Blue Carbon Feasibility Assessment at the Duck Creek DPI Research Station

WRL RR 2022/272, FINAL, July 2023

By William Glamore, Valentin Heimhuber & Duncan Rayner

UNSW Water Research Laboratory

UNSW SYDNEY

UNSW Water Research Laboratory

UNSW SYDNEY

Blue Carbon Feasibility Assessment at the Duck Creek DPI Research Station

WRL RR 2022/272, FINAL July 2023

By William Glamore, Valentin Heimhuber & Duncan Rayner

Project details

Report title	Blue Carbon Feasibility Assessment at the Duck Creek DPI Research Station
Authors(s)	William Glamore, Valentin Heimhuber & Duncan Rayner
Report no.	2022/272
Report status	FINAL
Date of issue	17th July 2023
WRL project no.	RG220733
Project manager	Prof William Glamore
Client	NSW Department of Regional NSW
Client address	Division of Primary Industries, DPI Fisheries 1243 Bruxner Highway, Wollongbar, NSW, 2477
Client contact	Mr Patrick Dwyer Patrick.dwyer@dpi.nsw.gov.au

This project was funded by the NSW Government under the Marine Estate Management Strategy. The ten-year Strategy was developed by the NSW Marine Estate Management Authority to coordinate the management of the marine estate. www.marine.nsw.gov.au

UNSW
Water Research Laboratory

www.wrl.unsw.edu.au
110 King St Manly Vale NSW 2093 Australia
Tel +61 (2) 8071 9800 ABN 57 195 873 179

This report was produced by the Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Sydney,

This report should be cited as:
Glamore, W., Heimhuber, V., and Rayner, D. (2022) Blue Carbon Feasibility Assessment at the Duck Creek DPI Research Station. WRL Research Report 272, July 2023.

Contents

List of tables

List of figures

1 Introduction

The NSW Department of Primary Industry (henceforth DPI) manages a 192-hectare (ha) research station at Duck Creek, Pimlico for cattle grazing, including a cattle genomics research project. The site is situated on the right bank of Emigrant Creek at the junction with the Richmond River estuary approximately 7.8 km from the ocean entrance (Figure 1.1). Estuarine macrophytes (mangroves and saltmarsh) occupy intertidal areas around the site perimeter and have the potential to establish within the site if tidal barriers are removed or modified. DPI is currently investigating the feasibility of the site, or individual sections within the property, for registration in accordance with the Australian Clean Energy Regulator's (CER) "Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022" (hereafter, The Blue Carbon Method) of the Emissions Reduction Fund (ERF) (CER, 2022).

