Hexham Swamp Climate Change Risk and Opportunities Assessment

WRL TR 2024/22, June 2025

By T A Tucker and J Zhu

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Contents

List of tables

List of figures

1 Introduction

Hexham Swamp is a ~2,700-hectare wetland located on the south bank of the Hunter River's South Arm to the west of Newcastle (Figure 1.1). The Awabakal and Worimi peoples are the traditional custodians of Hexham Swamp, traditionally named Burraghihnbihng. Hexham Swamp includes Rocky Knob on the western floodplain which was gazetted as an Aboriginal Place in 2022. NSW Government (2022) has recognised that the Rocky Knob Aboriginal Place is important to local Aboriginal people "as a place of spiritual connection and ceremony" and "a place where cultural practices and stories can be passed on to future generations."

The tidal connectivity between Hexham Swamp and the estuary was reduced in 1971 due to the construction of floodgates on Ironbark Creek (Winning and Saintilan, 2009). Drainage of the wetland resulted in dramatic changes to the vegetation including the loss of almost 800 hectares of saltmarsh and mangrove habitat (Winning and Saintilan, 2009). In 2008, the Hexham Swamp Rehabilitation Project was implemented and the reintroduction of tidal flows began over a three stage process (HLLS, 2021). Implementation of the project was completed in May 2013 with the successful opening of the floodgates on Ironbark Creek. Ongoing monitoring of the wetland has continued throughout the project to measure the progressive reestablishment of tidal wetland habitat. A recent vegetation survey recorded 109 hectares of saltmarsh habitat, 185 hectares of mangrove habitat, and a decline in phragmites from 1,005 hectares prior to opening, to 763 hectares in 2021 (King, 2021). Survey data indicates that tidal wetland habitat extent continues to expand across the wetland.

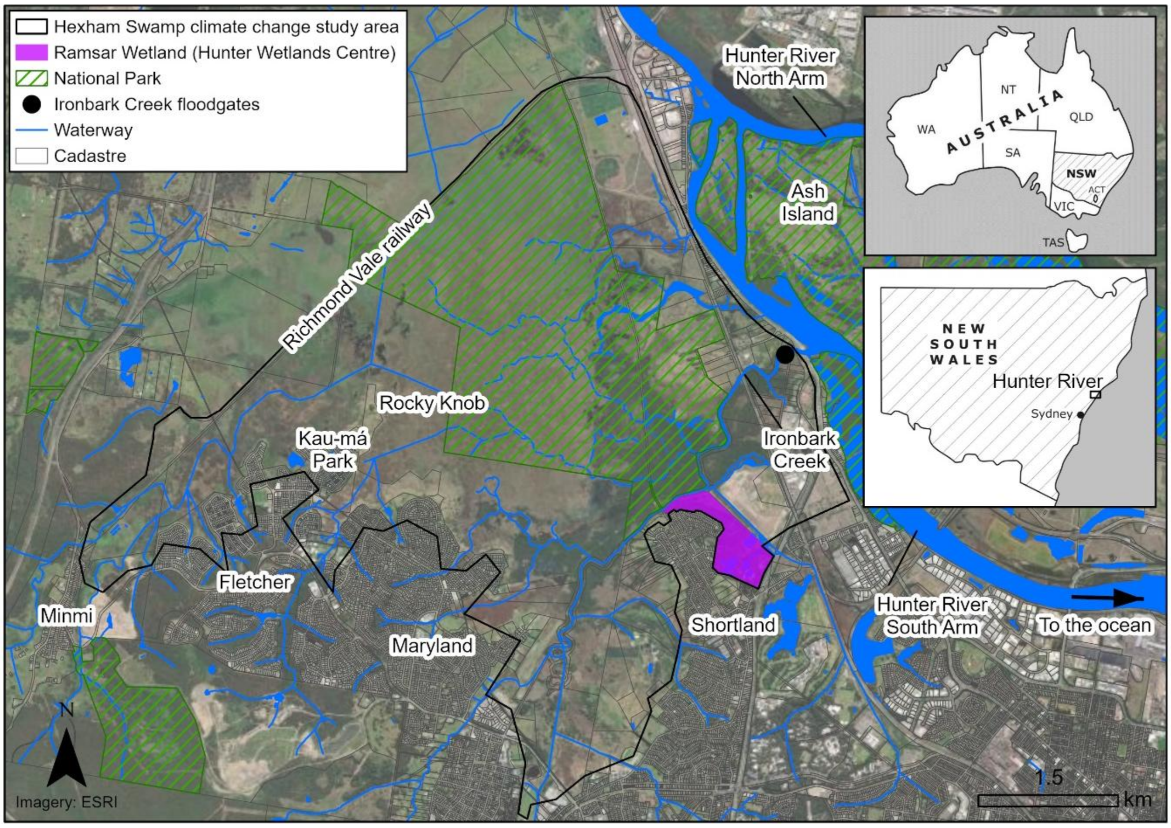

Figure 1.1 Hexham Swamp study site

Hexham Swamp is an important natural asset on the lower Hunter River that forms part of the Hunter Wetlands National Park and includes areas recognised under the Ramsar Convention on Wetlands. Hunter Local Land Services (HLLS), along with the NSW National Parks and Wildlife Services (NPWS) are the current land managers for a large proportion of the wetland. Following the success of the Hexham Swamp Rehabilitation Project (Boys and Fowler, 2022), and recognising its importance, HLLS are seeking to understand the risks and opportunities that the wetland will face under a changing climate.

Into the future, climate change caused by the anthropogenic release of greenhouse gases to the atmosphere will have a significant impact on coastal environments such as estuaries and wetlands. These environments will be doubly impacted, facing changes from the ocean (e.g. sea level rise) as well as the upper catchment (e.g. more extreme rainfall) (Heimhuber et al., 2019c). Proactive planning at sites like Hexham Swamp will ensure that the impacts of climate change can be managed. Furthermore, opportunities which arise as a result of climate change can be planned for to ensure that the natural values of Hexham Swamp are retained and where possible promoted into the future.

The following report provides a high-level hydrological risk and opportunity assessment for Hexham Swamp to assist HLLS and other land managers to ensure the values provided by the wetland continue into the future. This report has been divided into the following sections:

- **Section 1** (this section): an overview of the study site and rationale behind this investigation.
- **Section 2**: a conceptual understanding of the wetland processes. This considers present day processes, the continued expansion of the tidal wetland, and the pressure that the wetland will face under climate change. This conceptual understanding provides an important foundation for the hydrological risk and opportunity assessment.
- **Section 3**: the findings of the hydrological climate change risk and opportunity assessment.
- **Section 4**: recommendations based on the outcomes of the hydrological risk and opportunity assessment and broader literature and data review completed during this investigation.
- **Section 5**: a list of references used throughout this investigation.
- **Appendix A**: a literature and data review that was used to inform the conceptual understanding of wetland processes.
- **Appendix B**: a summary of a site inspection conducted on 6 June 2024
- **Appendix C**: the framework used to complete the hydrological climate change risk and opportunity assessment.

2 Conceptual understanding of Hexham Swamp

2.1 Preamble

The following section provides a conceptual understanding of the wetland processes for Hexham Swamp. The conceptual understanding is primarily based upon a scientific understanding of the physical processes influencing the wetland habitat on a floodplain scale. This analysis reviewed historical numerical modelling results but did not include any new numerical modelling. A literature and data review has been completed to inform the conceptual understanding (Appendix A). This appendix provides technical detail regarding the conceptual processes. A site inspection was also conducted to inform the conceptual understanding. Details regarding the site inspection is provide in Appendix B.

Understanding that Hexham Swamp is still adapting to the changes in hydrology initiated through the restoration project, a conceptual understanding has been provided for the following three conditions:

- Current wetland (Section 2.2): Describing the present-day processes influencing the wetland.
- Tidal wetland re-establishment (Section 2.3): Describing how the wetland processes continue to change habitat across the wetland as a result of the Hexham Swamp Rehabilitation Project.
- Climate change (Section 2.4): Describing how climate change will influence the wetland processes in the future.

2.2 Current wetland processes

Figure 2.1 provides a summary of the current wetland processes for Hexham Swamp. This highlights two key hydrological drivers for the wetland:

1. Catchment hydrology: Rainfall is the primary source of freshwater for Hexham Swamp. Rainfall tends to be seasonal (with increased rainfall from December to April). Rainfall also varies significantly on a decadal (El Niño Southern Oscillation) and interdecadal (Interdecadal Pacific Oscillation) scale. This means the hydrology across the wetland will have significant variance across both short and medium timeframes.
2. Ocean tides: Hexham Swamp is connected to the ocean via Hunter River at three locations (Ironbark Creek, Hartin’s Creek, and another connection further north). The majority of flow between the wetland and downstream estuary occurs through Ironbark Creek. Tidal inflows are a source of saline water that allow for the establishment of tidal wetland habitat.

2.3 Tidal wetland re-establishment

Figure 2.2 provides a description for key processes that will influence how Hexham Swamp continues to evolve as a result of tidal restoration. Analysis of vegetation survey data indicates that the extent of tidal wetland habitat continues to expand. This will continue for the foreseeable future until an equilibrium condition occurs. Note, due to climate variability the interface between freshwater and tidal wetland habitat will always fluctuate. However, in the absence of climate change, a point would eventually be reached whereby the tidal limit would fluctuate around a median wetland extent, rather than continuing to increase as is currently being observed. Key influences on the ongoing establishment of tidal wetland habitat, include:

- **Vegetation lifecycle:** Recent research has shown that the establishment of mangroves can be predicted though modelling their lifecycle (Henderson and Glamore, 2024a). Traditionally, tides have been used to predict mangrove extent (e.g. Hughes et al. (2022) and Wen et al. (2023)), however, this has been shown to be only one indicator for habitat extent (Henderson and Glamore, 2024b). Instead, the recent research by Henderson and Glamore (2024a) found that inputs including reproduction, seed dispersal, plant establishment, and plant development needed to be considered to predict mangrove extent. Key environmental inputs into the Henderson and Glamore (2024a) model also include season, tide data, evapotranspiration, and flood levels. Saltmarsh habitat is expected to be similarly influenced by environmental drivers including sea level, sediment supply, erosion, freshwater input, human influences, and competition with other vegetation (Adam, 2002).
- **Climate:** For tidal wetland habitats (saltmarsh and mangroves) to establish, they will need to outcompete existing vegetation such as phragmites. One key adaptation feature of coastal wetland habitats is their capacity to withstand high salinity conditions, unlike freshwater vegetation. Analysis of salinity data within Hexham Swamp indicates that sustained high levels of salinity only occur during drier conditions (as rainfall can dilute or flush saltwater from the system). Subsequently, further establishment of tidal wetland habitat is only likely to occur seasonally when high levels of salinity in the wetland favour their establishment. Once they are established, tidal wetlands can continue to persist for long durations in areas where saltwater is diluted or flushed from the system (Henderson and Glamore, 2024a).

2.4 Climate change processes

Figure 2.3 provides a summary of the wetland processes that will influence Hexham Swamp due to climate change (for additional details refer to Appendix A4). The five physical climate processes considered in this study are:

- Changes to rainfall
- Sea level rise
- Changes to temperature and evapotranspiration
- Changes to ocean acidification
- Changes to wind

Changes to rainfall, sea level rise, and changes to temperature/evapotranspiration are expected to have the largest impact on Hexham Swamp. Comparatively, changes to ocean acidification and wind are expected to have relatively minor impacts on Hexham Swamp.

Each of these first order processes are expected to have a range of flow on effects for Hexham Swamp. The scale and range of these flow-on effects will vary depending on how the world responds to climate change. Some key changes that can be expected as a result of climate change that will significantly influence Hexham Swamp include:

- **Average rainfall:** In the near future, it is unlikely that the influence of climate change will be discernible from natural climate variability. In the far future, there is medium confidence that winter rainfalls will decrease. Summer rainfall is expected to increase under high emission scenarios, however, there is low confidence in these estimates and significant uncertainty remains.
- **Extreme rainfall:** Extreme rainfall events are predicted to become more intense into the future. That is, an event with the same recurrence period will result in an increased volume of rainfall.
- **Sea level rise:** Sea level rise is forecast to occur under all future scenarios. The scale of sea level rise will depend on the world's response to climate change. Between 0.38 m and 0.82 m of sea level rise is expected (compared to 1995 to 2014 baseline) by the year 2100.
- **Temperature and evapotranspiration:** Temperature and evaporation are both expected to increase under climate change. This will have flow-on effects to the biogeochemistry in Hexham Swamp and also the establishment of tidal wetland habitat.

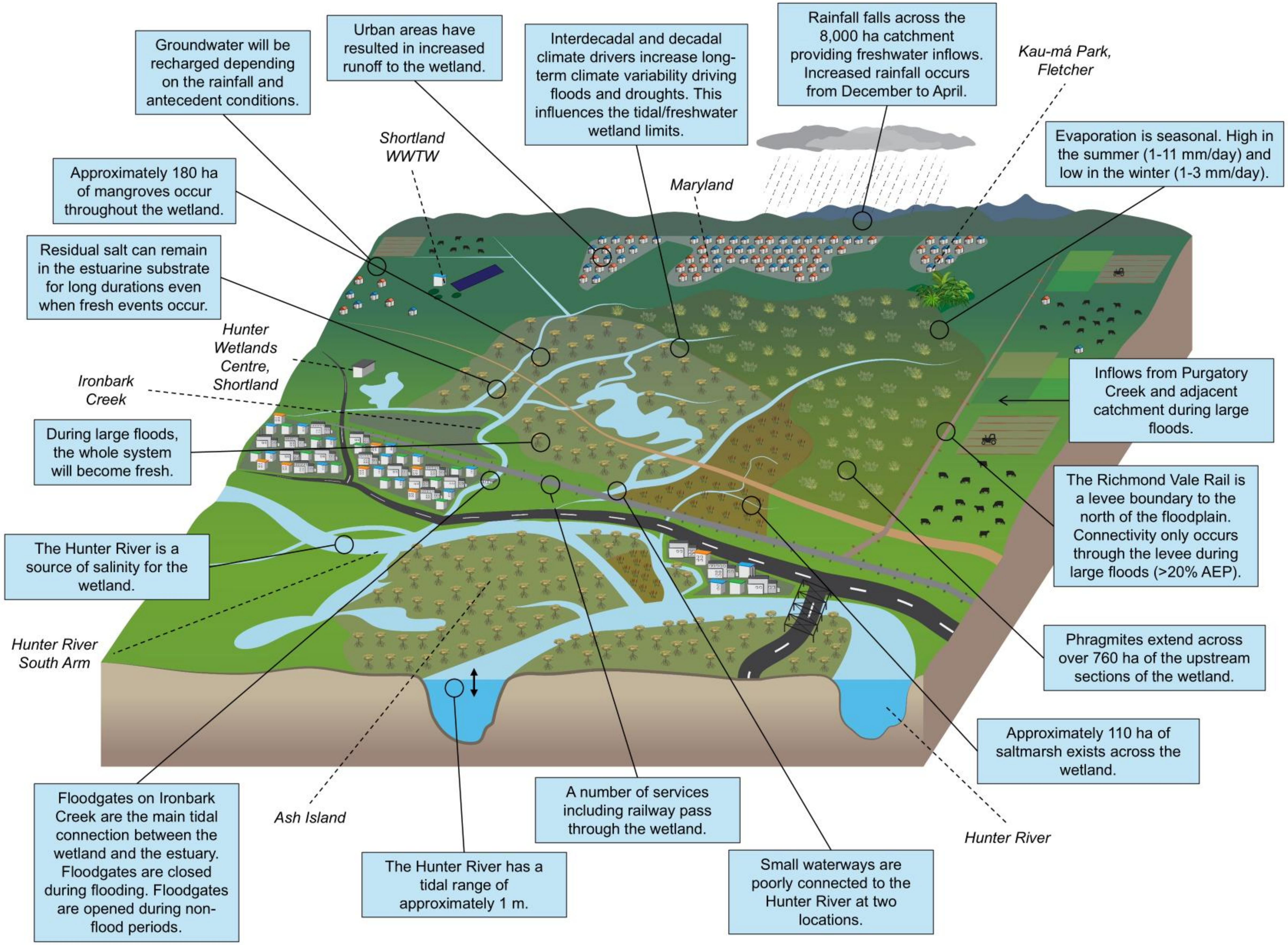

Figure 2.1 Current wetland processes at Hexham Swamp

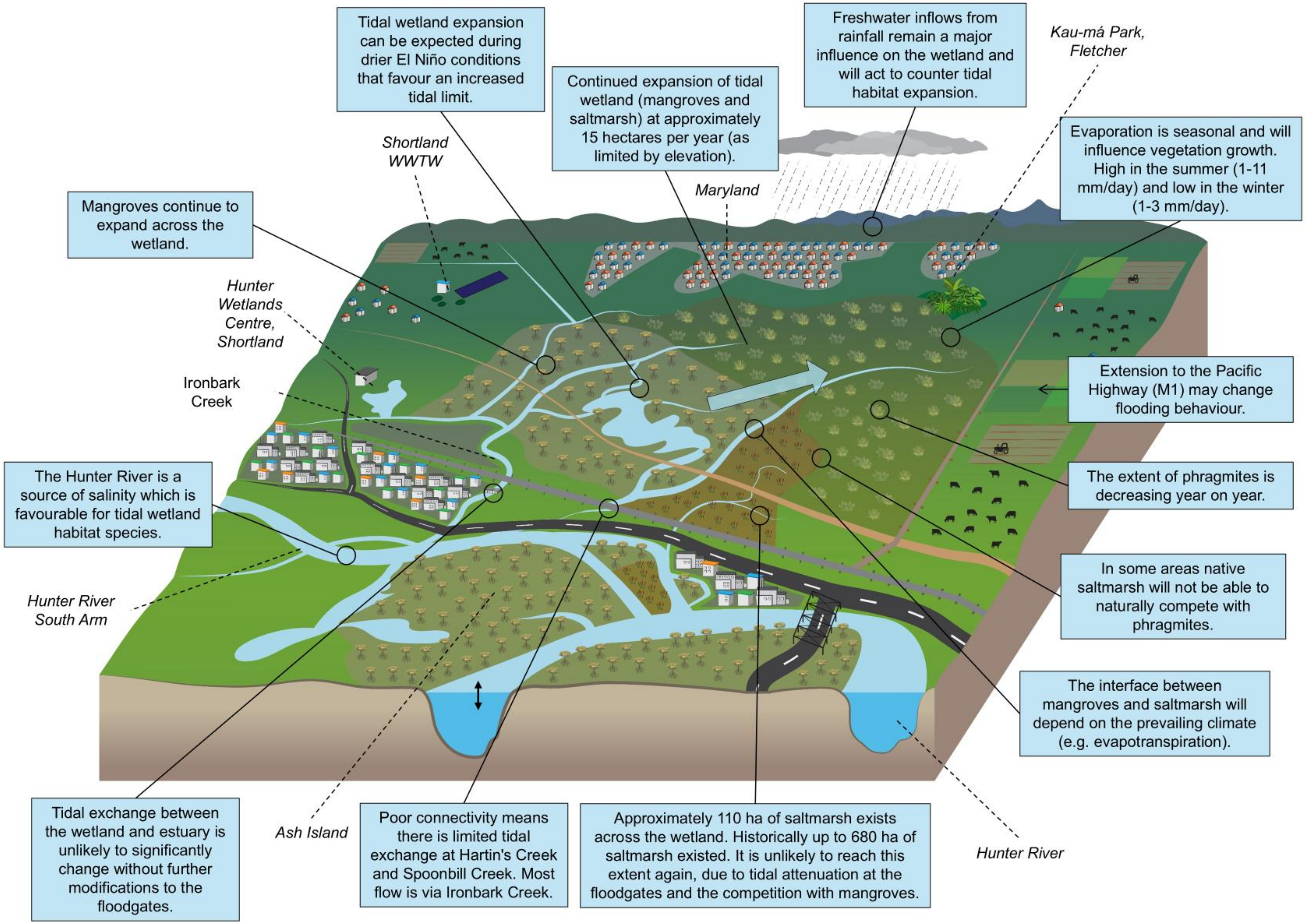

Figure 2.2 The continued establishment of tidal wetland habitat at Hexham Swamp in the near future based on existing data; approximately 2035

