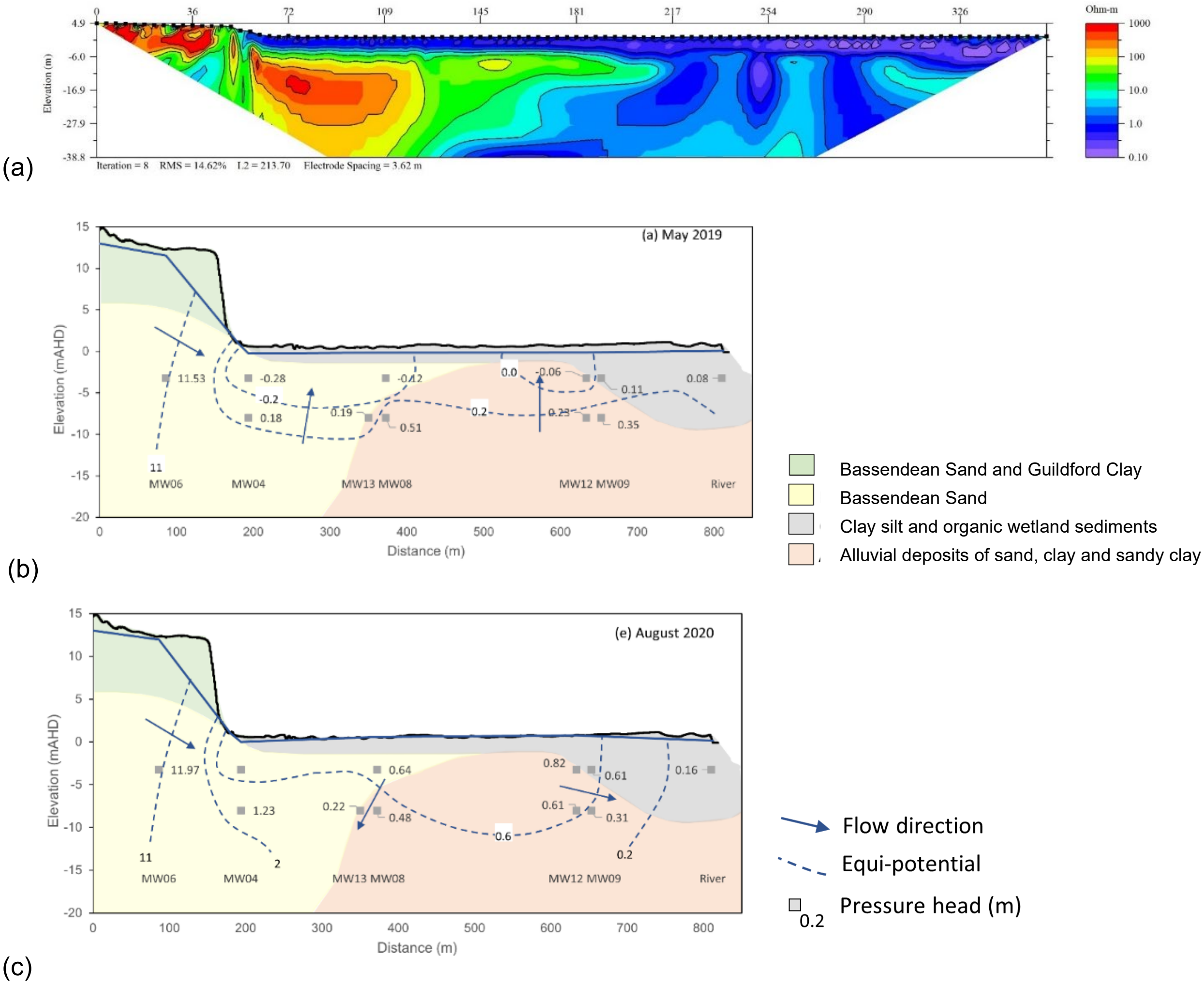


Figure 11: Resistivity geophysics survey showing a conductive thin layer of wetland sediments over resistive interbedded layers of Bassendean Sand and Guildford Clay (a); Interpreted groundwater flow directions during summer (b) and winter (c).