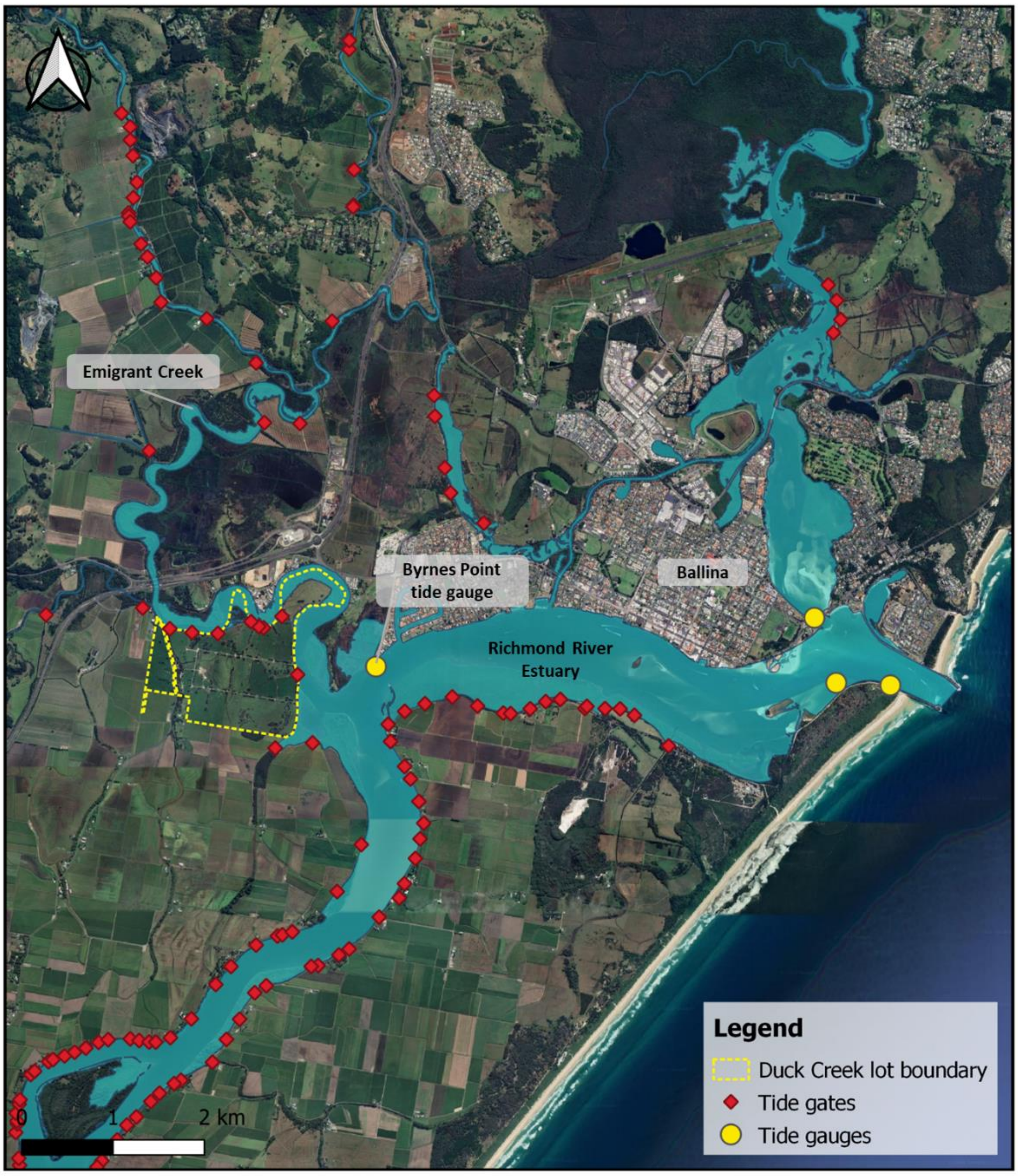

Figure 1.1: Location of the Duck Creek DPI research station, near Ballina, NSW. Also shown are the locations of tidal floodgates and tidal gauges within the Richmond River estuary.

For this study, a blue carbon feasibility assessment was undertaken at the Duck Creek DPI property by the UNSW's Water Research Laboratory (this report). The hydrological assessment comprised the following three components:

1. Preliminary hydrological assessment of existing blue carbon opportunities aligned to the minimum requirements for a CER registered blue carbon project.
2. Preliminary hydrological assessment of future blue carbon opportunities; and,
3. Design of a monitoring and reporting program.

Figure 1.2 outlines the best-practice process for assessing and implementing blue carbon restoration projects (Heimhuber *et al.,* 2022). This feasibility assessment is comprised of Step 1 (Site scoping and feasibility), as well as the 'opportunity identification' part of Step 2 (Site assessment & blue carbon method certification). In addition, a preliminary monitoring program is designed for one of the tidal introduction opportunities (Step 4, monitoring and adaptive management).

This study is a first-pass feasibility assessment of the potential tidal restoration options across the property between now and the end of this century. It is intended to determine eligible tidal restoration options (if any) that can be used to develop a staged tidal restoration action plan for the property. The tidal restoration action plan will need to carefully balance the social, economic, and environmental uses/values of the existing site versus the potential risks and benefits of an alternative site management approach. Additional detailed planning studies (Step 2, Figure 1.2) are recommended before the project proceeds to CER registration or prior to undertaking on-ground tidal inundation works.

This report details the methods and results of the Duck Creek blue carbon feasibility assessment and is structured into the following chapters:

2. Data collection and processing
3. Site hydrology
4. Blue carbon feasibility assessment
5. Design of a monitoring and reporting program
6. Summary and discussion