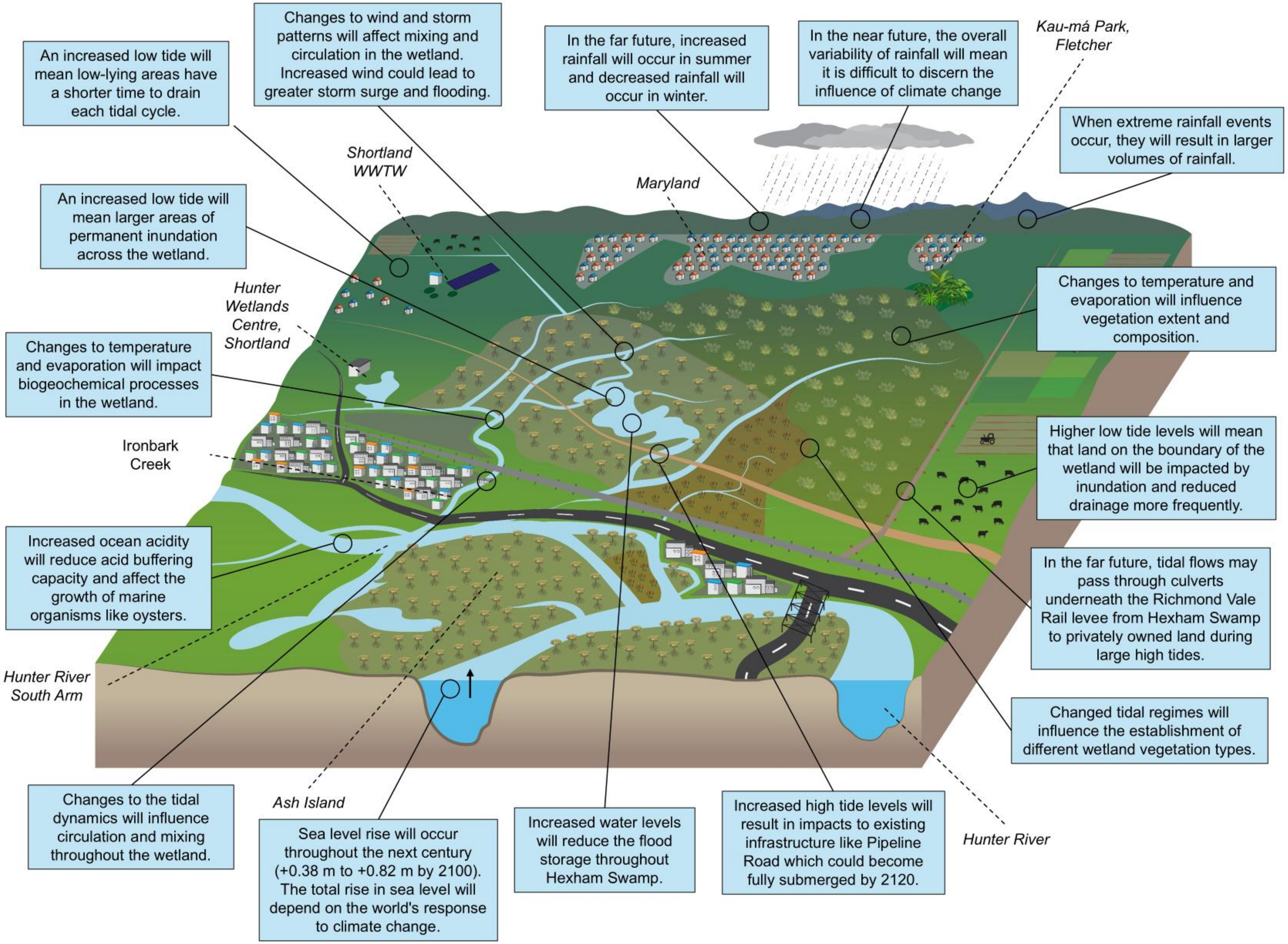

Figure 2.3 Influence of climate change on wetland processes at Hexham Swamp into the far future; approximately 2050 to 2100

3 Hydrological climate change risk and opportunity assessment

3.1 Preamble

A hydrological climate change risk and opportunity assessment has been completed to inform the future management of Hexham Swamp. The assessment has been completed by assessing how the ecosystem services provided by Hexham Swamp will be influenced in the future due to climate change. Ecosystem services identified for Hexham Swamp are outlined in Section 3.2. Following this, Section 3.3 outlines the results of the hydrological risk and opportunity assessment. Details regarding the assessment methodology, including the mapping of climate change impacts to ecosystem services is outlined in Appendix C.

Note, in addition to impacting ecosystem services, climate change will have impacts on built infrastructure at Hexham Swamp. This includes assets such as access tracks, walking paths, floodgates and culverts, and the Hunter Wetlands Centre. For example, sea level rise will result in increased or permanent inundation of access tracks. While the focus of this assessment has been on the wetland values, the utility of these built assets and costs to maintain them (including potential impacts to ecosystem services) should be considered alongside ecosystem services when future planning for Hexham Swamp.

3.2 Ecosystem services

Coastal environments provide a range of ecosystem services. Utilising the framework provided by Haines-Young and Potschin (2018), ecosystem services provided by Hexham Swamp have been identified (Table 3.1). These ecosystem services have then formed the basis of the hydrological risk and opportunity assessment.

Table 3.1 Ecosystem Services provided by Hexham Swamp (adapted from Haines-Young and Potschin (2018))

Service type	Definition	Subservices relevant for Hexham Swamp
Provisioning	Products derived from ecosystems	Food (e.g. commercial fisheries)
Regulation and maintenance	Benefits derived from the regulating capacity of ecosystems processes	Climate regulation (e.g. carbon sequestration) Habitat and biodiversity support (e.g. maintaining key fish nursery areas, important bird habitat, and/or natural seed banks) Mitigation of extreme events (e.g. flood mitigation) Regulation of soil quality (e.g. acid sulfate soils) Regulation of water quality (e.g. nitrogen removal)
Cultural	Non-material benefits from ecosystems	Enabling education and research Cultural heritage, existence and spiritual value Tourism and recreational use (e.g. bird watching and recreational fishing)

3.3 Hydrological risk and opportunity assessment

Climate change will pose a range of risks and opportunities to the ecosystem services provided by Hexham Swamp. Table 3.2 summarises the risks and opportunities for Hexham Swamp. This highlights key areas that should be considered in future planning for Hexham Swamp. A detailed breakdown of the hydrological risk and opportunity assessment methodology is provided in Appendix C.

Table 3.2 Risk or opportunities for Hexham Swamp's ecosystem services under climate change

Ecosystem service	Risk or opportunity	Range of risks or opportunities[1]
Food	Extreme opportunity	Climate change will result in an increase in tidal wetland habitat which supports commercial fisheries.
Climate regulation	Extreme opportunity	Climate change will result in an increase in tidal wetland habitat which is a natural carbon sink.
Habitat and biodiversity support	Extreme opportunity Extreme risk	There will be large increases in tidal wetlands and subsequently habitat/biodiversity as a result of climate change. The habitat and biodiversity support provided by freshwater wetlands will be significantly reduced as a result of climate change.
Mitigation of extreme events	Extreme risk	The flood storage currently provided by Hexham Swamp will be reduced in the future due to sea level rise. The reduction in flood storage may be exacerbated by changes to the catchment inflows due to climate change (e.g. more intense events) as well as catchment development.
Regulation of soil quality	High opportunity	The service provided by Hexham Swamp to mitigate the impacts of acid sulfate soils will increase due to sea level rise.
Regulation of water quality	Medium opportunity Medium risk	Sea level rise will mean Hexham Swamp can better regulate the impacts of acid sulfate soils. Increased temperature will reduce the level of oxygen in the water column and ability for the wetland to regulate water quality.
Enabling education and training	Unknown	While there are ongoing educational and training opportunities offered through HLLS and the Hunter Wetlands Centre, there is insufficient information linking hydrological changes to this ecosystem service. Further research is required to map physical or ecological changes to this service and understand the risks/opportunities.
Cultural heritage, existence and spiritual value	Unknown	There is clear evidence that Hexham Swamp provides valuable ecosystem services by enabling cultural heritage, existence and spiritual value. There is insufficient information linking hydrological changes to this ecosystem service. Further research with key stakeholders is required to map physical or ecological changes to this service and understand the risks/opportunities.
Tourism and recreational use	Extreme opportunity Extreme risk	There will be large increases in tidal wetlands due to climate change. This will be positive for recreational fishing and tourism (e.g. bird watching). There will be a large decrease in freshwater wetlands due to climate change. This poses a risk to tourism (e.g. bird watching) where there are habitat shifts.

[1]See Appendix C for detailed referenced explanation.

4 Management recommendations

4.1 Overview

Several recommendations for the future management of Hexham Swamp have been developed using the conceptual understanding of Hexham Swamp's hydrology and the subsequent climate change risk and opportunity assessment. The following section outlines each of these recommendations.

4.2 Recommendation 1: Implement climate change adaption and management activities

Historically, data collection at Hexham Swamp has focused on the implementation and monitoring of the Hexham Swamp Rehabilitation Project. Following the successful completion of this project, monitoring of water levels and salinity inside the wetland was discontinued (the last measurements were in 2016). While existing vegetation monitoring provides valuable insights into the long-term changes occurring across the site, it is recommended that this be supplemented with continuous water level and salinity monitoring. A monitoring program that includes water level and salinity monitoring could provide valuable information regarding the wetland's response to a changing climate.

Salinity and water level measurements would serve two purposes. First, this type of data can provide detailed high-frequency information on the hydrology within Hexham Swamp. This would include:

- Understanding how the wetland stores water (especially tidal water)
- Understanding flow behaviour throughout the wetland system (and monitoring if it is changing)
- Providing evidence as key drivers of wetland habitat (e.g. La Nina / El Nino will influence water levels and salinity data that could indicate that vegetation change is imminent allowing advanced planning)
- Measuring wetland changes which are occurring because of underlying seasonal variability or climate change (i.e. supporting vegetation survey data with hydrological data)

Secondly, water level and salinity data are important inputs when developing models that can be used to predict hydrological and ecological changes. By pre-empting these changes (e.g. changes to flow patterns, water levels or vegetation), informed management actions can be developed to safeguard ecosystems services.

The number and location of water level and salinity sensors would depend on available funding. It is recommended, as a first pass, that one station be established in the open water west of Pipeline Road near Hartin's Track, and one station be established within Ironbark Creek upstream of the floodgates.

Floodplain elevation data is important for understanding the hydrology throughout Hexham Swamp. While there have been several LiDAR surveys conducted over the years, they are not well suited to capture the ground elevation within the wetland habitat. Future efforts should instead focus on survey approaches that are not influenced by vegetation density or ponding of water to determine the wetlands true surface elevation. For example, Real Time Kinematic (RTK) GPS survey equipment which uses satellite positioning to measure the ground surface elevation at a discrete location identified by a surveyor could be used. This, coupled with high frequency water level data, would provide valuable information on how much water is entering and leaving the swamp in a tidal cycle, and where the significant flow paths are.

4.3 Recommendation 2: Investigate the future connectivity of Ironbark Creek with the estuary

The ecosystem services provided by tidal wetland habitat were identified to be a significant opportunity for Hexham Swamp. Currently, the floodgates are maintained on Ironbark Creek to exclude minor flood events originating in the Hunter River up to 1.8 m AHD (Haines et al., 2005). This is just below the 10% annual exceedance probably (AEP) flood event which peaks at 1.88 m AHD across Hexham Swamp (Smith, 2008). Under climate change, extreme rainfall events will occur more frequently meaning the floodgates will need to be closed more often to achieve the current flood mitigation objectives. Furthermore, sea level rise will pose a major risk to the flood storage capacity of Hexham Swamp that will be exacerbated by changes to catchment rainfall (i.e. more extreme rainfall events) and catchment development. The reduced ability to mitigate extreme events was identified as a risk for Hexham Swamp under climate change.

Into the future, work will need to take place to manage flood risks across Hexham Swamp and the greater lower Hunter region in the face of a changing climate. This presents an opportunity to reassess the purpose of the Ironbark Creek floodgates which will be impacted by sea level rise (Waddington et al., 2022; Smith and Simpson, 2019; Glamore et al., 2021), changes to catchment rainfall (Dowdy et al., 2015), and catchment development. In addition to assessing flood risk, an analysis should be completed to determine the level of flood protection provided by the floodgates. This should consider the value of flood protection provided by the floodgates weighed against the value of tidal wetland habitat. Note, the Ironbark Creek floodgates are an asset managed by the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) through the Hunter Valley Flood Mitigation Scheme (HVFMS). It is recommended that ongoing management of the Ironbark Creek floodgates consider the environmental benefits provided by Hexham Swamp.

Flood risk is an important issue for the local community. At all stages throughout the investigations the community should be consulted. Consultation should include communication and education regarding sea level rise, the implications this has on flooding, and the values provided by Hexham Swamp.

Sea level rise will impact all connections between Hexham Swamp and the Hunter River (see Appendix A2.5). In addition to assessing the connectivity through Ironbark Creek, it is also recommended that connectivity through other locations (i.e. Hartin's Creek and Spoonbill Creek, see Appendix A2.5) be investigated to understand the potential influence of sea level rise.

4.4 Recommendation 3: Develop a plan for habitat change

For a number of ecosystem services (habitat and biodiversity support, regulation of water quality, and tourism and recreational use), risks and opportunities were identified. In these circumstances a trade-off will be required (e.g. freshwater wetland habitat in lieu of tidal wetland habitat). The importance of these trade-offs should be acknowledged. If maximising ecosystem services is deemed to be important, a plan should be established to determine the preferred trade-off between each ecosystem type (note, this will need to consider typical wet/dry seasonality that influences the interface between tidal and freshwater habitat). When rationalising this trade-off, the costs and feasibility of each option should be considered. For example, maintaining freshwater wetlands into the future under sea level rise may become increasingly expensive. The current management strategy is to allow the wetland to naturally self-design, however, any updated strategies should also consider climate change.

Where appropriate, existing plans could be utilised to inform the development of the plan (e.g. Haines (2012)). This will ensure historical knowledge is captured within an updated plan that now considers climate change. Suggested items for inclusion within the action plan include:

- Clear identification of preferred targeted habitat types and extent under various climate scenarios (e.g. different ranges of sea level rise).
- Consultation with relative experts and stakeholders to confirm that the current restoration strategy as a self-designing system remains appropriate under future climate scenarios.
- Appropriate monitoring (e.g. water levels) to inform the adaptive management (noting that existing monitoring programs exist, i.e. vegetation monitoring within the Hexham Swamp Rehabilitation Project which may already achieve some of these outcomes).
- Regular consultation with appropriate subject matter experts (e.g. the Ecosystems and Threatened Species group within the Hunter Central Coast Branch of NSW Department of Climate Change, Energy, the Environment and Water).

4.5 Recommendation 4: Future land use planning

The existing wetland boundary was established considering present day sea levels. As sea level rise occurs, land located above the current wetland boundary will become vulnerable to inundation and reduced drainage (Waddington et al., 2022; Harrison and Tucker, 2024). An opportunity exists now to identify areas that will be susceptible to sea level rise and plan how they can be managed into the future. Indeed, this was recently investigated by the Hunter Estuary Alliance (HEAL) for the Hunter River estuary Coastal Management Program (CMP). As part of the risks, vulnerabilities and opportunities assessment completed for the CMP, Harrison and Tucker (2024) provided a first pass assessment which identifies over 100 hectares of land that will be moderately or majorly impacted in the near future. It is likely that these findings will lead to actions during the final implement, monitor, evaluate and report stage of the CMP. For example, a similar investigation could be completed on a local scale to inform the specific management of Hexham Swamp. A staged planning approach, which considers areas likely to be impacted by sea level rise first, would allow for the proactive management to maximise the ecosystem services into the future.

Any planning assessments like this should also consider the future development of the suburbs surrounding Hexham Swamp. In addition to sea level rise reducing flood storage, climate change will influence the variability of rainfall events causing high intensity events to occur more frequently (Dowdy et al., 2015). Furthermore, as the catchment is developed and permeable surfaces replaced with impervious surfaces like roads and roofs, the impacts of catchment rainfall can be exacerbated. These impacts have the potential to flow into Hexham Swamp and should be a key consideration when assessing the wetland boundaries, its flood mitigation services, and the subsequent land zoning.

Note, land outside of the Hexham Swamp study area (e.g. Black Hill to the northwest on the other side of the Richmond Vale railway) provides an opportunity for lateral expansion of the wetland. When planning the future of Hexham Swamp, significant opportunities (like expansion to Black Hill) should be assessed alongside the risks posed by sea level rise.

4.6 Recommendation 5: Investigate social and cultural impacts of climate change and continue to engage with the local community

This investigation has identified how climate change will result in physical changes across Hexham Swamp and the subsequent risks and opportunities. It is unclear how climate change will affect social and cultural values of Hexham Swamp, such as the ecosystem services it provides regarding enabling education and training, and cultural heritage, existence and spiritual value. It is recommended that investigations be completed to understand the risk or opportunities associated with these ecosystem services.

There is already an excellent record of community engagement and education at Hexham Swamp through HLLS, the Hunter Wetlands Centre and a long-standing partnership with the Hunter Bird Observers Club. It is important that changes resulting from climate change continue to be clearly communicated to the local community that will be affected. This will be especially true where impacts that result from climate change could be incorrectly associated with historical project activities from the Hexham Swamp Rehabilitation Project.

Specific investigations that could be implemented to address this recommendation may include:

- Develop a forum for land managers (e.g. HLLS, NPWS, Hunter Water, Awabakal Stakeholders, local residents, Landcare, the Hunter Bird Observers Club, and the Hunter Wetlands Centre) to collaboratively engage with one another to ensure a unified approach to manage climate change. This could be implemented through a range of pathways such as regular email newsletters or flyers, community events (such as information days), or individual knowledge exchange programs.
- Consult with the Awabakal Stakeholders to better understand the impact of sea level rise on the Rocky Knob Aboriginal Place.
- Engage with the Hunter Bird Observers Club to assess how climate change will affect recreational birdwatching at Hexham Swamp and implement the shorebird action plan for Hexham (Formby et al., 2020).
- Consult with local fishers to determine how climate change will affect recreational fishing linked to Hexham Swamp (Taylor et al., 2018; Taylor et al., 2024).

It is likely there will be ongoing opportunities to engage with social and cultural interests to assist with the management of Hexham Swamp under a changing climate. For example, as outlined in Formby et al. (2020), local birdwatching groups can provide valuable data regarding the local bird population in response to a changing climate. Since the impacts of climate change are inevitable, early and proactive planning that involves the local community and Awabakal Stakeholders will be required to minimise risks and maximise opportunities posed by climate change. This will ensure the ecosystem services provided by Hexham Swamp are valued, maintained and expanded into the future.

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Appendix A Literature and data review

A1 Preamble

An extensive number of investigations have been completed to characterise the physical processes at Hexham Swamp. A large proportion of these investigations were completed prior to restoration in order to inform the restoration of the wetland (Haines et al., 2005). Since restoration activities (which occurred in three stages from 2008 to 2013) there has been ongoing research to monitor the restoration progress (HLLS, 2021). In many instances, recent environmental data has also been collected by government organisations and can be used to characterise wetland processes (MHL, 2024a; Jeffrey et al., 2001). Hexham Swamp has also been a key study site for many research articles which add further insight into the wetland processes (Haines, 2013; Winning and Saintilan, 2009; Rogers et al., 2013).

The following appendix provides a review of available literature and data of physical processes as relevant for the current state (Appendix A2), a hypothetical equilibrium state (Appendix A3), and a future wetland influenced by climate change (Appendix A3.4). This information has then been used to develop the conceptual diagrams of the wetland processes presented in Section 2 of this report.