3.4 Water and Sediment Quality

Interpretation of groundwater chemistry suggests a progressive mixing line from northwest to southeast. The progressive increase in chloride concentration is consistent with the groundwater interpretation of autumn and winter recharge of brackish to hypersaline waters. In addition, the results suggest a significant contribution to water chemistry in pool SW03 from the flow of the Woolcock Ct Drain.

Interpretation of sulphate isotopes and the ratio of sulphate to chloride concentrations suggests sulphate reduction is occurring progressively through the wetland though complicated by regular recharge of river water bringing new sources of sulphate. Furthermore, there are indications the depletion of the heavy isotope of sulphur in upgradient groundwater and water in the Kitchener St and Woolcock Ct drains are indicative of historical groundwater pollution. Depletion of the sulphur isotope occurs from the roasting of sulphur for the production of super phosphate and sulphuric acid, as occurred historically in Bassendean. Groundwater pollution from these activities was known to have occurred (Kellenberger, 1998). Oxidation of pyrite can also lower $\delta^{34}S$ and therefore there may be a contribution from the aquifer in response to lowering of water tables, the recent drying and groundwater abstraction. (Mebus, et al., 2000).

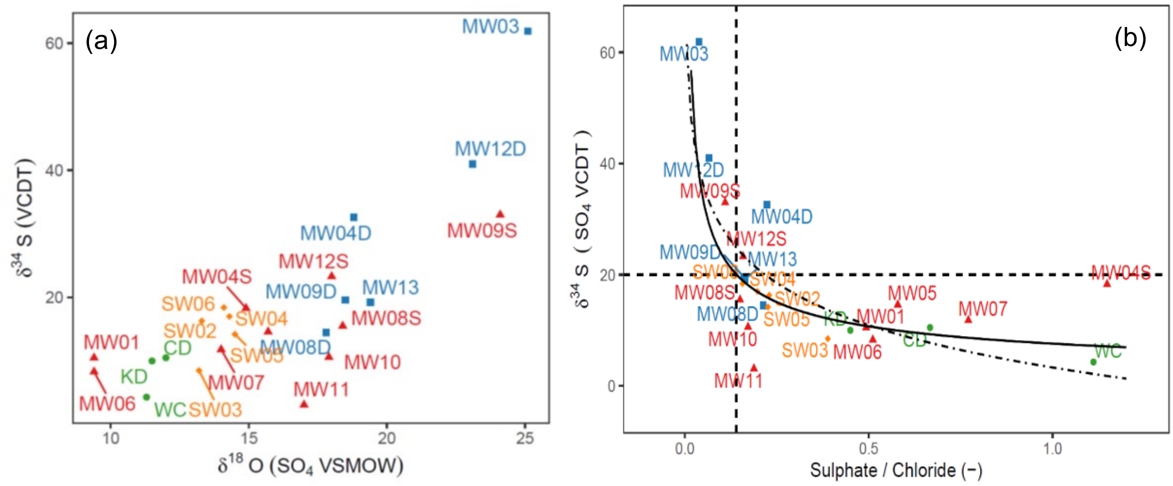


Figure 12: A positive relationship between sulphur and sulphate oxygen isotopes with sites closer to the river progressively enriched (a) and negative relationship between sulphur isotopes and the ratio of sulphate to chloride concentrations (b).