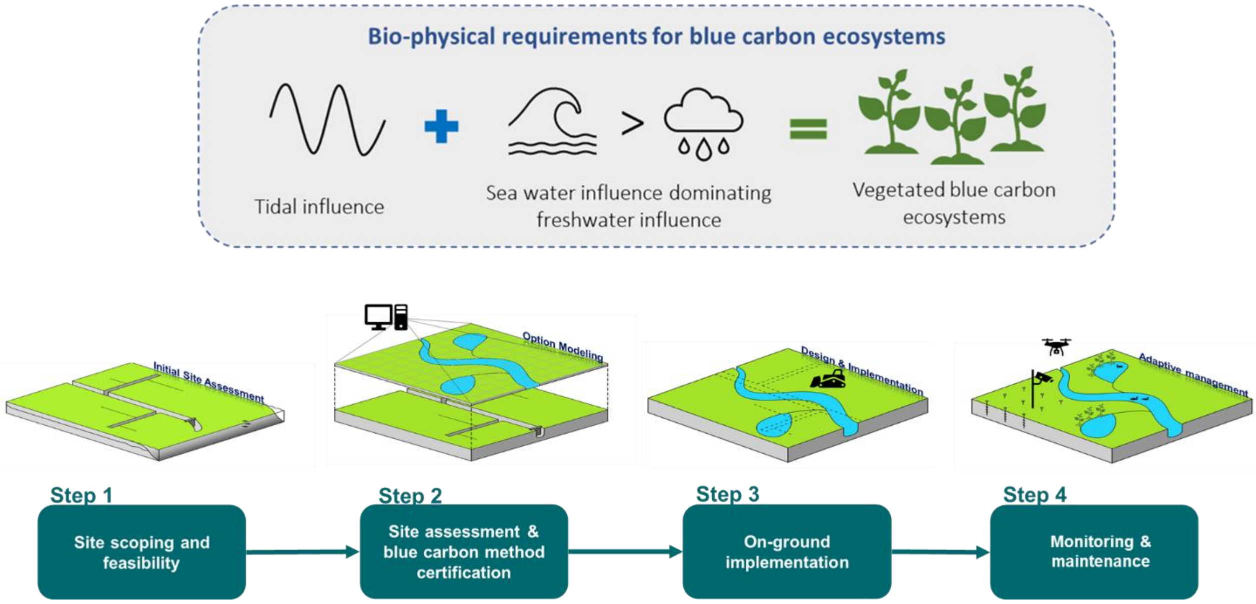

Figure 1.2: Schematic outlining the 'best-practice' process of assessing and implementing blue carbon restoration projects (source; Heimhuber et al., 2022).

1.1 Site background

The Duck Creek Research Station was commissioned as a partner site to the larger Wollongbar Primary Industries Institute circa 1894 (NSW Government, 1894). The 192 ha Duck Creek DPI research station is located approximately 7.8 km upstream of the mouth of the Richmond River Estuary near Ballina, NSW (Figure 1.1). The site is located on the Richmond River floodplain, which covers an area of approximately 620 km^2 (considering all areas up to 5 m AHD). The Duck Creek Research Station presently acts a key location for DPI's Southern Multi Breed cattle genetics evaluation project and provides a geographical and data linkage into corresponding research conducted in northern tropical production systems. The Wollongbar/Duck Creek sites are the second longest standing research station maintained by DPI.

The Duck Creek property has an average elevation of 0.77 m AHD, which is below the highest astronomical tide (HAT). The site is predominately covered with pasture grasses used for cattle grazing and feed production, while many of the adjacent neighbouring properties are currently under sugar cane cultivation. The property has undergone extensive hydrological modification over the previous century, including the construction of a regional levee, internal bunds, and an extensive network of drainage channels. Some of these modifications can be readily observed in the historic aerial images shown in Figure 1.3.

Before major engineering interventions, the site consisted of intertidal wetlands and fresh or brackish backswamps. These habitats can be observed in the 1942 aerial image in Figure 1.3. This wetland-dominated site was described by Neville Morrow, farm assistant at Duck Creek between 1955 and 2004, as:

"That country was all freshwater and saltwater. What wasn't saltwater was high ground with freshwater locked behind it."

In the Richmond River floodplain, the natural drainage system was modified via the construction of drains and levees. These works commenced in the 19th century and continued throughout the 20th and 21st centuries. Significant drainage works during the 20th century were primarily undertaken to promote dry land agricultural production and prevent saline intrusion into low-lying floodplain areas (Tulau, 2011). These State funded flood mitigation works included deepening and straightening of existing drainage systems and the installation of drainage control structures such as one-way tidal floodgates. Tulau (2011) noted that despite the terminology, the 1950-70s 'flood mitigation' schemes were overwhelmingly wetland drainage schemes.

Figure 1.4 shows two recent high resolution aerial images taken after periods of high rainfall. The extensive network of major and minor drains that was constructed on the property can be readily observed in aerial images. All areas of the property that are on the landward side of the regional flood levee are effectively drained and used for cattle grazing or silage production. Areas that might experience prolonged inundation after rainfall are highlighted in Figure 1.4. However, further investigations would be required to support this observation. For context, Figure 1.6 shows selected photographs from a variety of key features across the site. The locations of these photographs are shown in Figure 1.5.