A2 Current wetland processes

A2.1 Local catchment hydrology

During day-to-day conditions, rainfall is the primary source of freshwater inflows to Hexham Swamp. This includes direct rainfall over the wetland area (~2,750 ha) and rainfall over the local catchment which flows into Hexham Swamp. The total catchment area (including the wetland and its local catchment) is approximately 8,000 ha (see Figure A.1). Note, another 4,000 ha to the east of the Richmond Vale Rail Trail is connected with Hexham Swamp during large floods (>20% AEP). Connectivity of the floodplain on either side of the Richmond Vale Rail Trail is limited by three culverts (Figure A.2). As part of the Hexham Swamp Rehabilitation Project a series of bunds were proposed adjacent to these culverts to prevent tidal connection between Hexham Swamp and the privately owned land on to the east. The design was aimed to limit tidal connectivity while still allowing floodwater to flow from east to west into Hexham Swamp. HLLS (2021) noted that these bunds were constructed and were effectively limiting tidal connectivity between each side of the Richmond Vale Rail Trail.

Limited groundwater data is available to understand its contribution to catchment inflows during day-to-day conditions. Investigations of groundwater have generally focused on the floodplain and understanding acid sulfate soils (RCA, 1998). Regional groundwater contours were identified by TfNSW (2021) and indicate that groundwater generally travels from west to east across the site (Figure A.3). An exception to this occurs at the northeast of the site where a former coal tailings stockpile is associated with raised groundwater levels. Conceptually, it is expected that following rainfall, the regional aquifer surrounding Hexham Swamp would recharge and provide a baseflow into the wetland. The rate of this flow would reduce depending on antecedent rainfall. Development of the catchment has reduced the groundwater recharge as impervious surfaces such as roofs and roads result in increased direct runoff into the local stormwater network rather than infiltration (Haines, 2013).

Generally, large scale flooding is driven by the Hunter River spilling its banks and not through local catchment inflows (Smith, 2008; TfNSW, 2021). East coast low events can cause increased tidal levels and localised flash flooding at Hexham Swamp, however, this is generally localised and inundation is limited to below 1.8 m AHD (Haines et al., 2005). During large floods the entire wetland system will become fresh. Flooding like this is generally event based and once floodwaters have receded, the interface between tidal and freshwater areas of Hexham Swamp will be governed by the local catchment inflows (i.e. tidal intrusion increases as freshwater inflows decrease). The Ironbark Creek floodgates are generally managed for flood mitigation purposes although they may also be closed to manage mosquitos (Haines, 2011; Haines, 2012). The opening and closing of the floodgates are managed by the Hunter Valley Flood Mitigation Scheme (HVFMS). The floodgates are kept open during day-to-day conditions and closed when there is a flood warning for the Hunter River (pers. comms. C. Skerda).

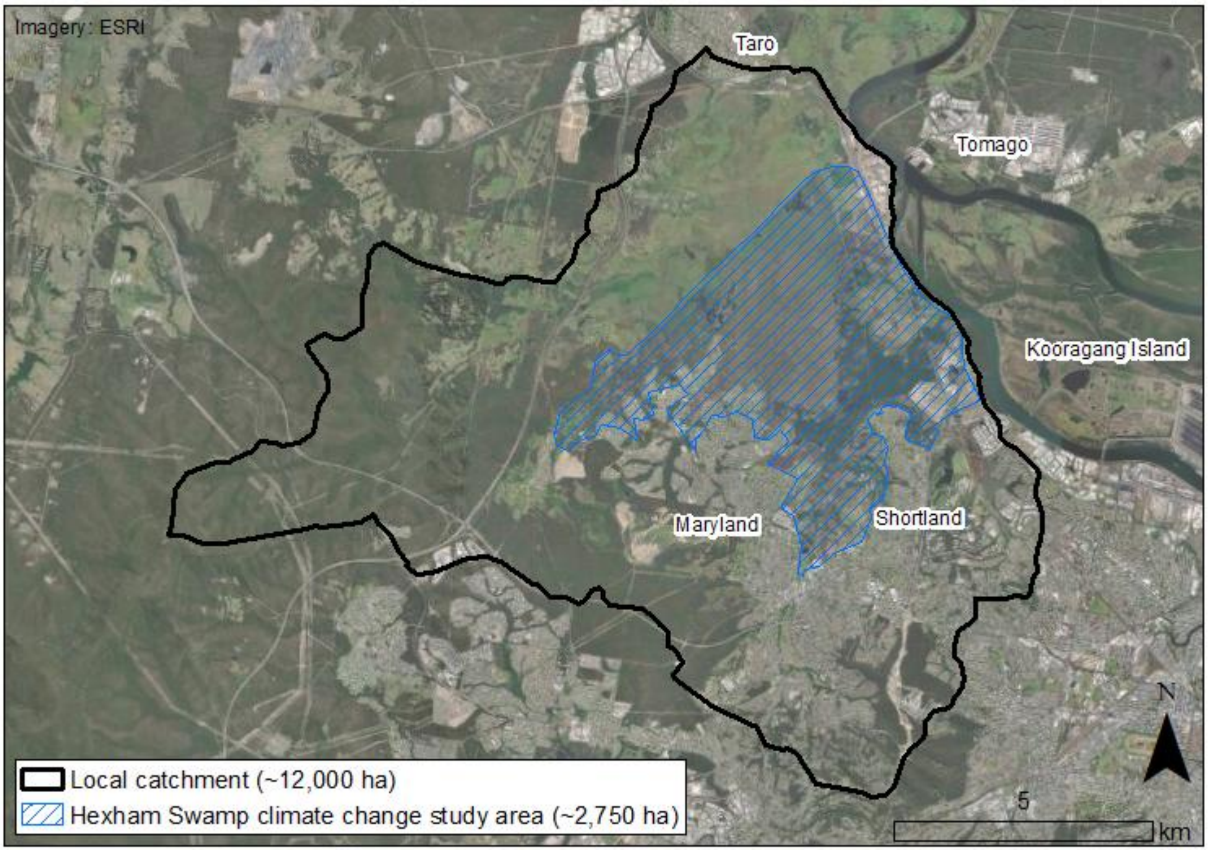

Figure A.1 Hexham Swamp local catchment

Figure A.2 Culverts under the Richmond Vale Rail Trail (Haines et al., 2005)

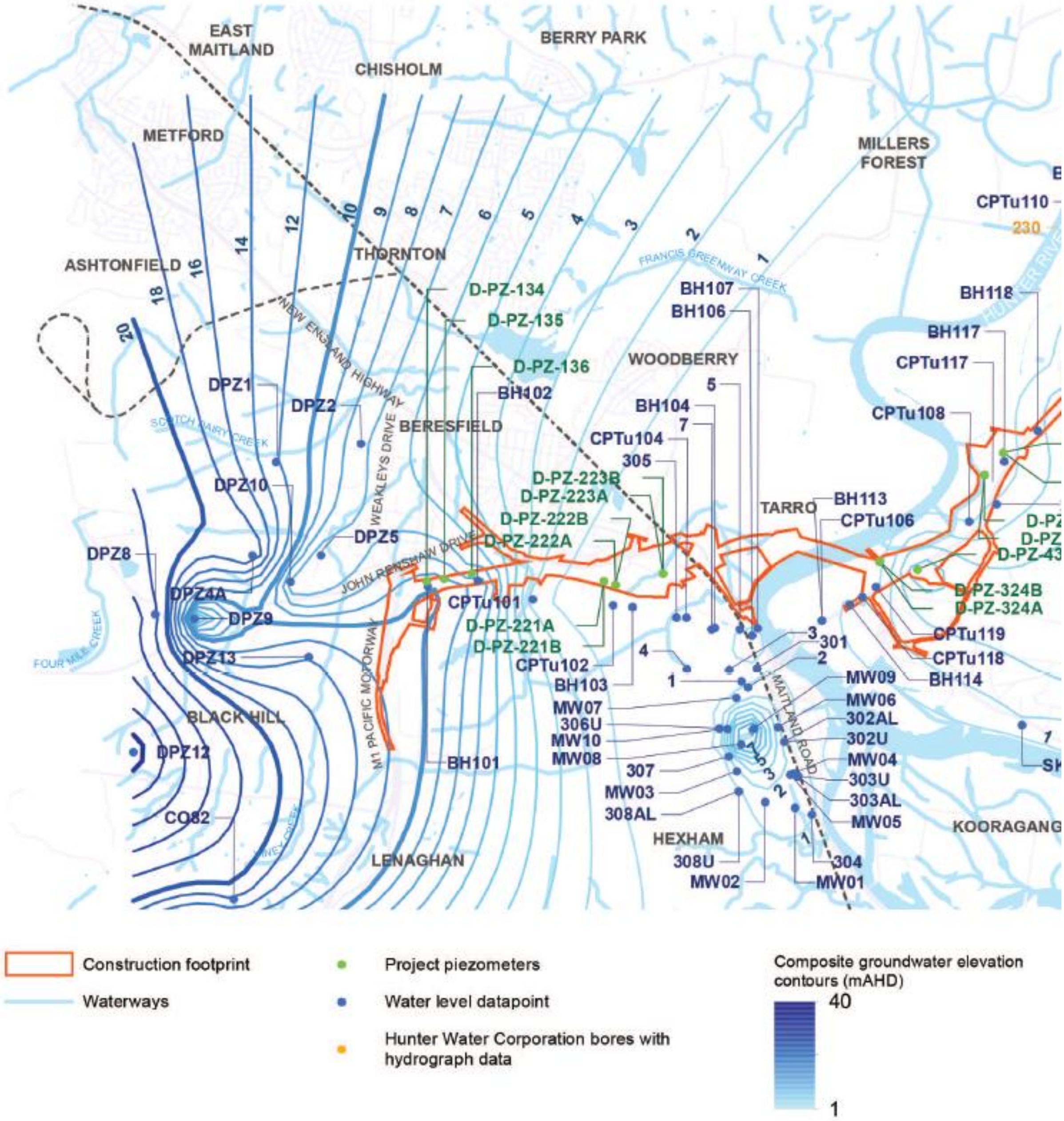

Figure A.3 Regional groundwater level contours (TfNSW, 2021)

Long term rainfall data was available from the Queensland Governments SILO database since 1989 (Jeffrey et al., 2001) which is based on data collected by the Australian Governments Bureau of Meteorology. This data has been presented in Figure A.4 and shows that there is an increase in the median rainfall across the wetland between December and April. Interestingly, the median rainfall in June is comparable to December rainfall totals. Outliers indicate that flood events can occur all year round, with larger events tending to occur between January and August.

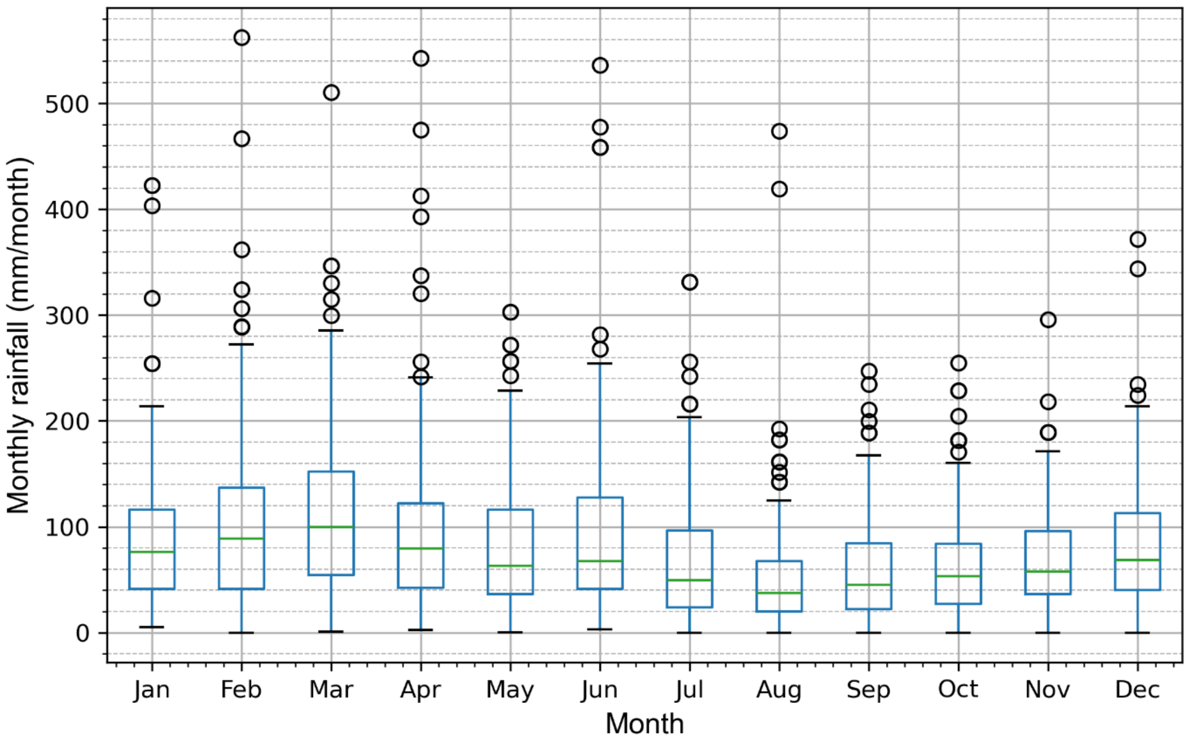

Figure A.4 Monthly rainfall statistics for 1989 to 2023 (Jeffrey et al., 2001)

Box plots show 25th and 75th percentiles (boxes), median (green lines), interquartile range (whiskers) and outliers (circles).

Figure A.5 and Figure A.6 present the monthly statistics for daily evaporation and maximum daily temperature, respectively (Jeffrey et al., 2001). Evaporation and temperature are strongly correlated, with strong seasonal trends. High levels of evaporation and high temperatures occur in the summer months (December and January) while low levels occur in winter months (June and July). Higher rainfall levels coincide with low evaporation in June meaning that there is likely to be an increase in the freshwater influence across Hexham Swamp at this time of year.

The seasonality of temperature measurements will likely have a significant impact on the vegetation extent and biogeochemical processes throughout Hexham Swamp. While there is limited research into this space, a recent investigation has shown that climatic factors (like temperature) will be important for understanding the extent and change of habitat types into the future (Henderson and Glamore, 2024b).

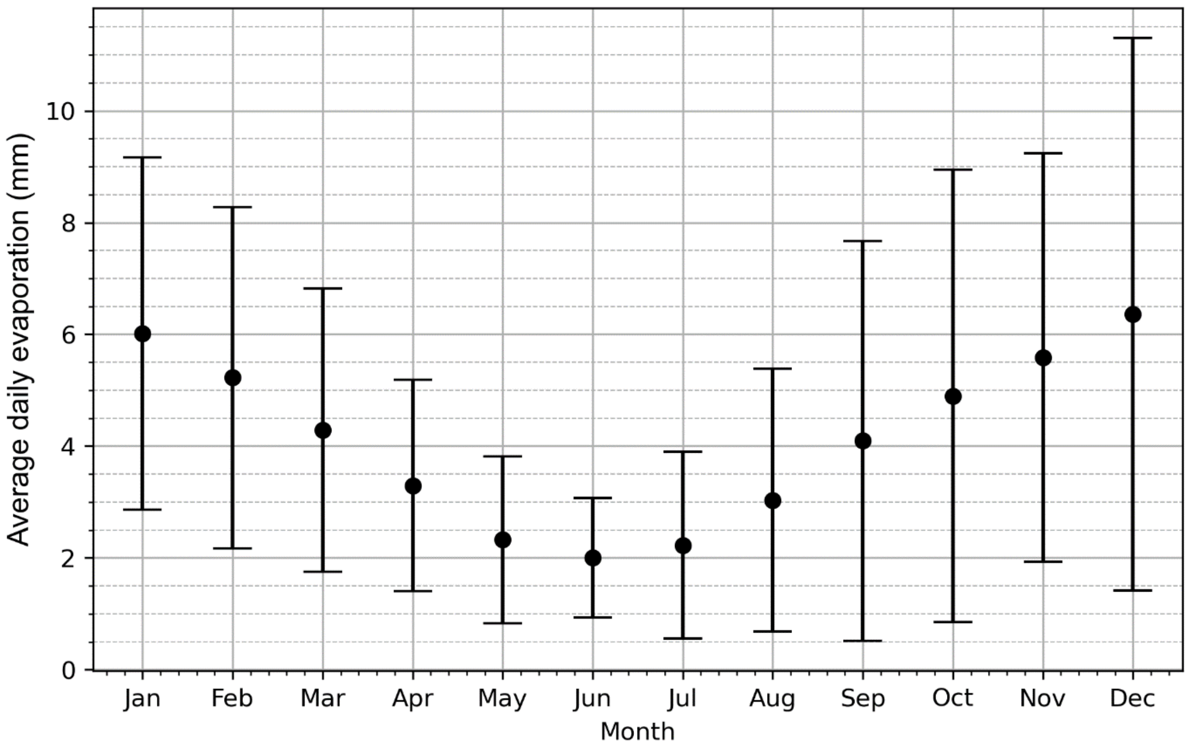

Figure A.5 Average daily evaporation statistics by month for 1989 to 2023 (Jeffrey et al., 2001)

Plot shows the median for each month (dots) and total range for each month (whiskers).

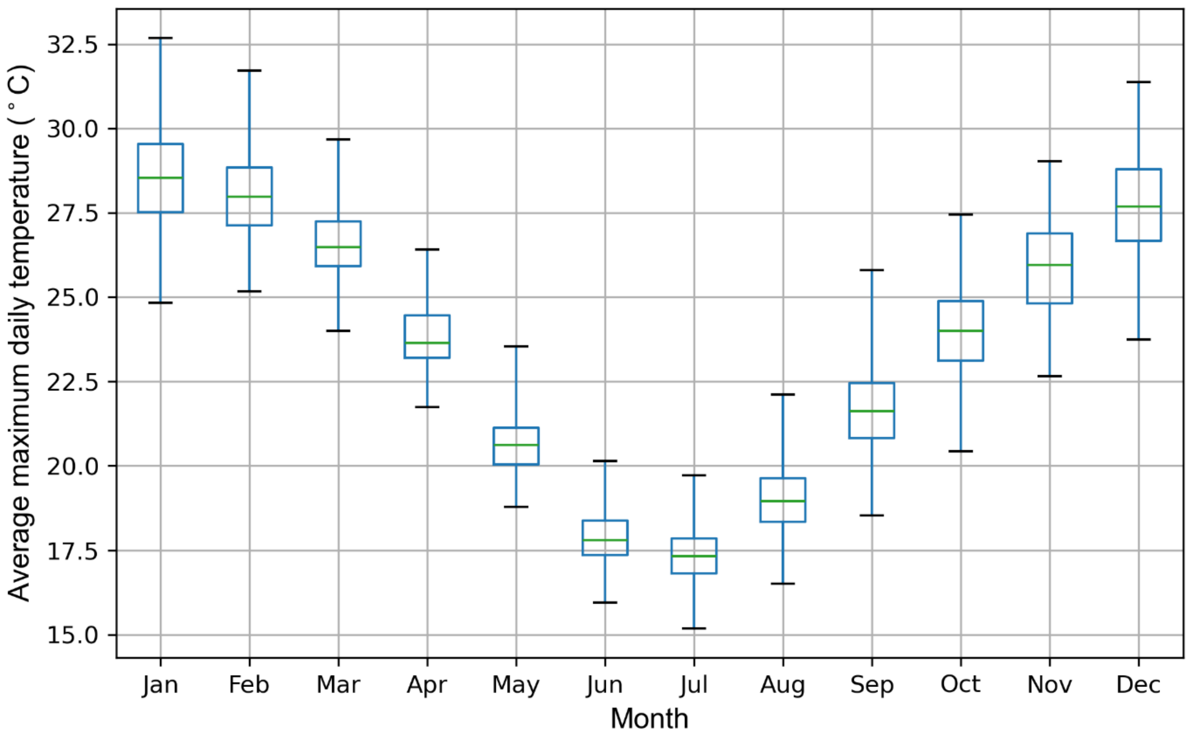

Figure A.6 Average daily maximum temperature statistics by month for 1989 to 2023 (Jeffrey et al., 2001)

Box plots show 25th and 75th percentiles (boxes), median (green lines) and total dataset range (whiskers).