Concentrations of several metals exceeded Australian and New Zealand guidelines for fresh and marine waters (Figure 13). As surface waters are brackish to saline, the marine guidelines, where available, are likely to be more applicable. Note these guideline values are for indicative use only and site-specific values may need to be derived. Concentrations of aluminium, cobalt, copper and zinc more frequently exceeded the available marine water quality guideline vales. Zinc concentrations were particularly high in the Woolcock Ct Drain, followed by the Chapman St and Kitchener St drains. Surface waters near the outlet of the Woolcock Ct Drain (SW03) also had high zinc concentrations. Aluminium followed a similar distribution, whereas cobalt looked to be primarily sourced from the Woolcock Ct Drain and in association appeared in high concentrations at SW03. High concentrations of copper were seen in the Chapman St and Kitchener St drains, and high lead concentrations were only found in the Chapman St Drain during runoff event sampling. Relatively higher PO_4^{3-} concentrations were observed in the surface waters of the Chapman St Drain in comparison to groundwater, surface waters and other drain water. Nitrate concentrations in contrast were highest in the upgradient groundwater monitoring wells and in the pre-event drain water above Reid St in the Chapman St Drain.

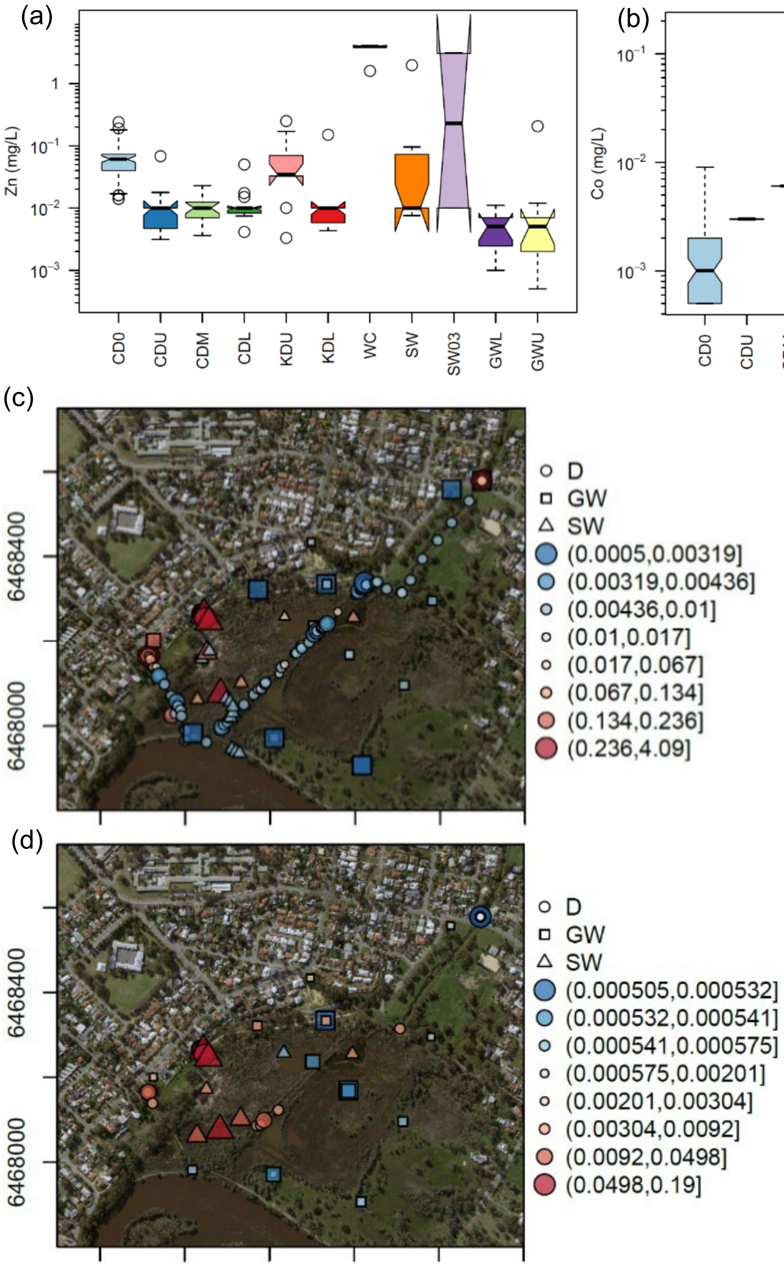
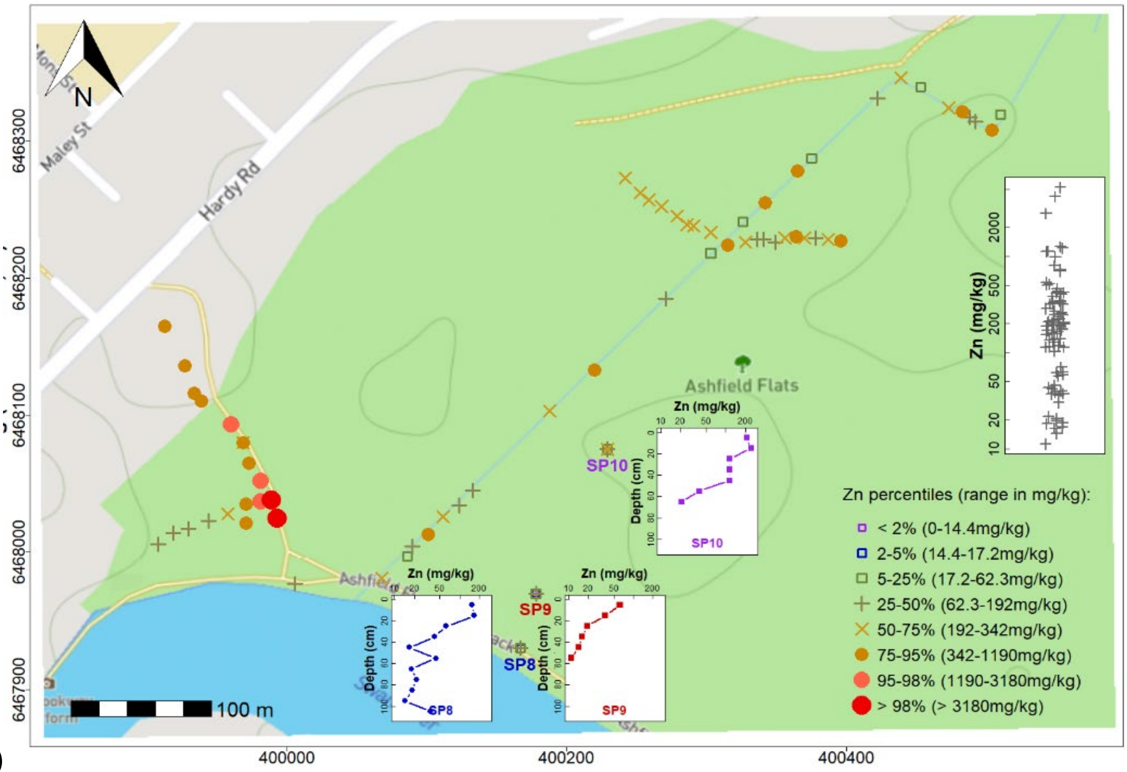


Figure 13: Distribution of Zn (a,c), and Co (b,d) concentrations in waters (mg/L) in selected parts of the Chapman St Drain (CD), Kitchener St Drain (KD), Woolcock Ct Drain (WC), surface water (SW) and groundwater (GW).