Figure 1.7 depicts the influence of the extensive drainage works on the onsite hydrologic conditions**.** Before the drainage works, vegetated backswamp areas used to retain local rainfall and runoff for prolonged periods, providing wetland ecosystem services, while also minimising the exposure of acid sulfate soils (ASS). Since construction of the drainage works, local rainfall and runoff is drained from the site via a network of low-gradient drainage channels and end of system tidal floodgates (e.g., see picture 4 in Figure 1.6). These tidal floodgates allow the water in the drainage networks to flow into the estuary when the tide water level is lower than the water level upstream of the gate but restricts tidal flows in the upstream/landward direction. Consequently, rainfall inputs to the site are rapidly drained (typically within 5 days), resulting in mostly dry land pastures and a lowered groundwater table. This has the potential to exacerbate ASS risks in parts of the property.

ASSs are naturally occurring sediments that underlay most coastal floodplains of NSW. When exposed to oxygen, via excavation or lowering of the watertable, potential ASSs react to form actual ASSs, which lowers the pH and potentially solubilise heavy metals (e.g., iron and aluminium) (Stone et al., 1998). Broad-acre drainage of ASSs can impact downstream waterways and aquatic ecosystems. Excavation of ASS is regulated and requires approval in NSW.

Figure 1.8 shows state-wide ASS risk mapping, and soil acidity (pH) data for nearby soil profiles (Naylor et al., 1998). The state-wide mapping indicates that the property has a high risk of ASS. Local soil profiles indicates that acidic soils have been measured within the property, however, the distribution of ASS appears to be variable.

Figure 1.3: Historical aerial images of the Duck Creek site from 1942 and 1966, depicting the drainage works undertaken onsite.

Figure 1.4: Recent high-resolution aerial images of the Duck Creek site, depicting the current land cover and drained character of the site. The white circles in the top image highlight areas of prolonged inundation during wet periods.

Figure 1.5: Location of geolocated photographs shown in Figure 1.6

Figure 1.6 Georeferenced photographs showing the drainage channel network, end of drain culverts, tidal floodgates, and relict mangroves inside the regional levee (photo #5). See Figure 1.5 for photograph locations.