Long term climate drivers such as the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) will also influence Hexham Swamp over longer timescales. Figure A.7 shows the cumulative rainfall residual (i.e. annual rainfall minus the average annual rainfall) alongside the southern oscillation index (an indicator for ENSO) to show the historic hydrology for Hexham Swamp. Throughout the data record there have been exceedingly dry interannual periods (e.g. 1895 to 1910 and 1935 to 1945), as well as extreme wet periods (e.g. 1888 to 1895 and 1945 to 1950). Drought such as the Millenium Drought, can be clearly seen in Figure A.7 (2001 to 2009) and are typically associated with El Niño (red) periods. Similarly wet periods (such as in the 1950s, 1970s, and recently in 2021/22) are associated with La Niña (blue) periods. During dry (drought) times, it can be expected that the influence of the tide (and saline water) will extend further into Hexham Swamp. Conversely, during wet (flood) periods, the system will become increasingly dominated by freshwater vegetation and habitats. The impacts of these long-term climate drivers on the hydrology will also have flow on affects to the soil moisture and salinity which are also important for vegetation growth and establishment. A fluctuation between wet and dry habitats is natural and can be expected to occur over decadal timescales as demonstrated by Figure A.7.

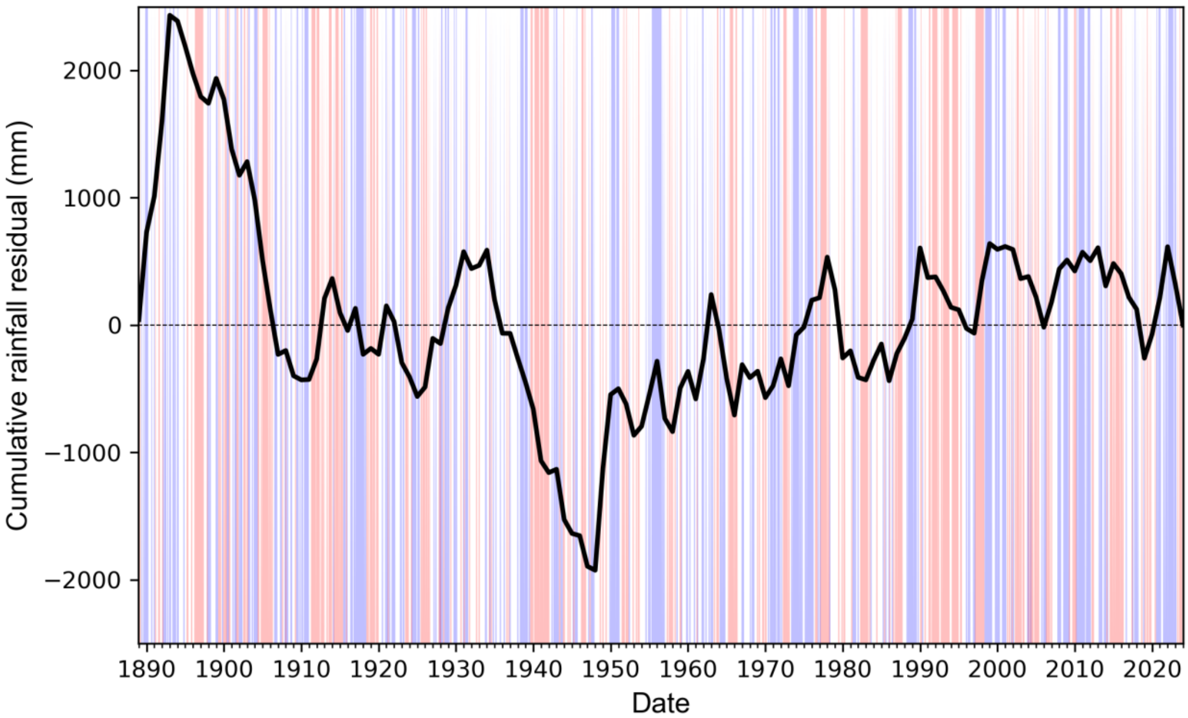

Figure A.7 Cumulative rainfall residual and southern oscillation index (blue indicates La Niña, red indicates El Niño) (Jeffrey et al., 2001; BOM, 2025)

Note: the rainfall residual is calculated as the average annual rainfall subtracted from the total annual rainfall.

A2.2 Water levels

Water levels were monitored within Hexham Swamp between 2006 and 2016 (McPherson and Lewis, 2016). This included a period prior to the restoration works (completed between 2008 and 2013). Analysis of the water levels show that there was a clear increase in the maximum water levels upstream of the floodgates (Morris Jetty) following restoration (Figure A.8).

In the Hunter River, Manly Hydraulics Laboratory maintain two water level gauges, one at Hexham Bridge (MHL, 2024a) and one at Stockton Bridge (MHL, 2024b). While these datasets do not provide insight into what is occurring within Hexham Swamp, they can be used to provide current information on the water level boundary downstream of the wetland at the Hunter River. The mean tidal planes are shown for the last 20 years in Figure A.9. Over this period the tidal planes have fluctuated by less than 0.13 m. The tidal range between mean low water and mean high water tidal planes has remained close to 1 m for this duration.

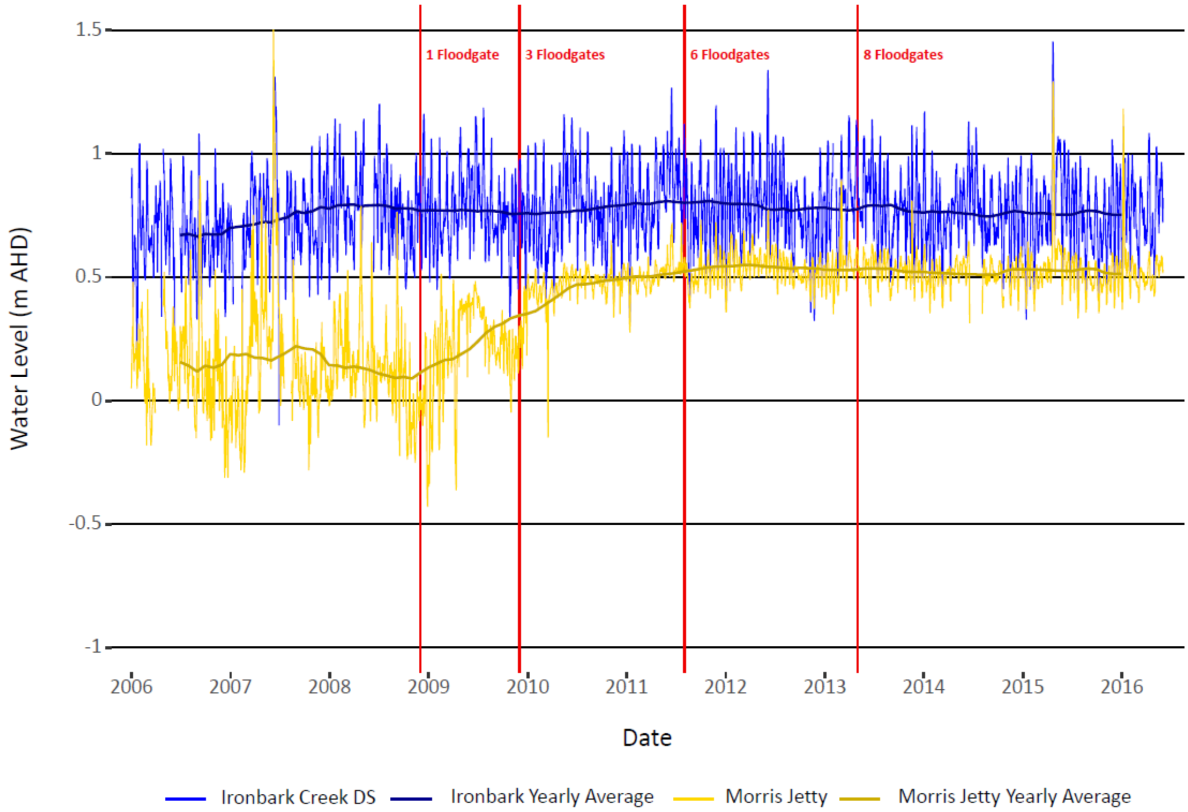

Figure A.8 Daily maximum water levels downstream (Ironbark Creek) and upstream (Morris Jetty) of the Ironbark Creek floodgates from 2006 to 2016 (McPherson and Lewis, 2016)

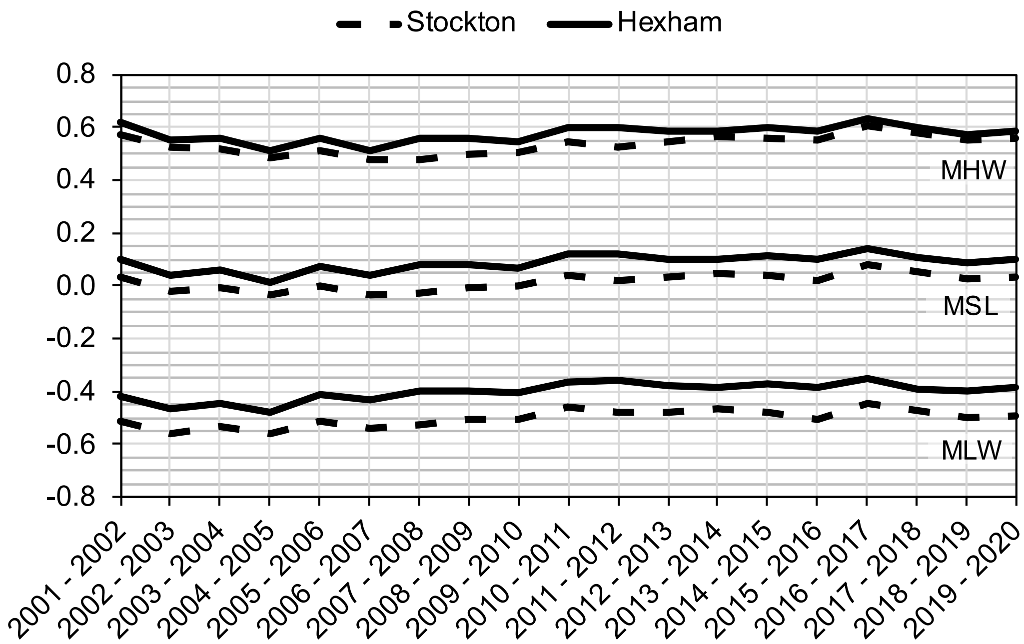

Figure A.9 Mean High Water (MHW), Mean Sea Level (MSL) and Mean Low Water (MLW) at Hexham Bridge and Stockton Bridge since 2001 (Dakin, 2023)

A2.3 Water quality

In addition to water levels, McPherson and Lewis (2016) collected a range of water quality measurements throughout Hexham Swamp, and identified the following trends:

- Dissolved oxygen has a seasonal variance (decreasing in summer) and has slightly lower levels within the wetland compared to the downstream estuary. Across the wetland dissolved oxygen tended to fluctuate between 2 mg/L and 6 mg/L.
- pH initially dropped following the opening of the floodgates before having a steady increase. Water upstream of the floodgates is slightly more acidic than downstream in the Hunter River.
- Turbidity increases with large rainfall events. Turbidity within the wetland has tended to remain higher than levels in the Hunter River estuary.
- Salinity was found to have an unexplained 4-year cycle within Ironbark Creek with no discernible change pre- and post-restoration. Measurements in the western region of Hexham Swamp showed no indication of tidal ingress at the end of the monitoring. For further analysis of salinity data refer to Appendix A3.2.

A2.4 Vegetation

Since restoration of tidal flows to Hexham Swamp, there has been an increase in the estuarine vegetation extent. Regular mapping of the vegetation has been completed to monitor the extent at which estuarine vegetation is increasing. The most recent survey was completed in 2021 and indicates that there is now 519 ha of estuarine wetlands compared to 109 ha prior to the restoration works (King, 2021; Winning and Saintilan, 2009) (Figure A.10). As expected, the estuarine sections of Hexham Swamp are located to the east of the wetland where tidal flows have been restored (via Ironbark Creek). Phragmites continue to dominate the central part of the wetland where they span an area of approximately 720 ha., however King (2021) noted that the extent of tidal wetland continues to expand across the wetland.

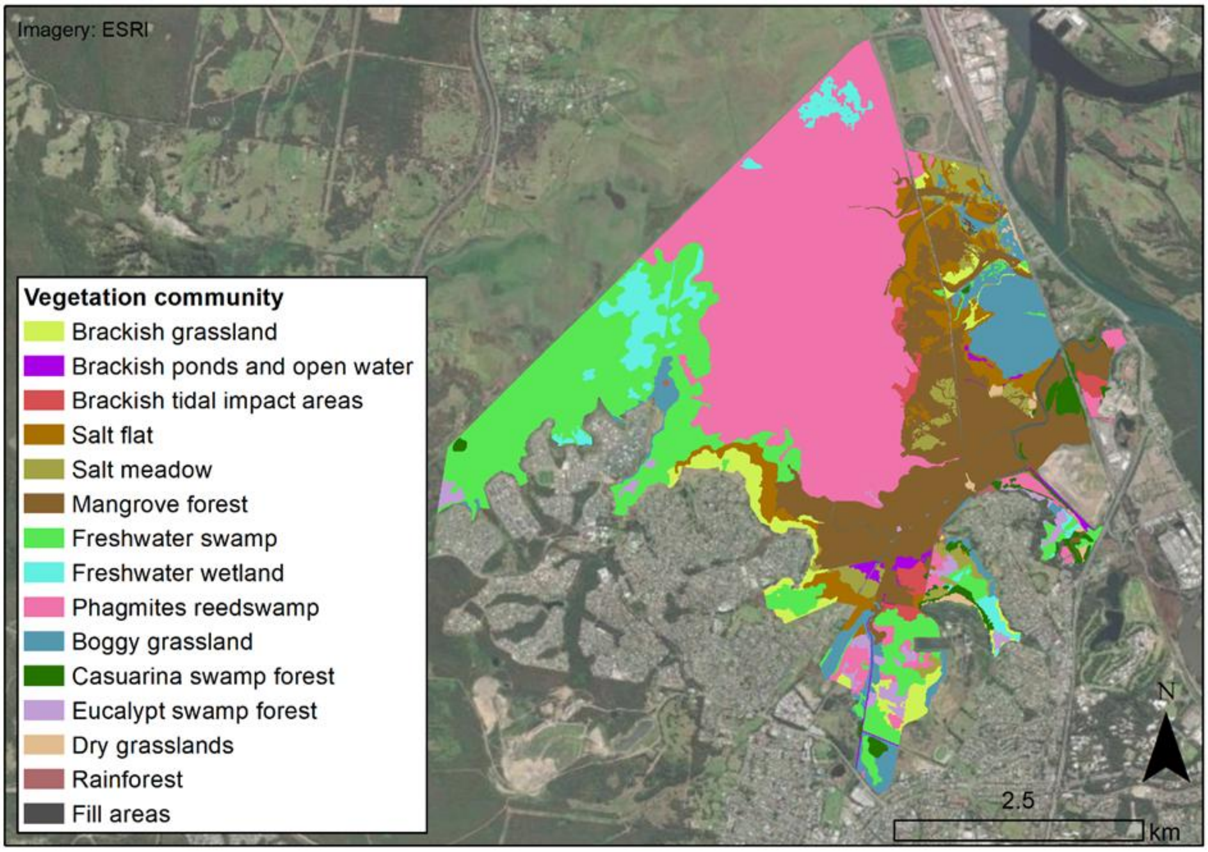

Figure A.10 2021 vegetation at Hexham Swamp (King, 2021)

A2.5 Tidal connectivity

Hexham Swamp is connected to the Hunter River estuary at three locations (Figure A.11). The primary connection is via the Ironbark Creek floodgates (Figure A.12). There are eight floodgates across eight square (2.13 m wide by 2.13 m high) culverts. The culverts have an invert elevation of -1.07 m AHD. When the floodgates are in the most open position, the bottom of the flap still obstructs a small portion at the top of each culvert.

The floodgates remain in the most open position unless a flood is predicted, at which point they are closed until flood levels recede (Haines, 2012).

A set of four floodgates connect Hartin's Creek to the Hunter River (Figure A.13). Observations provided by Hunter Local Land Services for this structure indicated that it was in poor condition. There is extensive growth of mangroves on the Hexham Swamp side of the floodgate structure indicating that there is tidal connectivity (even if it is somewhat restricted) between the Hunter River and Hexham Swamp via Hartin's Creek. Culverts underneath Maitland Road, the railway tracks and Hartin's Track further restrict the connectivity at this location.

Another small connection between Spoonbill Creek and the Hunter River is located further north of these structures (see Figure A.11). Inspection of aerial imagery indicates that there is rubble blocking this connection on the downstream side (Figure A.14). Despite this, mangrove growth within Hexham Swamp upstream of this connection also indicates that there is some level of tidal connectivity.

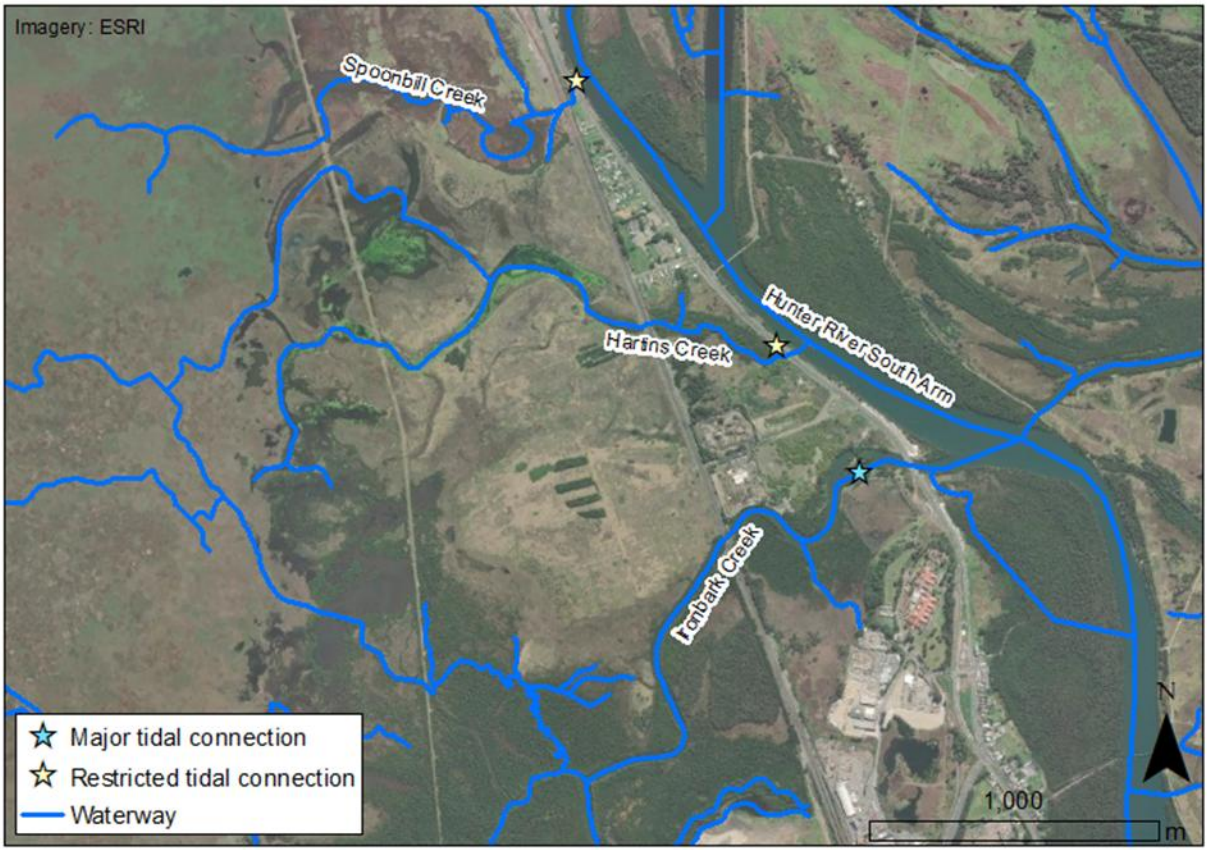

Figure A.11 Location of key structures connecting Hexham Swamp to the Hunter River

Figure A.12 Ironbark Creek floodgates with gates lifted to maximum opening height

Figure A.13 Photo of four floodgates connecting Hartin's Creek to Hexham Swamp (Credit: Peggy Svoboda)

Figure A.14 Aerial imagery of northern connection between Hexham Swamp (left) and the Hunter River (right) (source: Nearmap)

Note, the connectivity through the smaller structures (i.e. Hartin's Creek and the northern connection) is likely to be limited, especially in comparison to flows through the Ironbark Creek floodgates. Mapped waterways and channels visible in aerial imagery (Figure A.11) indicate that water can flow through Ironbark Creek and around to Hartin's Creek and the surrounding floodplain. Flow from the northern connections, or Ironbark Creek, are both potential pathways by which tidal wetland habitat has established across the floodplain in this area.