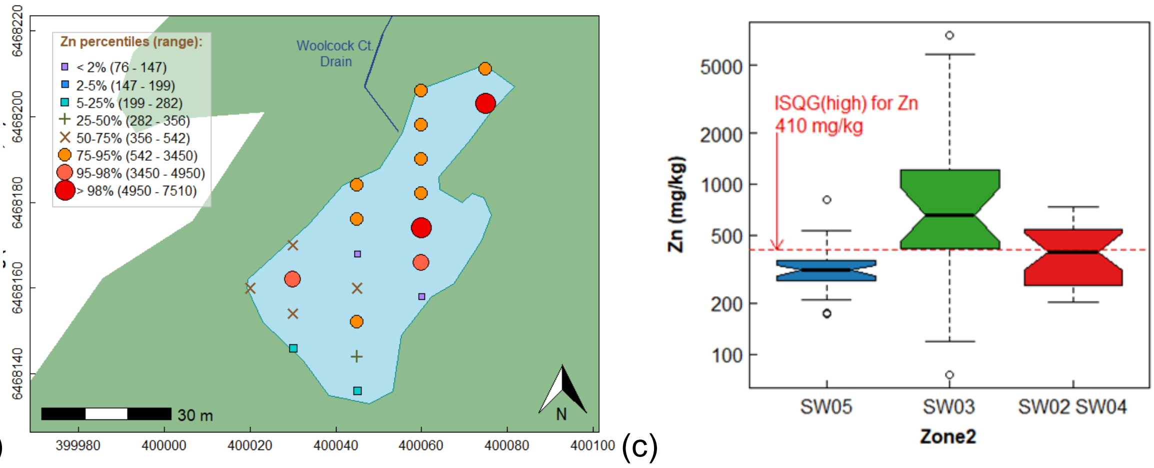
As expected, the site contains actual acid sulphate soils and potential acid sulphate soils. The sediment samples had field pH values in the range of 3.4 to 7.9. The net acidity of soil types, with the exception of shallow soils along the western boundary, exceeded the relevant DWER action management criteria. Surficial soils along the western boundary, external to the wetland/vegetated areas do not require management with respect to ASS. PASS have been identified within sediment along the length of the Chapman St Drain. The PASS is predominantly in the form of pyrite although isolated pockets of potential Monosulphidic Black Oozes (MBOs) were present in the drain based upon the acid volatile sulphur concentrations and visual observations.

A significant positive relationship between iron and sulphur was found across all sites ($p<0.001$, $R^2 = 0.13$) however, when separated by wetland zone, the relationship was strongest for the SW03 wetland (i.e. S ~1.97 Fe - 5.07, with concentration units of mg/kg, $p<0.002$, $R^2 = 0.37$) and not significant for SW02, SW04 and SW05. The strong relationship at SW03 is consistent with sulphate reduction and formation of FeS and/or FeS_2 in the sediments there.

Most sediment samples contained zinc concentrations (74 out of 78) that exceeded the Interim Sediment Quality Guidelines ISQG-Low level, and 33 samples exceeded the ISQG-High level. The high exceedances were mostly in wetland SW03. Most (56 out of 78) samples contained copper concentrations exceeding ISQG-Low, and eight samples exceeded ISQG-High, six in the SW05 wetland, and two in the SW02 SW04 zone. Many samples exceeded ISQG-Low levels for As, Pb, and Ni, but no samples exceed ISQG-High.



(a)



(b) (c)

Figure 14: Distributions of Zn across the site (a) in SW03 (b) and distributions at specific wetland pools (c).

The wetland pool SW03 appears to be a site with significant accumulation of Zn and Co likely sourced from contaminated groundwater discharged by the Woolcock Ct Drain. Salt-marshes tend to naturally accumulate metals, however there looks to be opportunities to manage the water quality from the Woolcock Ct and Kitchener St drains to mitigate potential impacts of these metals to the wetland flora and fauna.

4 Conclusions

Ashfield Flats Reserve contains the largest remaining example of the threatened Temperate Coastal Salt-Marsh Community in the Swan and Canning Estuary. The key members of the ecological community are the various halophytes, species of Tecticornia and Salicornia. Amongst the threats to this ecological community are urbanisation, pollution and climate change induced sea-level rise. The hydrological study evaluated aspects of these pressures.