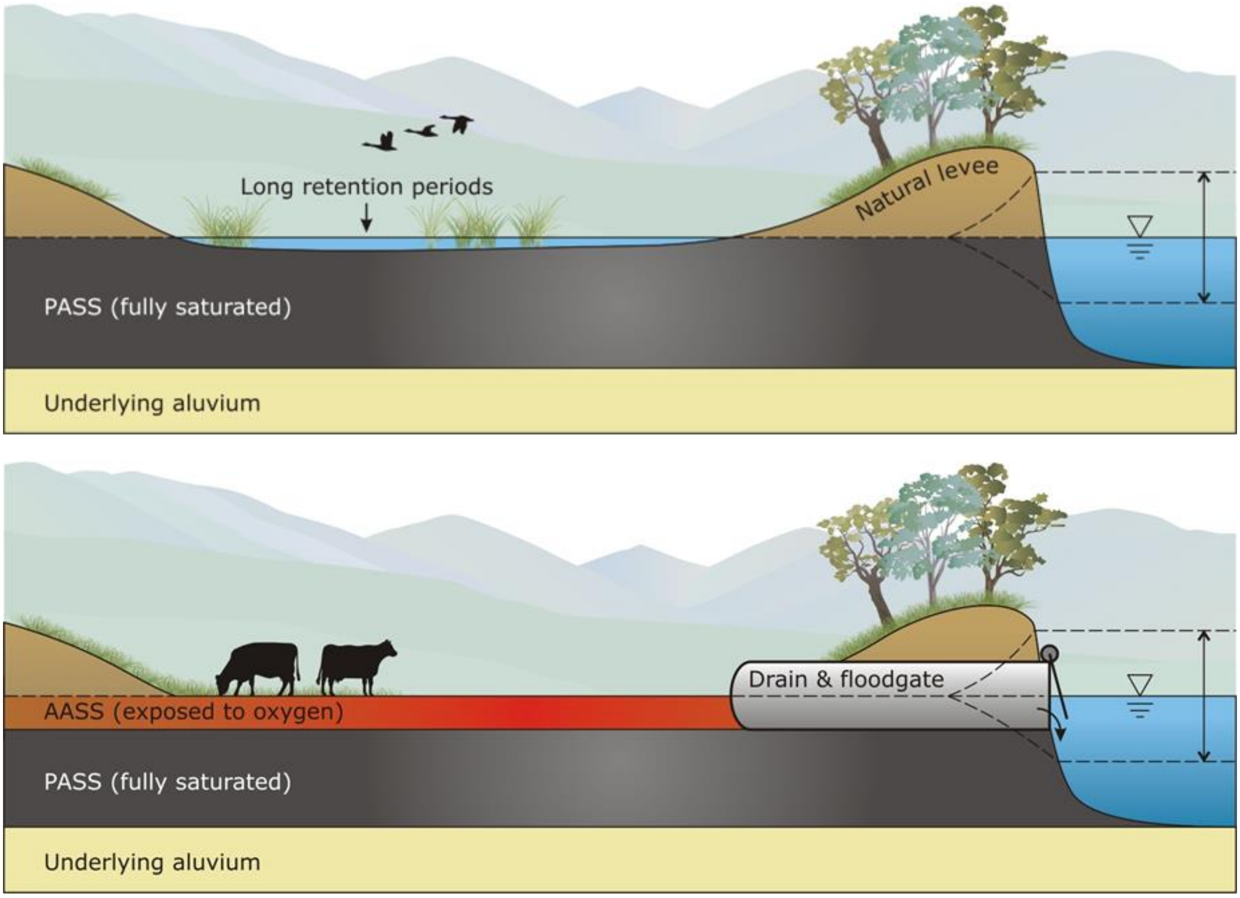

Figure 1.7: Conceptual schematic of the Duck Creek site before and after the construction of drainage works. Note that artificial drainage encourages oxidation of acid sulfate soils creating acidic conditions.