Numerical modelling of Hexham Swamp was completed by Haines et al. (2005) and Haines (2011) to determine the likely extent of inundation from the tide that would occur following modification of the floodgates. Interrogation of model results can provide further insight into the connectivity across the floodplain. Figure A.15 compares numerical model results for inundation extent (a scenario where eight floodgates are fully open) against the most recent vegetation mapping (completed in 2021). When interpreting this data, it should be recognised that there are significant uncertainties in the floodplain elevation data that was incorporated into the model (see Appendix A2.6). Furthermore, tidal inundation does not necessarily correlate with tidal wetland vegetation growth, which is dependent on a range of factors such as salinity levels, tide elevations and climate. This is the likely reason why the tidal wetland extent and modelling predictions do not match exactly.

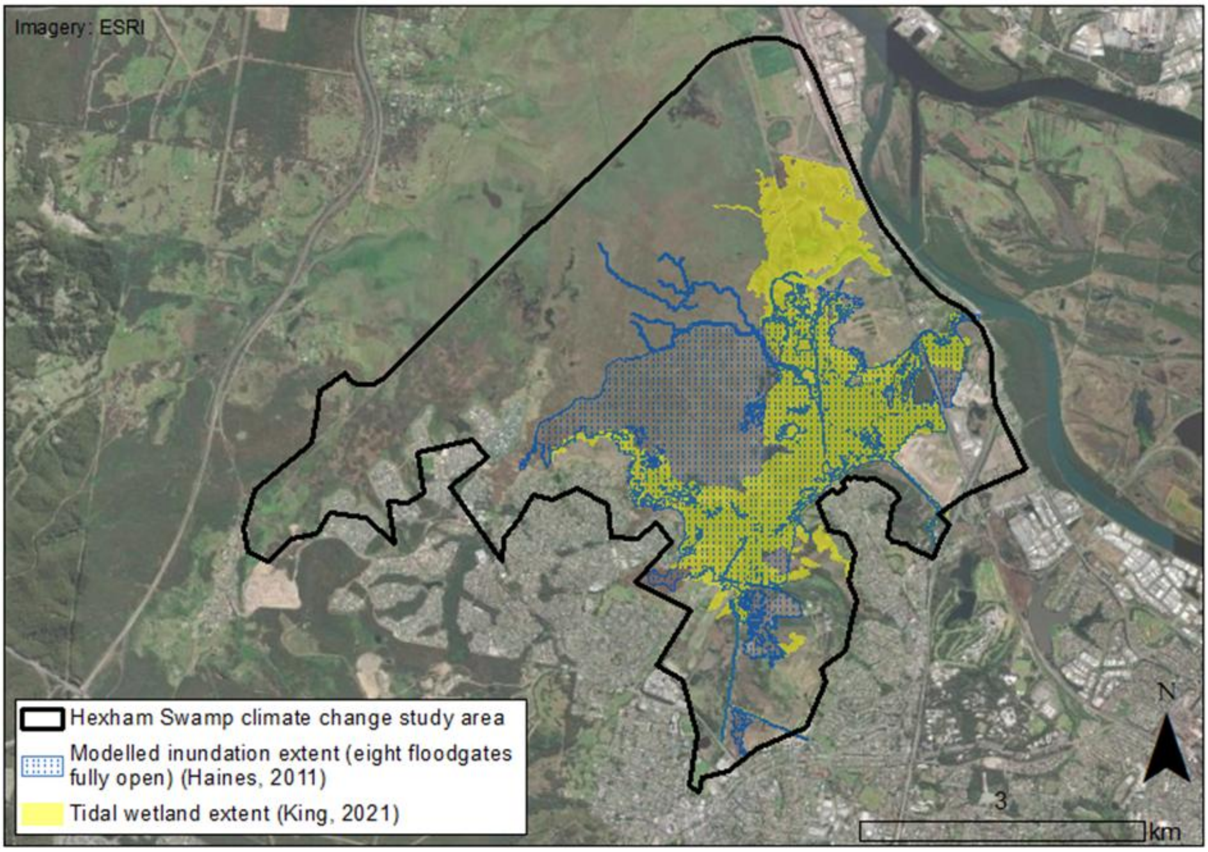

Figure A.15 Comparison of numerical model results and vegetation mapping

A2.6 Floodplain elevation

Surveys of the floodplain surface elevation have been completed on a number of occasions including in 2008 (1 m horizontal resolution) (Haines et al., 2005), 2012 to 2014 (1 m horizontal resolution) (DFSI, 2014), and 2019 (0.5 m horizontal resolution) (Pietsch, 2020). The latter two surveys were conducted using LiDAR technology (limited metadata is available for the Haines et al. (2005) dataset although it is also likely to be based on LiDAR technology). These types of surveys are excellent for covering large areas; however, they can be limited in wetland environments for two reasons:

1. Where there is dense vegetation, LiDAR elevation data collected can be incorrect (i.e. too high) as the survey measures the top of vegetation and does not provide a true representation of the ground surface.
2. Where there is open water, the LiDAR is unable to penetrate the surface of the water and again gives a false high reading for the surface elevation.

One way to account for these errors is to complete a ground truthing survey. Figure A.16 shows a corrected digital elevation model (DEM) that was created by Haines et al. (2005). While some ground truthing point exists, they are sparsely located. There is a high level of uncertainty across the DEM, especially on the western side of the wetland.

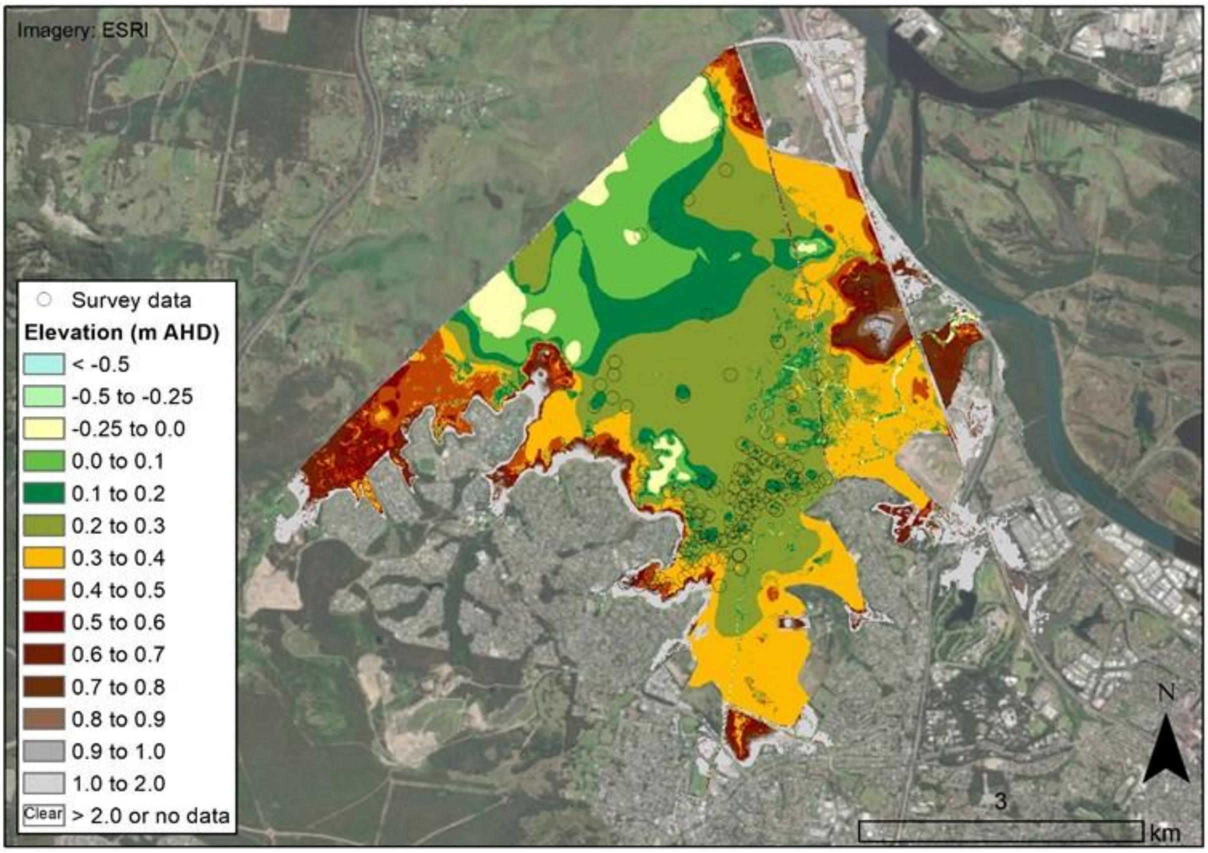

Figure A.16 2008 survey data with survey correction point identified (Haines et al., 2005)

The three surveys of the floodplain elevation have been compared in Figure A.17. This shows the uncertainty of these surveys with a large proportion of the floodplain varying in elevation anywhere from 0 m AHD to more than 1.0 m AHD. This also highlights the importance of additional data collection to verify the accuracy of DEM's in wetland environments (as shown in Figure A.16).

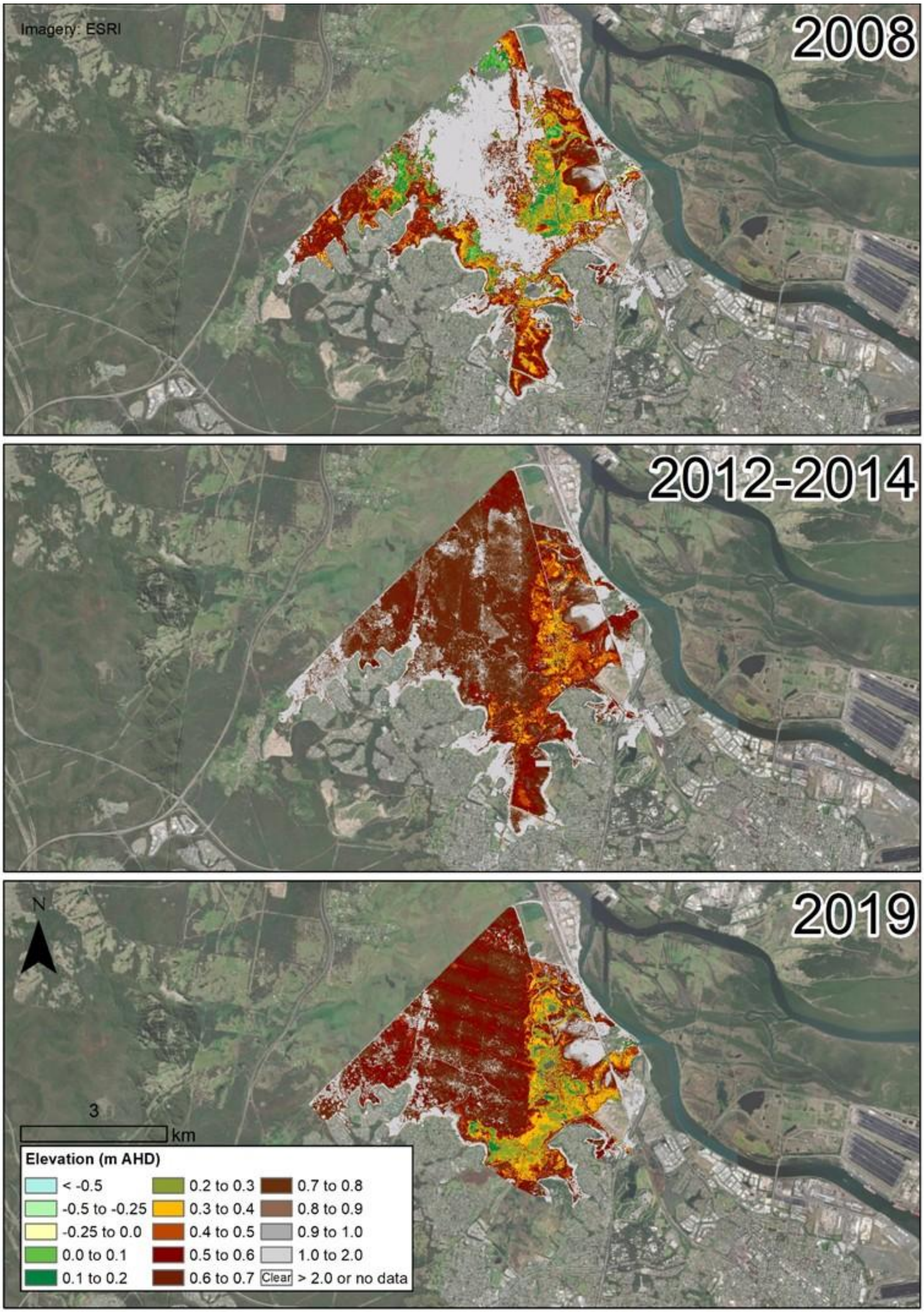

Figure A.17 Comparison of LiDAR surveys at Hexham Swamp (Haines et al., 2005; DFSI, 2014; Pietsch, 2020)

A3 Equilibrium wetland state

A3.1 Preamble

Hexham Swamp was converted to a freshwater wetland for a period of almost 40 years following the construction of the Ironbark Creek floodgates in 1971 (Winning and Saintilan, 2009). Over this period there was a drastic change in the habitat across the wetland. Vegetation mapping of the wetland extent was completed in 1996 and shows extensive saltmarsh habitat throughout the wetland (Figure A.18) (for comparison see Figure A.10).

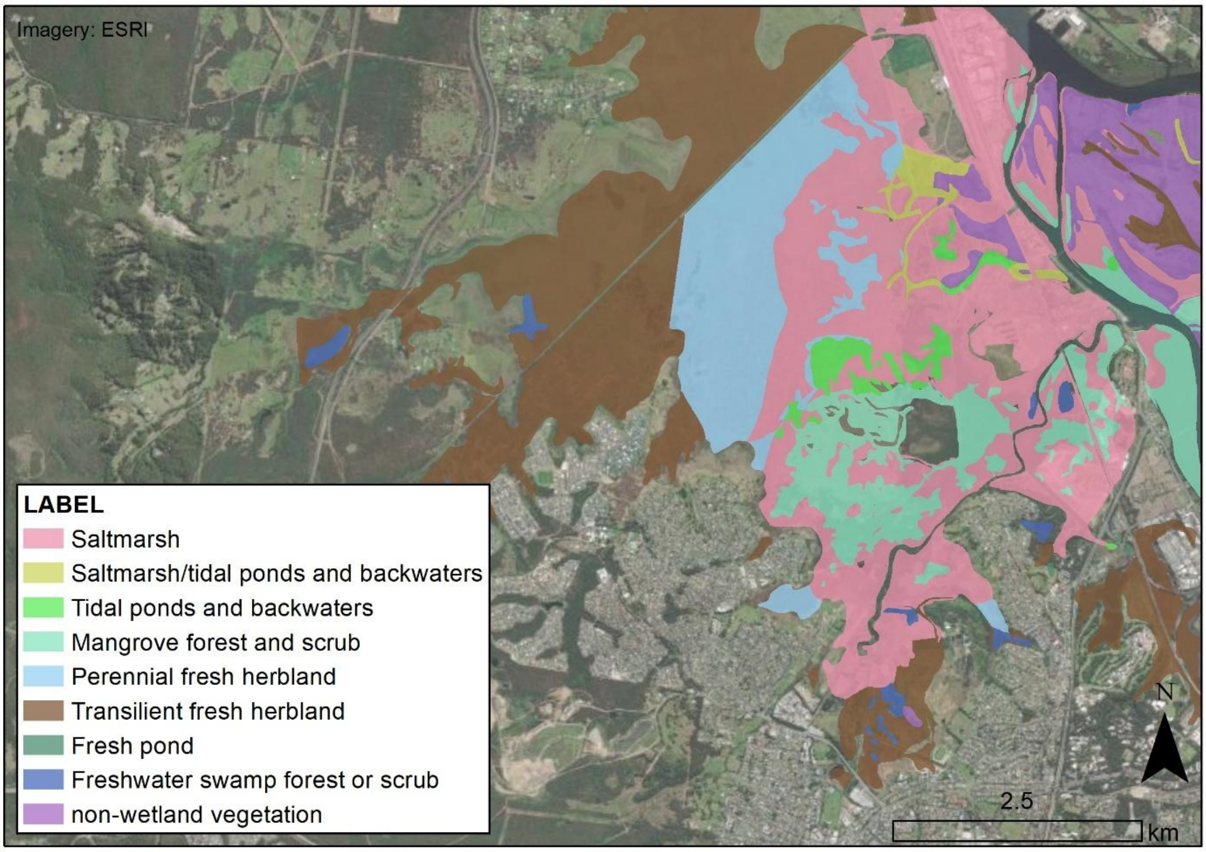

Figure A.18 1966 vegetation extents for Hexham Swamp (Winning, 1996)

Winning and Saintilan (2009) calculated that construction of the floodgates resulted in a 94% decline in mangroves (180 ha to 11 ha), a 92% decline in saltmarsh (681 ha to 58 ha) and a 530% increase in Phragmites (170 ha to 1,005 ha) between 1971 and 2005 (34 years). In their study, Winning and Saintilan (2009) observed that over this period, the changes to vegetation had not stabilised, highlighting the long timeframe that changes to ecology occur over.

The Hexham Swamp Rehabilitation Project was completed in May 2013 with the opening of eight of the floodgates on Ironbark Creek. Like the change to freshwater habitat, the transition back to estuarine habitat will occur over a long period of time (i.e. decades). The following section reviews available vegetation (Appendix A3.3) and water level/quality data (Appendix A3.2) to identify any trends in the ongoing development of the estuarine wetland.

A3.2 Water levels and water quality

Long term water level data and water quality data was collected by Manly Hydraulics Laboratory for a period of 10 years from June 2006 to June 2016 (McPherson and Lewis, 2016). This included a 3-year period following the opening of all eight the floodgates (Stage 3) which occurred in May 2013 (note, the floodgates were still closed on occasion during this period for flood mitigation purposes). Unfortunately, no long-term data was available since June 2016 meaning that any recent trends in water levels or water quality remain unknown.

Analysis of water levels has been completed by McPherson and Lewis (2016) and HLLS (2021). While there were clear changes in monitoring parameters from 2008 to 2013 as the staged floodgate opening occurred, since the opening of all eight floodgates, there has been no clear trend in water level or water quality measurements (see previously in Figure A.8).

Lack of observed changes in water level and water quality data does not indicate an equilibrium condition (analysis of vegetation data clearly indicates that the habitat at Hexham Swamp continues to change, see Appendix A3.3). Review of the water level data completed for this current study found that levels are driven by catchment inputs and management of the floodgates (e.g. opening/closure for flood mitigation). Figure A.19 shows that closure of the floodgates in July 2014 resulted in a lowering of the average water levels, while flooding in May 2015 resulted in an increase in the average water levels. Further changes in water levels across the wetland will be small in comparison to these background drivers for water levels. Similarly, the high variability of water quality parameters driven by the catchment hydrology will mean that it is often difficult to determine the cause for increases or declines.