Modelling also suggests that sea-level rise is a significant threat to the ecological community. In the absence of sufficient sediment accretion the system is expected to switch from an ephemerally wet salt flat to a brackish system permanently flooded and connected with the Swan River. Changes to submergence and salinity as a result will place significant challenges on the halophytes species.

There is also clear evidence of polluted groundwater discharging directly into the wetlands via urban drainage. Zinc, cobalt and several other metals exceed Australian and New Zealand Guidelines for marine waters in the discharge from that drain and elevated levels of zinc in sediments exceed interim sediment quality guidelines near the drain outlet. The wetland looks to be providing a significant ecosystem service, trapping, and storing metal-contaminated groundwater before it discharges to the Swan River. Isotope and chemical analyses of water samples is suggestive that the source of that pollution is consistent with acidified groundwater associated with the manufacture of fertilisers and/or sulphuric acid. Intervention to limit further metal impact to the wetland may be needed to maintain a healthy system though at present toxicological impacts, if any, are not known. Any future management activities that may disturb the soils, including disturbance to the urban drains may need to consider the associated potential for adverse outcomes.

References

Colmer T. D., Vos, H., and Pedersen O., (2009). Tolerance of combined submergence and salinity in the halophytic stem-succulent Tecticornia pergranulata. Annals of Botany 103: 303-312.

Colmer, T. D. and Flowers, T. J., (2008). Flooding tolerance in halophytes, New Phytologist, 179, 964-974.

Crase, B., Liedloff, A., Vesk, P. A., Burgman, M. A., and Wintle, B. A. (2013). Hydroperiod is the main driver of the spatial pattern of dominance in mangrove communities. Global Ecology and Biogeography, 22(7), 806-817.

DBCA (2019) Ashfield Flats Flora and Vegetation Report. Department of Biodiversity Conservation and Attractions, Species and Communities Program, Perth.

DBCA (2021) Ashfield Flats Hydrological Study. Department of Biodiversity Conservation and Attractions, Species and Communities Program, Perth.

Eliot, M., and Pattiaratchi, C. (2010). Remote forcing of water levels by tropical cyclones in southwest Australia. Continental Shelf Research, 30(14), 1549-1561.

English, J. P., and Colmer, T. D. (2011). Salinity and waterlogging tolerances in three stem-succulent halophytes (Tecticornia species) from the margins of ephemeral salt lakes. Plant and Soil, 348, 379–396.

English, J. P. and T. D. Colmer. (2013). Tolerance of extreme salinity in two stem-succulent halophytes (Tecticornia species). Functional Plant Biology, 40:897-912.

Estrelles, E., Prieto-Mossi, J., Escribá, M. C., Ferrando, I., Ferrer-Gallego, P., Laguna, E., ... & Soriano, P. (2018). Hydroperiod length as key parameter controlling seed strategies in Mediterranean salt marshes: The case of Halopeplis amplexicaulis. Flora, 249, 124-132.

Equinox, (2013). Fortescue Marsh: Synthesis of ecohydrological knowledge. Unpublished report to Fortescue Metals Group. October 2013, available at https://www.epa.wa.gov.au/sites/default/files/PER_documentation/1989-appendix-5e-equinox260.pdf.

Gouhier, T. C., A. Grinsted, V. Simko (2019). R package biwavelet: Conduct Univariate and Bivariate Wavelet Analyses (Version 0.20.19). https://github.com/tgouhier/biwavelet

Grinsted, A., J. C. Moore, and S. Jevrejeva (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics, 11, 561-566.

Jiao, J. J., and Z. H. Tang (1999). An analytical solution of groundwater response to tidal fluctuation in a leaky confined aquifer. Water Resources Research 35 (3), 747–751, doi:10.1029/1998WR900075.

Jay, D.A., (1991). Green's law revisited: tidal long wave propagation in channels with strong topography. Journal of Geophysical Research, 96 (20), 585–598.