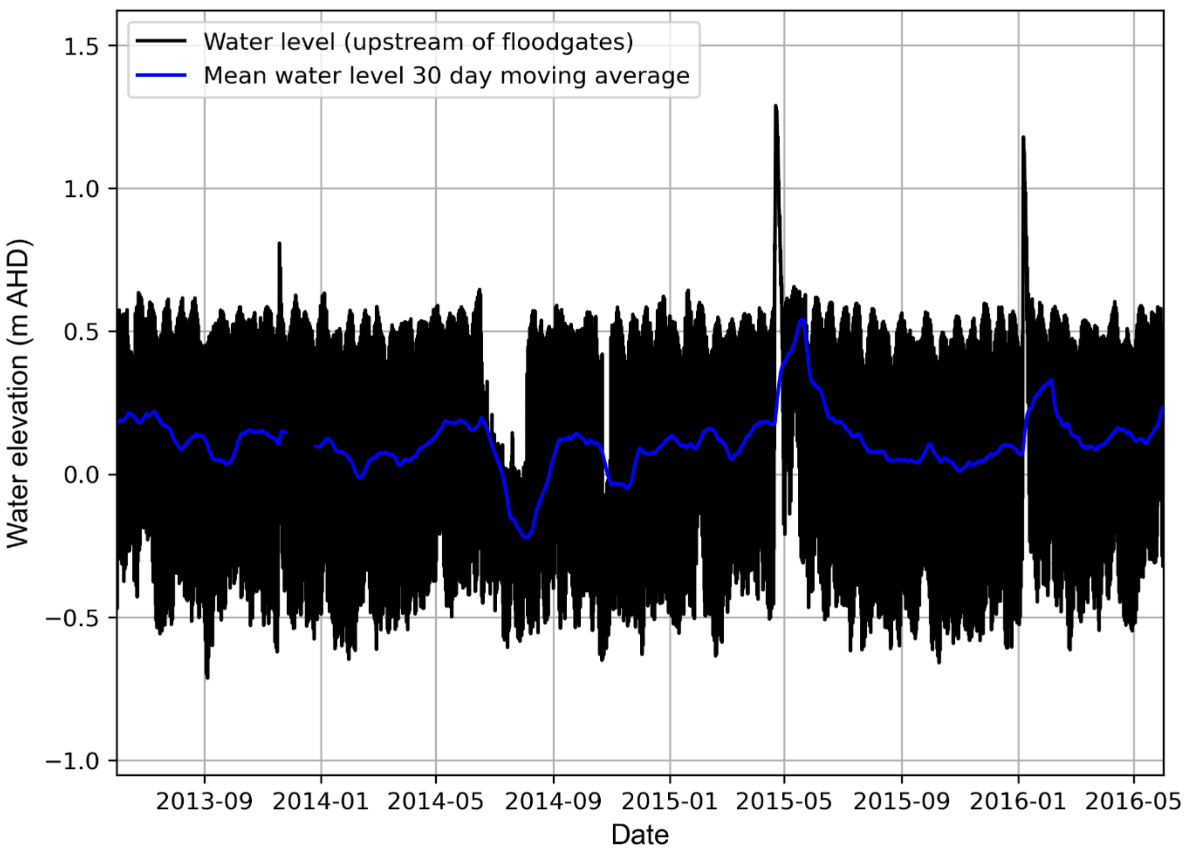

Figure A.19 Water levels upstream of the Ironbark Creek floodgates compared to the 30 day moving average for the high tide (data source: McPherson and Lewis (2016))

A3.3 Vegetation

The most recent vegetation mapping of Hexham Swamp was completed by King (2021). This was the third survey conducted since all eight of the floodgates on Ironbark Creek were opened. Changes in the extent of key vegetation species (saltmarsh, mangroves and phragmites) is shown in Figure A.20 and Figure A.21. Since the opening of the floodgates, mangrove and saltmarsh habitat has continued to expand across the wetland and now covers approximately 300 ha. Since the opening of the floodgates, the extent of Phragmites continues to reduce and now spans approximately 763 ha across Hexham Swamp (see the right-hand axis of Figure A.20).

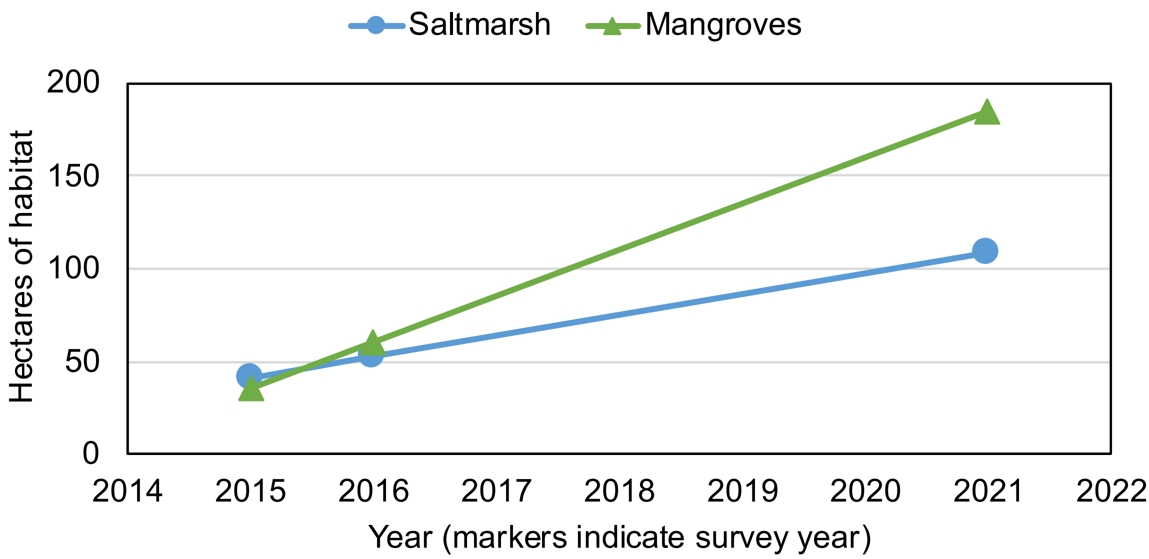

Figure A.20 Increase in tidal habitat extent since 2015 (King, 2021)

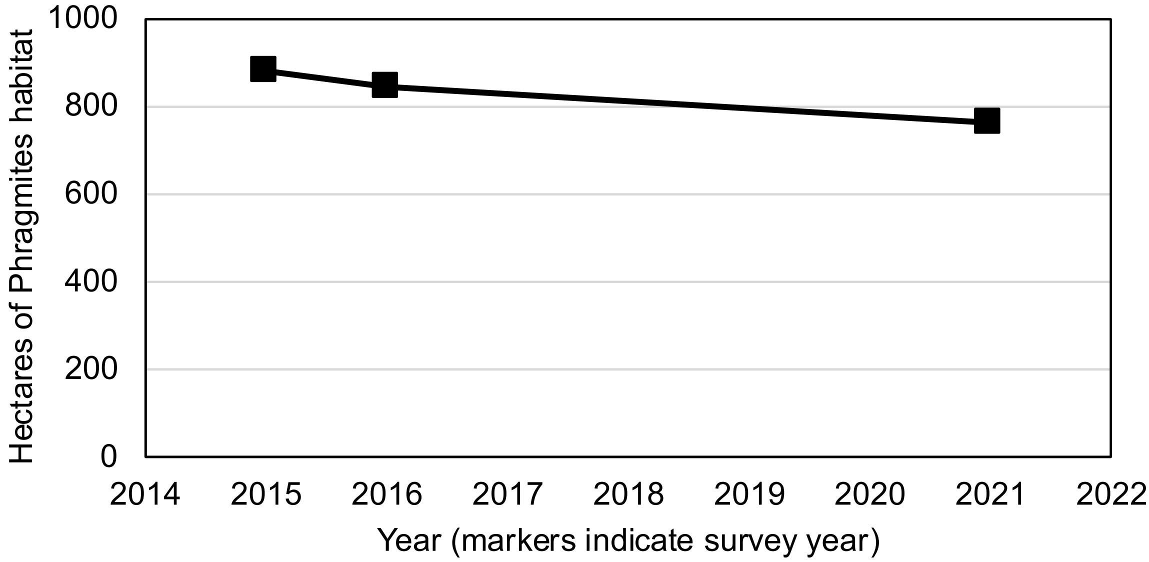

Figure A.21 Decrease in Phragmites habitat extent since 2015 (King, 2021)

Changes in vegetation extents indicate that the system has not yet reached an equilibrium state. It is likely that the extent of tidal wetland vegetation will continue to increase across Hexham Swamp in the future.

Phragmites are the dominant vegetation species across the floodplain and the establishment of further tidal wetland habitat will depend on their ability to compete with the existing Phragmites. Factors that will influence this competition include germination cycles, salinity, temperature, and rainfall (Greenwood and MacFarlane, 2006). Research conducted by Mauchamp and Mésleard (2001) observed that established Phragmites can survive in water with a salinity concentration of 25 parts per thousand (ppt) for at least 25 days. In the same study it was found that Phragmite seeds would germinate unaffected in salinities up to 10 ppt. It was found that only once salinity levels increase above 20 ppt that Phragmite seedlings would be unlikely to survive. Greenwood and MacFarlane (2006) had a similar finding that germination of seeds in water with a salinity of 30 ppt had a 2% chance of survival. Salinity data collected by McPherson and Lewis (2016) within Hexham Swamp indicated that even following restoration, low salinity levels favourable for Phragmites persist for extended durations (Figure A.22) and die off of Phragmites is likely to be driven by short (1 to 3 month) periods of extended high salinity. This highlights that the interaction between Phragmites and tidal wetland habitat is likely to be seasonally and climatically driven.

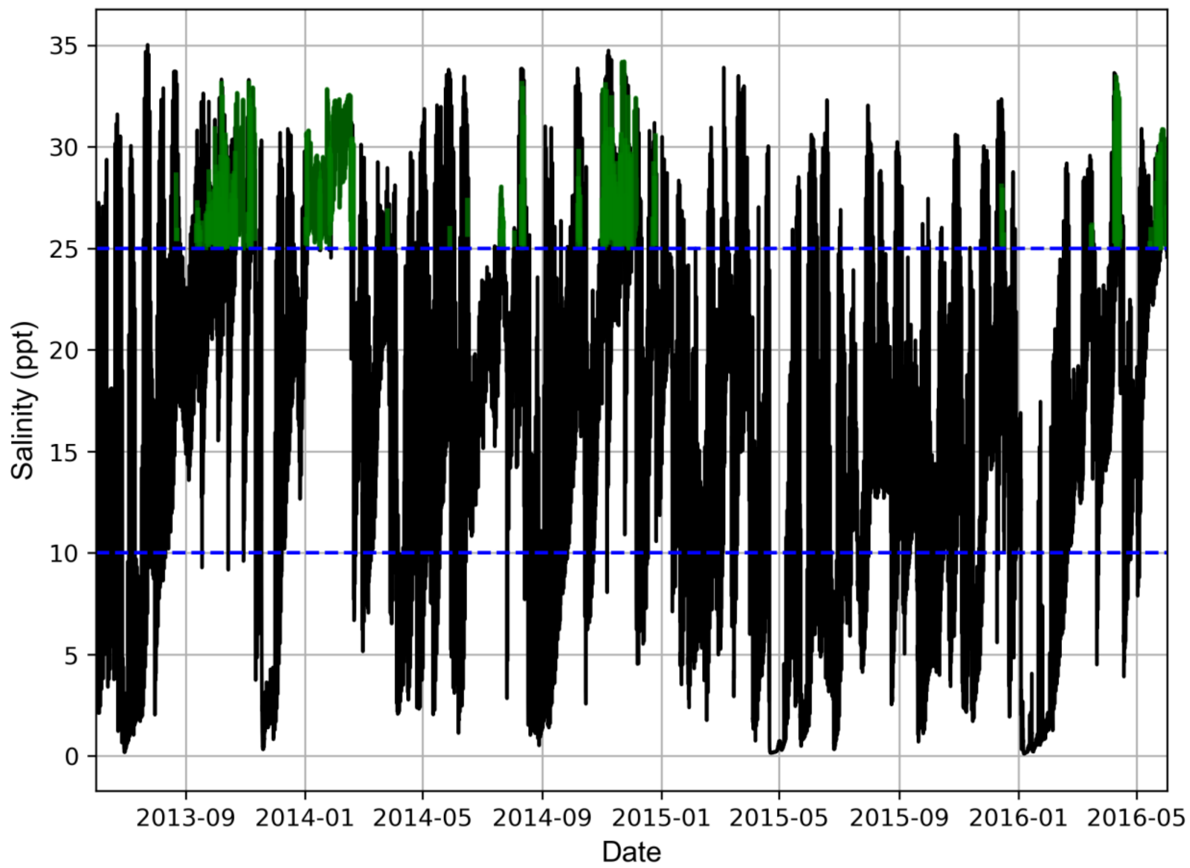

Figure A.22 Salinity recorded since restoration at the Morris Jetty station upstream of the floodgates by McPherson and Lewis (2016)

Black indicates all salinity data. Green indicates when salinity has been above 25 ppt for 25 days. Blue lines indicated key threshold values of 10 ppt and 25 ppt determined in literature.

Recent research has emerged that identifies the conditions required for mangroves (specifically *Avicennia marina*) to establish in coastal floodplains (Henderson and Glamore, 2024a). This research enables for the estimation of the potential extent for mangrove habitat based on a lifecycle approach that considers seedling propagation, tides, inundation duration, and evapotranspiration. Based on this knowledge, Henderson and Glamore (2024a) developed a model to simulate potential mangrove extent based on environmental variables. Unfortunately, there is insufficient water level data inside Hexham Swamp to model the potential mangrove extent (a minimum of 8 years of data is required). Modelling of mangrove extent has instead been completed using water level data collected by MHL (2024a) at Hexham Bridge (Figure A.23). Results highlight that there is significant interannual variability in the range suitable for mangrove establishment (e.g. in 2015 there is a large range of ~0.6 m compared to a smaller range of ~0.3 m in 2017). This was despite relatively uniform tidal ranges throughout this period (see Figure A.9). This highlights that over this period, factors other than the tide (i.e. inundation duration and evapotranspiration) had a significant influence on the potential habitat extent. While the exact range of growth inside Hexham Swamp will be significantly different due to the attenuation of tides that flow into the wetland, it is important to consider that there will be similar year on year differences in the potential extent associated with the prevailing climate.

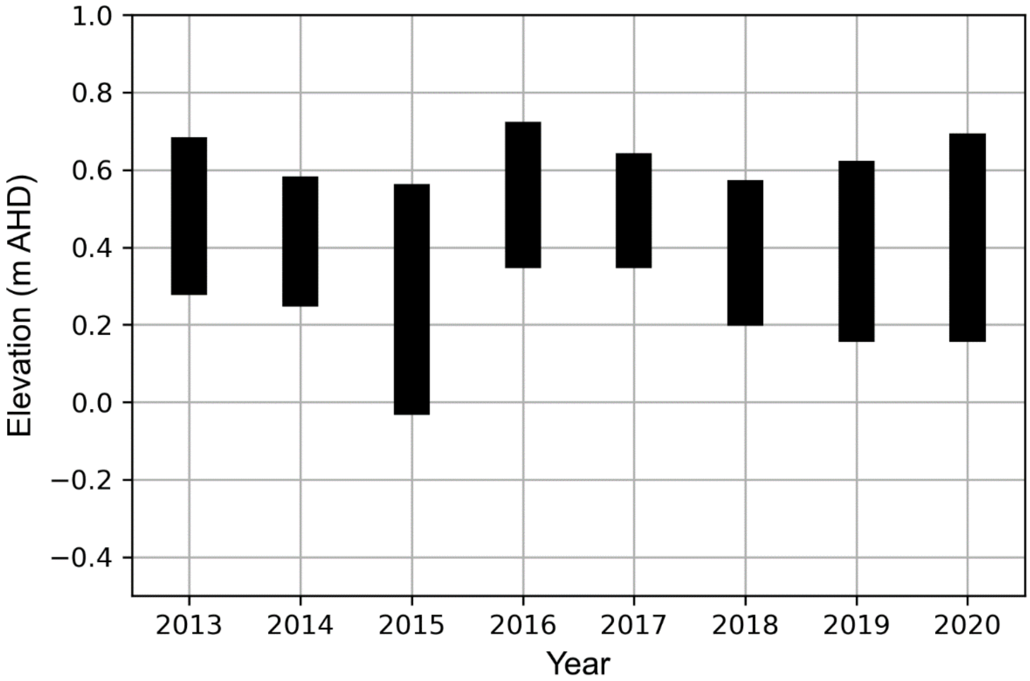

Figure A.23 Potential range suitable for mangrove growth at Hexham Bridge (Henderson and Glamore, 2024a)

A3.4 Potential extent of estuarine wetlands

Review of available data has indicated that the extent of tidal wetlands continues to increase across Hexham Swamp. Historical information for tidal wetland extents indicates that there is still significant potential for habitat to expand. Vegetation mapping completed in 1966 indicates that historically there was ~2,050 ha of tidal wetland habitat (Winning, 1996) compared to ~520 ha of tidal wetland habitat mapped in recent vegetation surveys (King, 2021).

It is unlikely that the historical extent of tidal wetland habitat will ever occur again at Hexham Swamp under present day conditions. The primary reason for this is that the Ironbark Creek floodgates remain in place and continue to restrict tidal inundation across the wetland. Hexham Swamp has also significantly changed due to drainage of the wetlands between the 1970s and 2010s. Impacts resulting from drainage (such as the drainage of acid sulfate soils) have altered the biogeochemistry and connectivity across the floodplain. These changes mean that the extent of restored wetland will be different to the historic wetland extent. Already mangroves have established in areas that were historically saltmarsh. Greenwood and MacFarlane (2006) also note that in some instances the changes to the hydrology may be favourable for invasive species (such as *Juncas acutus*) over native species (i.e. *Juncas kraussii)* and highlight that without intervention native species may not reestablish.

Despite this, tidal wetland habitat is anticipated to keep expanding throughout Hexham Swamp, especially when environmental variables favour tidal over freshwater habitats. Due to the influence of environmental variables (e.g. rainfall, salinity, evapotranspiration, etc.) on vegetation growth the location within the wetland where tidal wetland transitions to freshwater wetlands will always be variable. Conceptually, it can be expected that during wet seasons (e.g. La Niña) freshwater habitat will increase, compared to dry seasons (e.g. El Niño) when higher salinity levels will favour tidal wetlands. Long-term environmental drivers (including the IPO) will continue to influence the wetland extent over longer timeframes. The prevailing climate conditions will be the primary influence on wetland extent.

While in the absence of climate change, a point would eventually be reached whereby the maximum extent of the tidal wetland can no longer increase, it would still be expected that the actual tidal wetland extent would continue fluctuating due to climate variability around a ‘average’ wetland extent (i.e. expand to its maximum during dry periods and contract to its minimum during wet periods). Analysis of climate data shows that the inherent high variability makes the accurate prediction of potential habitat extent impossible, especially with limited available water level and floodplain elevation data inside Hexham Swamp.

A4 Climate change influence on wetland processes

A4.1 Overview

Estuarine environments, including tidal wetlands like Hexham Swamp, will increasingly be influenced by changes to the climate caused by the anthropogenic climate change. At a conceptual level, increased greenhouse gas emissions will result in changes to five climate processes with impacts to the estuarine environment, including (Heimhuber et al., 2019c):

- Changes to rainfall
- Sea level rise
- Increased temperature and changes to evapotranspiration
- Increased ocean acidity
- Changes to wind patterns

Figure A.24 illustrates how each of these first order impacts will affect the estuarine environment. In the context of Hexham Swamp, each of these impacts will have flow on effects that impact the physical (e.g. salinity, biogeochemistry, etc.) and ecological (e.g. biodiversity, habitat establishment, etc.) processes throughout the wetland. The following section provides a review of the status of science regarding the first order impacts on the environment, and a high-level discussion of their flow on effects.

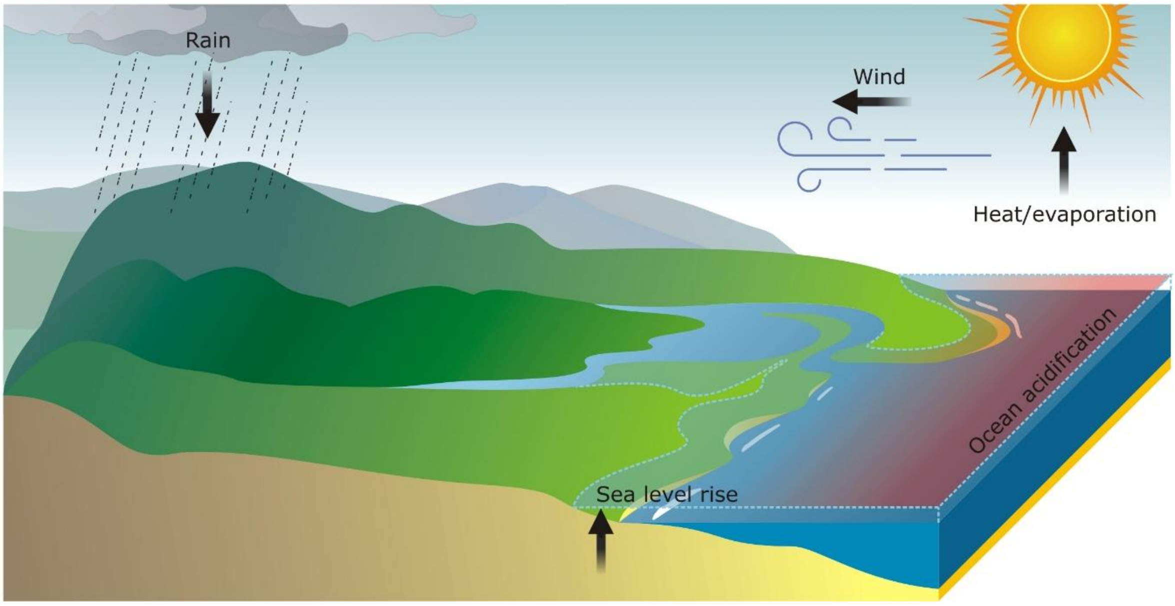

Figure A.24 The five first order impacts that increased greenhouse gas emissions will have on estuarine environments (Heimhuber et al., 2019c)

Extensive research has been conducted to identify how climate change will affect earth into the future (IPCC, 2023). In many instances, the scale of impacts associated with climate change will depend on the world's collective actions to mitigate the impacts of greenhouse gas emissions. To account for unknown future conditions, a range of scenarios have been developed that describe the worlds actions regarding climate change. These scenarios are known as Shared Socio-economic Pathways (SSPs) and represent different levels of global climate action. In total five SSPs have been developed including (IPCC, 2023):

- **SSP1-1.9** – Emissions decline from present day levels to net zero by 2050
- **SSP1-2.6** – Emissions decline from present day levels to net zero by 2070
- **SSP2-4.5** – Emissions remain at current levels until 2050 before declining
- **SSP3-7.0** – Emissions double by 2100
- **SSP5-8.5** – Emissions double by 2050

Prior to the development of SSPs, Relative Concentration Pathways (RCPs) were used to describe climate scenarios. Subsequently, much of the historic modelling of climate scenarios is presented with reference to RCPs. For the purpose of data presented in this report, RCPs can be considered equivalent to SSPs with the same number (e.g. RCP2.6 is equivalent to SSP1-2.6). Note, RCP6.0 does not have an equivalent SSP.

A series of numerical model simulations have been completed by research institutions around the world to understand the impacts of climate change on a local scale. This approach usually involves using Global Climate Models (GCMs) which include the entire planet at a resolution of approximately 200 km. To increase confidence in predictions, a range (or ensemble) of GCMs are used to provide a range of predicted future climates. Modelling of the climate for South East Australia has been conducted by CSIRO and BOM (2015). Their models have utilised an ensemble of over 40 GCMs that have been compared as part of a project known as CMIP5 (Model Intercomparison Project phase 5). The outputs from CMIP5 were then used to develop regional predictions for South East Australia by Dowdy et al. (2015).

Note, the information provided by GCMs can be difficult to interpret on a local scale. To overcome this, a process called downscaling using what are known as Regional Climate Models (RCMs) is implemented to increase resolution. The NSW and Australian Regional Climate Modelling (NARCLiM) project provides local estimates across NSW. NARCLiM allows for climate predictions on a 10 km or 50 km resolution across NSW. Three iterations of NARCLiM modelling exist: NARCLiM 1.0, NARCLiM 1.5, and NARCLiM 2.0. Analysis of results from NARCLiM 1.0 have been released for regional settings including the Hunter (OEH, 2014). Model results of NARCLiM 1.5 have also been released, however, there is limited analysis of this data available on a local scale (Nishant et al., 2021). NARCLiM 2.0 has recently been completed, however, results are yet to be released. Subsequently, for the purpose of this investigation, regional climate estimates provided by Dowdy et al. (2015) have been used to inform the future climate conditions with consideration given to analysis of NARCLiM data where information is available. Other predictions have been used for sea level rise and ocean acidity.

A4.2 Rainfall

Regional predictions for future rainfall are shown in Figure A.25. Overall, it is expected that in the near future natural climate variability will hide the influence of climate change. Moving into far future scenarios it can be expected that there will be a decrease in winter rainfall and an increase in summer rainfall (Dowdy et al., 2015). There is a medium confidence that winter rainfall will decrease, however, there is a significant uncertainty regarding an increase in summer rainfall. Increases only tended to occur in higher emission scenarios (i.e. RCP8.5). While there is significant uncertainty in these predictions, they are also supported by NARCLiM which indicates an increase in Autumn and Summer rainfalls in the coastal Hunter region (OEH, 2014; Nishant et al., 2021).

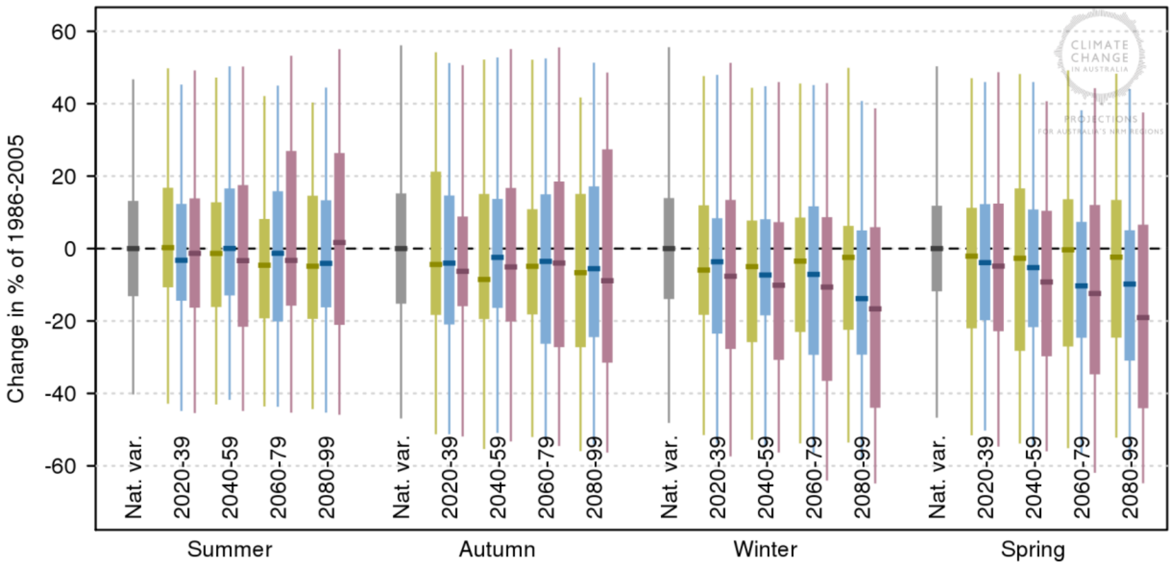

Figure A.25 Projected change in seasonal precipitation (Dowdy et al., 2015)

Anomalies are given in % relative to 1995 (1986-2005) under RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). Natural climate variability is represented by the grey bar. The middle (bold) line is the median value of the model simulations (20-year moving average climate); half the model results fall above and half below this line. The bars show the range (10th to 90th percentile) of model simulations of 20-year average climate. Line segments represent the projected range (10th to 90th percentile) of individual years considering year-to-year variability in addition to the long-term response (20-year average).

Under future climate change scenarios, a general decrease in annual rainfall is expected, however, the occurrence of extreme rainfall events is expected to increase. Dowdy et al. (2015) predicted that a 20-year rainfall event (with a 5% chance to occur in any given year) is expected to result in up to 30% (median 16%) more rainfall by 2090 (RCP4.5).

Environmental conditions across Hexham Swamp are highly influenced by rainfall. Subsequently, changes to rainfall due to climate change has the potential to significantly impact the values of the wetland. High variability in rainfall patterns will mean that in the near future it is unlikely that changes to day-to-day rainfall will be observed. Into the future, drier conditions during winter will allow for increased tidal influence. Conversely, during summer it can be expected that wetter conditions will prevail. Typically, extreme rainfall occurs throughout early stages of the year, and it would be expected that this would increase fresh conditions at these times within Hexham Swamp. Due to the high variability in rainfall predictions, it is difficult to predict the exact impact on the extent of tidal wetlands in Hexham, however, changing rainfall patterns will influence saline mixing and habitat establishment across the wetland.

A4.3 Sea level rise

Modelling of sea level rise has been completed for the ocean boundary of the Hunter River at Newcastle (see Figure A.26 and Table A.1). Median estimates for sea level rise range from 0.38 m to 0.82 m by 2100 depending on different climate scenarios (compared to 1995 to 2014 baseline). Numerical modelling of the Hunter River shows that provided there is no change in overbank inundation, negligible (<0.01 m) attenuation of ocean levels is expected to occur between Newcastle and Hexham (Harrison and Tucker, 2024). Therefore it is reasonable to assume that the levels provided in Figure A.26 and Table A.1 can be directly applied to the downstream boundary of Hexham Samp in the South Arm of the Hunter River and Ironbark Creek.

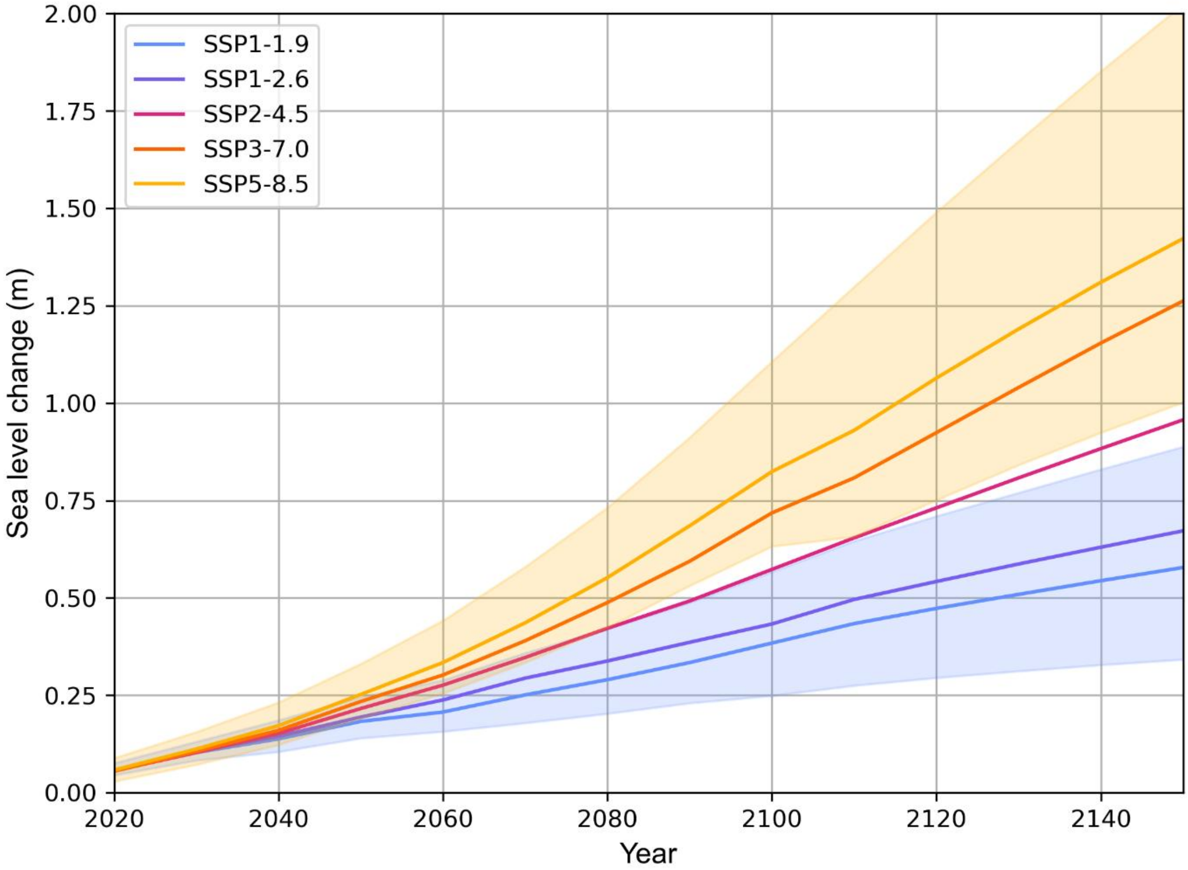

Figure A.26 Sea level rise projections at Newcastle (Fox-Kemper et al., 2021; Garner et al., 2021; Kopp et al., 2023)

Median values presented. Likely (17th and 83rd percentiles) indicated by shaded area for SSP1-1.9 and SSP5-8.5 sea level rise is relative to a baseline of 1995 to 2014.

Table A.1 Sea level rise projections at Newcastle (Fox-Kemper et al., 2021; Garner et al., 2021; Kopp et al., 2023)*

Scenario	2050 (m)	2100 (m)	2150 (m)
SSP1-1.9	0.18 (0.14–0.25)	0.38 (0.25–0.57)	0.58 (0.34–0.89)
SSP1-2.6	0.19 (0.14–0.27)	0.43 (0.30–0.62)	0.67 (0.43–1.02)
SSP2-4.5	0.22 (0.16–0.29)	0.57 (0.43–0.79)	0.96 (0.66–1.38)
SSP3-7.0	0.23 (0.18–0.31)	0.72 (0.55–0.96)	1.26 (0.90–1.74)
SSP5-8.5	0.25 (0.19–0.33)	0.82 (0.63–1.11)	1.42 (1.00–2.02)

*Median values presented with the likely (13th and 87th percentile) values shown in brackets. Sea level rise is relative to a baseline of 1995 to 2014.

Increased sea level rise will have the following impacts on Hexham Swamp:

- **Increased low tide levels:** Currently, low tide elevations fluctuate around -0.4 m AHD. As sea level rise occurs the low tide elevations will increase and result in larger areas of permanent inundation across the wetland. For the middle scenario (SSP2-4.5), low tide levels will increase above the majority of the floodplain by 2100. Where land is located below the high tide limit (which is increasing), the time it takes for land to drain will increase due to sea level rise (Waddington et al., 2022).
- **Increased high tide levels:** High tide water levels will also increase across Hexham Swamp, which will likely increase the area that is regularly inundated. Current high tides are approximately at 0.6 m AHD, which could increase to over 2 m AHD under the highest emission scenario by 2150. Existing infrastructure across the floodplain (e.g. Pipeline Road), are currently inundated on infrequent high tides. In the future this infrastructure could be permanently under water (by 2120 under high level emissions scenarios).
- **Reduced floodplain storage:** Hexham Swamp currently provides a level of flood protection due to its ability to store floodwaters. The existing wetland boundary was set at 1.5 m AHD (Haines et al., 2005). There is significant freeboard between high tides at present (0.6 m AHD) and the wetland limits (1.5 m AHD). Under sea level rise the ability for Hexham Swamp to store floodwaters will be reduced, increasing flood risk for surrounding areas.
- **Exacerbated extreme events:** The impact of extreme water level events (such as due to storm surge or king tides) will be exacerbated under sea level rise and impact land and infrastructure at higher elevations.

Changes to the tidal regime as a result of sea level rise will have many flow-on effects. For example, changes to salinity mixing can be expected (Heimhuber et al., 2019a). The extent and composition of wetland vegetation is also expected to significantly change based on the hydrology (Saintilan et al., 2018; Henderson and Glamore, 2024b).

A4.4 Temperature and evapotranspiration

Predictions for temperature (Figure A.27) and evapotranspiration (Figure A.28) have an increasing trend into the future under all scenarios (Dowdy et al., 2015). Local scale (NARCLiM 1.0 and NARCLiM 1.5) modelling supports this trend (OEH, 2014; Nishant et al., 2021).

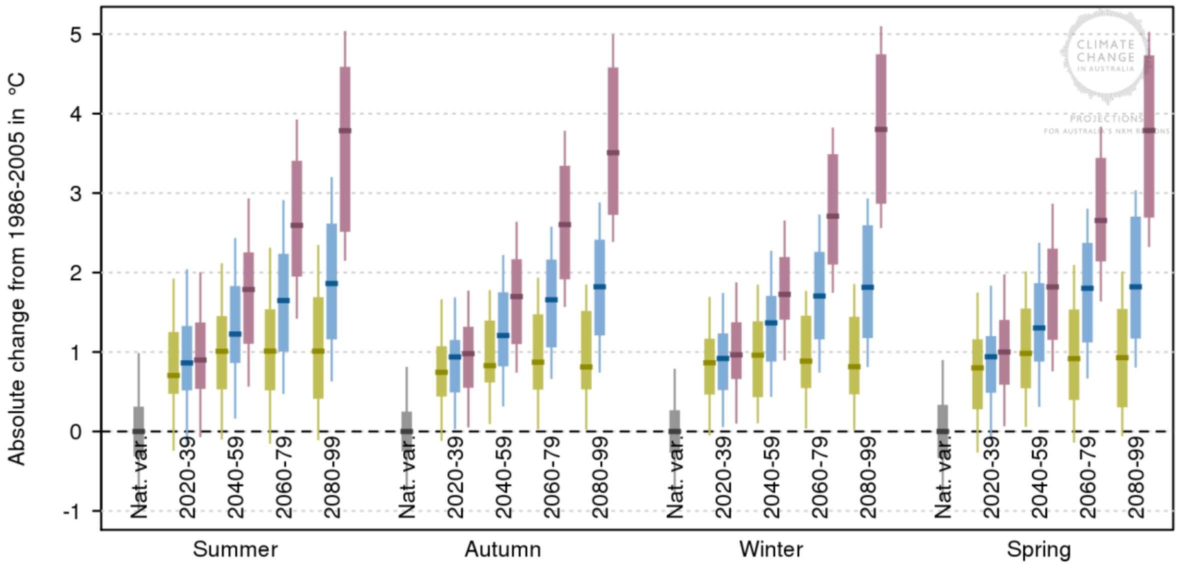

Figure A.27 Projected change in seasonal temperature (Dowdy et al., 2015)

Anomalies are given in % relative to 1995 (1986-2005) under RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). Natural climate variability is represented by the grey bar. The middle (bold) line is the median value of the model simulations (20-year moving average climate); half the model results fall above and half below this line. The bars show the range (10th to 90th percentile) of model simulations of 20-year average climate. Line segments represent the projected range (10th to 90th percentile) of individual years considering year-to-year variability in addition to the long-term response (20-year average).