Kellenberger, J. D., (1998). Ashfield groundwater contamination survey. Swan River Trust and Water and Rivers Commission, Perth, Western Australia.

Kilminster, K., and Cartwright, I. (2011). A sulfur-stable-isotope-based screening tool for assessing impact of acid sulfate soils on waterways. Marine and Freshwater Research, 62(2), 152-161.

Klaus, J., and McDonnell, J. J., (2013). Hydrograph separation using stable isotopes: Review and evaluation. Journal of hydrology, 505, 47-64.

Kukulka, T., and Jay, D. A., (2003), Impacts of Columbia River discharge on salmonid habitat: 1. A nonstationary fluvial tide model, Journal of Geophysical Research, 108(C9), 3293, doi:10.1029/2002JC001382.

Marchesini, V., Chuanhua, Y., Colmer, T. and Veneklaas, E. (2014). Drought tolerance of three stem-succulent halophyte species of an inland semi-arid salt lake system. Functional Plant Biology, 41(12), 1230-1238.

Matte, P., D. A. Jay, and E. D. Zaron (2013). Adaptation of classical tidal harmonic analysis to nonstationary tides, with application to river tides, Journal of Atmospheric and Oceanic Technology, 30(3), 569–589.

McGlynn, B. L., and J. J. McDonnell (2003). Quantifying the relative contributions of riparian and hillslope zones to catchment runoff, Water Resources Research, 39(11), 1310, doi:10.1029/2003WR002091.

Mebus, G., F.D´Amore, G.Darling, T.Paces, Z.Pang, J.Šilar (2000). Environmental Isotopes in the Hydrological Cycle, Principles and Applications, Vol. 4; Groundwater Saturated and Unsaturated Zone, p 317 – 424, International Atomic Energy Agency and United Nations Educational, Scientific and Cultural Organization

O’Callaghan, J., C. Pattiaratchi, D. Hamilton (2007). The response of circulation and salinity in a micro-tidal estuary to sub-tidal oscillations in coastal sea surface elevation, Continental Shelf Research, 27(14), 1947-1965, doi:10.1016/j.csr.2007.04.004.

Pattiaratchi, C. (2011) Coastal Tide Gauge Observations: Dynamic Processes Present in the Fremantle Record, pp 185 – 202, in Operational Oceanography in the 21st Century, ed. A. Schiller • G. B. Brassington, Springer, London, doi:10.1007/978-94-007-0332-2

Pechmann, J. H., Scott, D. E., Gibbons, J. W., and Semlitsch, R. D. (1989). Influence of wetland hydroperiod on diversity and abundance of metamorphosing juvenile amphibians. Wetlands Ecology and Management, 1(1), 3-11.

Petrone, K. C., Hughes, J. D., Van Niel, T. G., and Silberstein, R. P. (2010). Streamflow decline in southwestern Australia, 1950–2008. Geophysical Research Letters, 37(11).

Stephenson, A. G. (2016). Harmonic Analysis of Tides Using TideHarmonics. https://CRAN.R-project.org/package=TideHarmonics.

Swan River Trust (2007) Potential impacts of Climate Change on the Swan and Canning rivers, Swan River Trust, Perth, Australia.

Trefry, M. G., and Bekele, E. (2004). Structural characterization of an island aquifer via tidal methods. Water Resources Research, 40(1). W01505, doi:10.1029/2003WR002003

Turnadge, C., Crosbie, R. S., Barron, O., and Rau, G. C. (2019). Comparing methods of barometric efficiency characterization for specific storage estimation. Groundwater, 57(6), 844-859.

Veleda, D., R. Montagne, and M. Araujo (2012). Cross-Wavelet Bias Corrected by Normalizing Scales. Journal of Atmospheric and Oceanic Technology 29, 1401-1408

Wainwright, D., and Verdon-Kidd, D. (2016) A local government framework for coastal risk assessment in Australia. National Climate Change Adaptation Research Facility, Gold Coast.