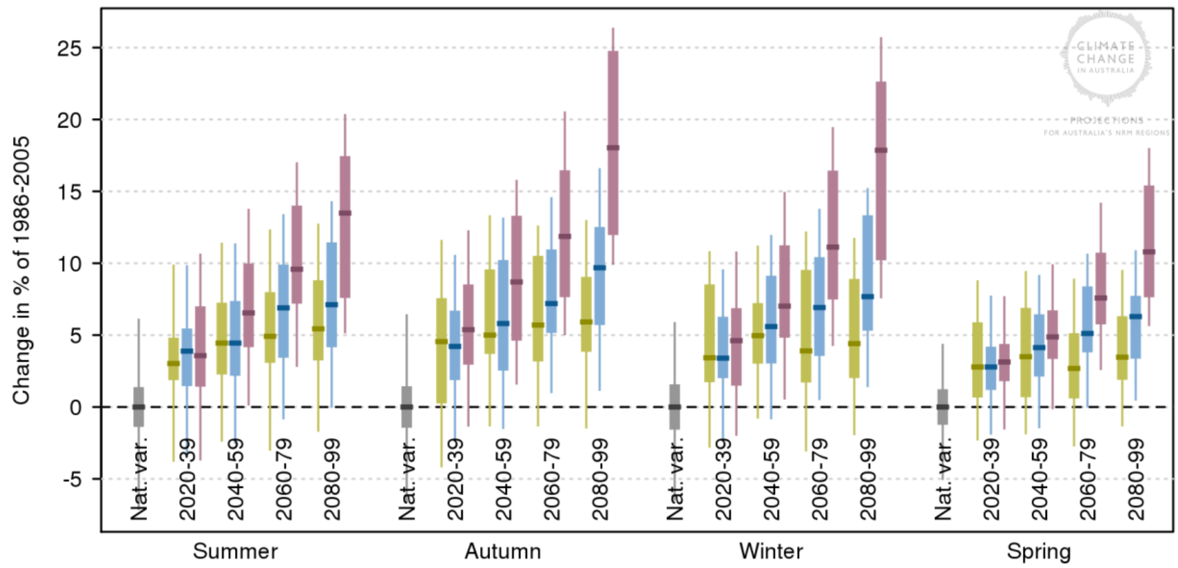

Figure A.28 Projected change in seasonal evapotranspiration (Dowdy et al., 2015)

Anomalies are given in % relative to 1995 (1986-2005) under RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). Natural climate variability is represented by the grey bar. The middle (bold) line is the median value of the model simulations (20-year moving average climate); half the model results fall above and half below this line. The bars show the range (10th to 90th percentile) of model simulations of 20-year average climate. Line segments represent the projected range (10th to 90th percentile) of individual years considering year-to-year variability in addition to the long-term response (20-year average).

At Hexham Swamp there will be a range of impacts associated with increased temperatures and evapotranspiration which could include (Heimhuber et al., 2019a; Saintilan et al., 2018; Henderson and Glamore, 2024b):

- Changes to temperature dependent biogeochemical processes (e.g. nutrient cycling)
- Changes to stratification and salinity (e.g. hypersaline conditions due to increased evaporation)
- Decreased oxygen solubility in waterways (favouring the occurrence of hypoxic events)
- Decreased carbon dioxide solubility which influences acidity and buffering capacity of waterways
- Changes to the extent and composition of wetland habitat

A4.5 Acidity

Climate change will influence acidity in two key ways that could influence Hexham Swamp (Heimhuber et al., 2019a):

- Climate change will impact rainfall patterns (see Appendix A4.2) that can facilitate high acid conditions (i.e. transport of acid from acid sulfate soils)
- Climate change will result in the increase of ocean acidity

Approximately 30% of all carbon dioxide released into the atmosphere is stored in the ocean (Dowdy et al., 2015). When absorbed by the ocean, carbon dioxide decreases the ocean acidity. Since pre-industrial times, the ocean pH has already dropped by 0.1 pH units from 8.17 (Pörtner et al., 2014). Since pH occurs on a logarithmic scale, although acidity has only changed by 0.1 pH units, this translates to a 26% rise in acidity (Dowdy et al., 2015; Pörtner et al., 2014). Further decreases in ocean pH levels by 0.13, 0.22, 0.28, and 0.42 pH units is expected to occur under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 climate scenarios, respectively (Pörtner et al., 2014).

At Hexham Swamp, ocean acidification would be expected to influence the following processes across the wetland (Heimhuber et al., 2019a; Dowdy et al., 2015):

- The solubility of metals
- Water chemistry
- The distribution and composition of ecosystems
- Ability to buffer acidic events

One of the major impacts associated with increased acidity results from decreased carbonate concentrations, a mineral that some marine organisms (such as oysters) require for their shells or hard skeletons (Dowdy et al., 2015). Along with impacts to ecosystem, ocean acidification is predicted to have negative effects on aquaculture, tourism and coastal protection (Dowdy et al., 2015; IPCC, 2023).

A4.6 Wind

Regional predictions for changes to wind generally indicate an increasing trend in Spring and Summer with a decreasing trend in Autumn and Winter (Figure A.29). It is difficult to project the exact influence of changes to wind on Hexham Swamp. Different wind patterns could influence a range of environmental variables across the wetland such as circulation and mixing of water (Heimhuber et al., 2019c). Wind is also an important factor during coastal storms. An increase in wind speed could result in impacts such as increased storm surge (Heimhuber et al., 2019b).

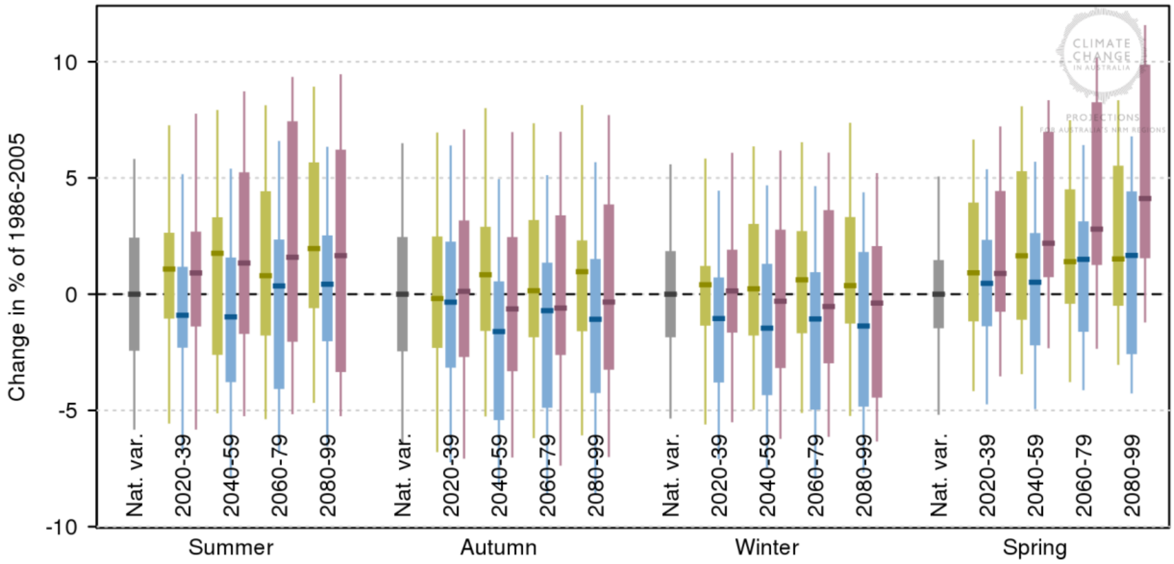

Figure A.29 Projected change in seasonal wind speed (Dowdy et al., 2015)

Anomalies are given in % relative to 1995 (1986-2005) under RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (purple). Natural climate variability is represented by the grey bar. The middle (bold) line is the median value of the model simulations (20-year moving average climate); half the model results fall above and half below this line. The bars show the range (10th to 90th percentile) of model simulations of 20-year average climate. Line segments represent the projected range (10th to 90th percentile) of individual years considering year-to-year variability in addition to the long-term response (20-year average).

Appendix B Site inspection

To inform the investigation, a site inspection was conducted on 6 June 2024. Representatives from HLLS and the UNSW Sydney Water Research Laboratory attended. The inspection included visiting key parts of the wetland, including:

- The Hunter Wetlands Centre
- The Ironbark Creek floodgates
- Driving along Pipeline Track to Ironbark Creek (returning via Hartin's Trail)
- Visiting Kau-má Park overlooking the western side of the wetland

During the inspection several RTK-GPS measurements were observed. These measurements included:

- Confirmation of the invert elevation and sizing of the Ironbark Creek floodgates (see Appendix A2.5).
- Identification that the southern extent of Pipeline Road has an elevation of +0.6 m AHD
- A 0.9 m diameter culvert underneath Hartin's Lane providing connectivity for Hartin's Creek has an invert elevation of -0.1 m

Several photos were also taken throughout the site visit (see Figure B.1 to Figure B.15).

Figure B.1 Hunter Wetlands Centre

Figure B.2 Upstream side of the Ironbark Creek floodgates

Figure B.3 The lifting mechanism on one of the floodgate flaps

Figure B.4 Ironbark Creek looking upstream from the floodgates

Figure B.5 Phragmites across Hexham Swamp (looking west from Pipeline Track)

Figure B.6 Iron floc in the bottom of a drain adjacent to Hartin's Track

Figure B.7 Tyres across the floodplain adjacent to the wetland

Figure B.8 Saltmarsh field growing to the west of Pipeline Track

Figure B.9 Mangroves growing at their upstream limit

Figure B.10 An open waterbody with mangroves growing on its fringes

Figure B.11 Looking north from the southern end of Pipeline Track

Figure B.12 A 0.9m diameter culvert underneath Hartin's Track allowing Hartin's Creek to flow

Figure B.13 Saltmarsh that had been trampled by stock

Figure B.14 Channels at the connection between Spoonbill Creek and the Hunter River

Figure B.15 Hexham Swamp looking east from Kau-má Park

Appendix C Hydrological risk and opportunity assessment method

A hydrological assessment of the risks and opportunities posed to ecosystem services provided by Hexham Swamp from climate change has been completed by mapping ecosystem services to physical or ecological indicators that will respond to climate change. Table C.1 outlines and provides justification for how each indicator was mapped to a range of ecosystem services.

A likelihood scale (shown in Table C.2) and consequence scale (shown in Table C.3) were then developed for the indicators based on the approach outlined by AGO (2006) and recommended for use in coastal planning across NSW (OEH, 2018). Both risks and opportunities that will result from climate change were considered. The combined risk matrix can be seen in Table C.4 and the combined opportunity matrix can be seen in Table C.5.

The risk and opportunity assessment applied to each of the indicators is provided in Table C.6.

Table C.1 Description of indicators used for the assessment and how they are linked to ecosystem services

Indicator	Linked ecosystem service	Description for how ecosystem service is linked to process
Habitat extent – tidal wetland	Provisioning (food)	Mangrove and saltmarsh habitats are important nutrition sources for fish, which subsequently support commercial fisheries (Heimhuber et al., 2023; Taylor et al., 2018). Increasing the extent of tidal wetland habitats therefore results in an increase in the provisioning (food) ecosystem services through improved commercial fisheries.
Habitat extent – tidal wetland	Climate regulation	Tidal wetland habitats are often referred to as 'blue carbon' due to their ability to naturally sequester carbon at high rates (Macreadie et al., 2021). They are able to store significant volumes of greenhouse gases in their biomass and through soil accumulation, and can prevent release of methane (a greenhouse gas), as occurs in freshwater wetlands (Lovelock et al., 2022).
Habitat extent – tidal wetland	Habitat and biodiversity support	Tidal wetland habitats are well known to be important nurseries for juvenile fish (Jänes et al., 2020). Surveys of Hexham Swamp also indicate that there is increasing diversity in vegetation and fauna associated with tidal wetlands (HLLS, 2021; Boys and Pease, 2017).
Habitat extent – tidal wetland	Tourism and recreational use	Tidal wetlands can support tourism and recreation as they provide important habitat for birdlife (Hexham Swamp adjoins/includes Ramsar listed areas important for the habitat they provide to migratory shorebirds), and also provide nutrition to fish that are used for recreational fishing (Taylor et al., 2024).
Habitat extent – freshwater wetland	Habitat and biodiversity support	Freshwater wetlands also provide important habitat for a range of vegetation and fauna. Examples of important fauna at Hexham Swamp include the Green and Golden Bell Frog and the Australasian Bittern (HLLS, 2021).
Habitat extent – freshwater wetland	Tourism and recreational use	Freshwater wetlands can also support tourism and recreation as they provide important habitat for birdlife. For example, the Australasian Bittern is a significant bird species historically known to inhabit Hexham Swamp that could encourage tourism (HLLS, 2021).
Flood storage	Mitigation of extreme events	Wetland habitats are able to provide a range of ecosystem services through mitigation of impacts of extreme storm events (Costanza et al., 2021; Mulder et al., 2020; Carnell et al., 2024). In the case of Hexham Swamp, its ability to mitigate extreme events is associated with its capacity to store floodwaters. Note that this service is also linked to the management of the floodgates.

Indicator	Linked ecosystem service	Description for how ecosystem service is linked to process
Water quality – dissolved oxygen	Regulation of water quality	Dissolved oxygen is important throughout biogeochemical cycling of water quality in wetlands (Mines, 2014). In the future, higher temperatures will mean there are lower levels of dissolved oxygen in the water, limiting the ability of the wetland to regulate water quality.
Water quality – acidity	Regulation of water quality	Acidity is another measure of water quality that wetlands (particularly tidal wetlands) can regulate (Ruprecht et al., 2018; Carnell et al., 2024).
Water quality – acidity	Regulation of soil quality	Exposed or acid sulfate soils provide a good indicator of poor soil quality. Wetlands are able to regulate the impact associated with acid sulfate soils in a number of ways (such as retaining high water levels to prevent their exposure, limiting transport of acid or allowing acid buffering in the case of tidal wetlands) (Ruprecht et al., 2018; Carnell et al., 2024).
Water quality – nutrients and sediments	Regulation of water quality	Wetlands are well known for their ability to regulate nutrients and sediment (Carnell et al., 2024). One of the mechanisms that makes wetlands effective at this is called denitrification, where the nutrient nitrogen is removed from water and released into the atmosphere (Seitzinger, 1988).
Unknown	Enabling education and training	There is clear evidence that Hexham Swamp and the Hunter Wetlands Centre provides valuable ecosystem services by enabling education and training (Hunter Wetlands Centre, 2025). Understanding and mapping how physical processes of climate change will impact this service is complex and requires further research to determine the level of risk/opportunity.
Unknown	Cultural heritage, existence and spiritual value	There is clear evidence that Hexham Swamp provides valuable ecosystem services by enabling cultural heritage, existence and spiritual value. This is evidenced by important Aboriginal Places located at the site such as the Rocky Knob Aboriginal Place (NSW Government, 2022). Understanding and mapping how physical processes of climate change will impact this service is complex and requires further research to determine the level of risk/opportunity. Note, when considering the existence value of Hexham Swamp, consideration should be given to the existing amenity it provides. This may be impacted by climate change in a number of ways. For example, Webb (2020) notes that under a changing climate the mosquito season may be extended.

Table C.2 Likelihood scale

Rating	Description of likelihood
Almost certain	More likely than not (probability is greater than 50%)
Likely	As likely as not (50/50 chance)
Possible	Less likely but still appreciable (probability is less than 50%)
Unlikely	Unlikely but not negligible
Rare	Negligible (close to zero probability)

Table C.3 Consequence scale

Risk or opportunity	Rating	Description of consequence
Risk	Catastrophic	Major widespread loss or detriment to the indicator and progressive ongoing loss or detriment to the indicator.
Risk	Major	Substantial loss or detriment to the indicator and danger of continuing loss or detriment to the indicator.
Risk	Moderate	Isolated but significant loss or detriment to the indicator that might be reversed with intensive efforts.
Risk	Minor	Isolated but noticeable examples of decline or detriment of the indicator.
Risk	Insignificant	Loss or detriment of the indicator is threatened but not impacted.
Opportunity	Insignificant	Slight increase or improvements in the indicator which may have been realised anyway.
Opportunity	Minor	Small but noticeable increases or improvement of the indicator.
Opportunity	Moderate	An isolated but significant increase or improvement of the indicator naturally arises. Further increase or improvement can be facilitated with intensive efforts.
Opportunity	Major	An increase or improvement in the indicator is naturally facilitated and may naturally continue to increase and improve without intervention.
Opportunity	Exceptional	A major increase or improvement in the indicator is naturally facilitated with abundance and results in the natural perpetuation of further increases or improvements of the indicator.

Table C.4 Risk matrix

	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	High	Extreme
Possible	Low	Medium	High	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Medium	Medium	High

Table C.5 Opportunity matrix

	Insignificant	Minor	Moderate	Major	Exceptional
Almost certain	Medium	High	High	Extreme	Extreme
Likely	Medium	Medium	High	High	Extreme
Possible	Small	Medium	High	High	High
Unlikely	Small	Small	Medium	Medium	High
Rare	Small	Small	Medium	Medium	High

Table C.6 Assessment of the risks or opportunities for physical indicators under climate change

Indicator	Linked ecosystem service	Consequence	Likelihood	Risk or opportunity	Predicted indicator change due to climate change at Hexham Swamp
Habitat extent – tidal wetland	Provisioning (food) Climate regulation Habitat and biodiversity support Tourism and recreational use	Major	Almost certain	Extreme opportunity	Tidal wetland habitat at Hexham Swamp is expected to either remain stable or increase under climate change. Sea level rise will result in an increase in the saltwater extent throughout the wetland. Increased evapotranspiration is likely to result in conditions that are favourable for saltmarsh over mangrove habitat (at higher elevations). However, increased water levels will favour the establishment of mangroves. In far future scenarios it is likely tidal wetland habitat will be impacted by coastal squeeze.
Habitat extent – freshwater wetland	Habitat and biodiversity support Tourism and recreational use	Major	Almost certain	Extreme risk	Freshwater wetland habitat at Hexham Swamp is expected to decline under climate change due to sea level rise and increased tidal influence across the wetland.
Flood storage	Mitigation of extreme events	Major	Almost certain	Extreme risk	The flood storage capacity provided by Hexham Swamp is expected to decline under climate change due to sea level rise. The volume available for flood storage will be reduced. This may be exacerbated by changes to the catchment inflows due to climate change (e.g. more intense events) as well as catchment development (Dowdy et al., 2015).
Water quality – dissolved oxygen	Regulation of water quality	Insignificant	Almost certain	Medium risk	Water quality associated with dissolved oxygen is expected to decline in the future. Increased temperatures reduce the saturation of oxygen in the water column. At the same time, increased water temperatures facilitate higher oxygen demand within wetland systems (e.g. through the breakdown of organic matter).

Indicator	Linked ecosystem service	Consequence	Likelihood	Risk or opportunity	Predicted indicator change due to climate change at Hexham Swamp
					Tidal flushing will increase with sea level rise; however, this will be controlled by the Ironbark Creek floodgates limiting its effectiveness.
Water quality – acidity	Regulation of water quality Regulation of soil quality	Moderate	Likely	High opportunity	Acidic runoff from acid sulfate soils (currently the largest contributor to poor quality acidic water) are expected to reduce as acid sulfate soils are no longer oxidised under sea level rise. On the other hand, ocean acidity due to climate results will mean tidal water flowing into Hexham Swamp is slightly more acidic. Lower levels of carbonate in this water may impact the growth of marine organisms (e.g. oysters and juvenile fish). Overall, less event based acidic events would be likely to occur, however, the average acidity throughout the system will be slightly more acidic.
Water quality – nutrients and sediments	Regulation of water quality	Insufficient data to assess	Insufficient data to assess	Unknown	Wetland habitats are a nutrient sink due to their denitrification potential. Unfortunately, the potential at Hexham will likely be limited by the preexisting high levels of nutrients in the Hunter River estuary (Tucker et al., 2024). High levels of nutrients can be harmful for wetland habitats. Further research is required to quantify these impacts into the future. The benefits provided by wetland would only be realised if other catchment management actions are implemented.