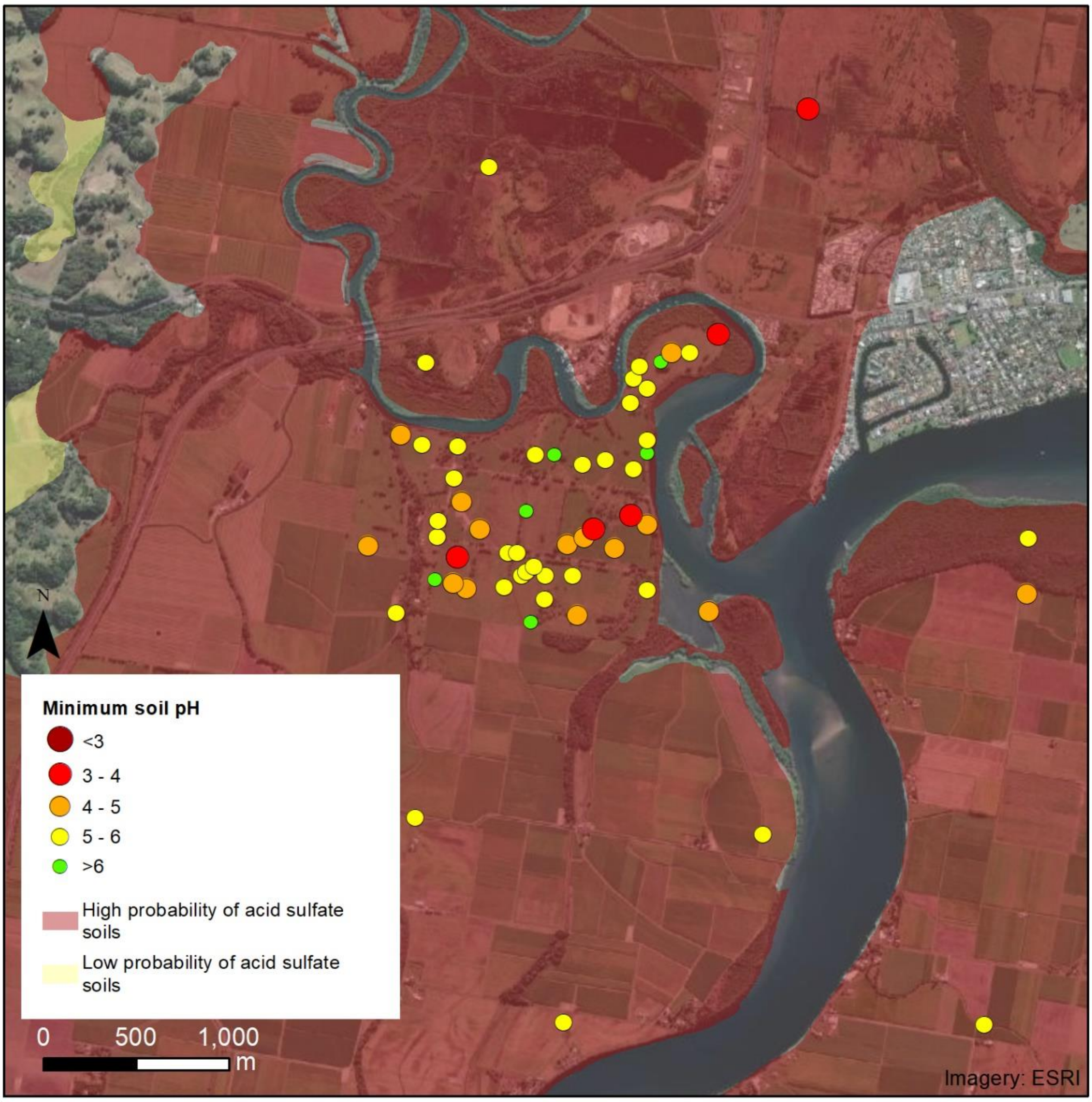

Figure 1.8: Acid sulfate soil risk mapping and soil profile data for the Duck Creek site and surrounding areas. Source: (Naylor et al., 1998)

2 Data collection and processing

2.1 Field data

An onsite field campaign was undertaken June 2-3, 2022, to conduct a hydrological inspection and spatial survey. This field campaign collected data necessary to develop an accurate understanding of water movements across the site under existing conditions. The fieldwork included the following activities:

- Topographic survey of accessible areas via a Trimble R10 RTK GNSS system with a max precision of ±8 mm horizontal and ±15 mm vertical. All GPS data were acquired in real time kinematic (RTK) mode via a nearby GPS CORSnet base station.
- Survey of key hydraulic structures such as drains, levees, tide gates and culverts via the RTK GPS.
- Ground elevation survey of existing blue carbon vegetation communities around the perimeter of the property.
- Collection of geolocated photos across the site including key hydraulic features.

Figure 2.1 shows the location of all geolocated photos taken across the property. These photos are provided as a data file that can be loaded into Google Earth or a suitable GIS system for future investigations. Figure 2.2 shows the GPS surveyed elevations taken from within the onsite drainage channels. In addition, bottom (or ground) elevations were surveyed at selected intertidal vegetation communities (i.e., existing saltmarsh and mangroves) to validate the predicted vegetation outcomes of different tidal restoration options. Elevations were surveyed at ground level either within a certain vegetation class or at the interface between subsequent vegetation classes (i.e., mangrove to saltmarsh; saltmarsh to coastal upland forest).

2.2 Additional datasets

In addition to data collected during the fieldwork, the following datasets have been acquired:

- **Rainfall:** Monthly mean rainfall data was sourced through the Australian Bureau of Meteorology for a weather station located at Ballina Airport near the site. The data is accessible here: http://www.bom.gov.au/climate/averages/tables/cw_058198.shtml

- **Evapotranspiration:** Monthly mean potential evapotranspiration data is not readily available through the Australian Bureau of Meteorology. Therefore, the data was sourced from a 2012 study undertaken by BMT WBM (BMT WBM, 2012).

- **Tide data**: Tide data was obtained for the Byrnes Point permanent tide gauge from Manly Hydraulics Laboratory. Tidal planes were obtained from the "OEH NSW tidal planes analysis 1990-2010 harmonic analysis" report (Couriel et al., 2012).

- **Digital elevation model (DEM)**: A pre-processed 1 m resolution LiDAR based DEM was obtained from ELVIS (https://elevation.fsdf.org.au/) titled *"Ballina 2010-06-26 2kmx2km 1 metre Resolution Digital Elevation Model"*. The DEM is shown in Figure 2.2 and Figure 2.3 and its specifications are as follows: "The 1 m metre DEM is produced using TIN (Triangular Irregular Network) method of averaging ground heights to formulate a regular grid. This data set contains ground surface model in ASCII grid format derived from C3 LiDAR (Light Detection and Ranging) from an ALS50ii (Airborne Laser Scanner). The model is not hydrologically enforced.

This data has an accuracy of ±0.3 m (95% Confidence Interval) vertical and ±0.8m (95% Confidence Interval) horizontal." (DFSI Spatial Services, 2021).

- **Existing estuarine macrophyte mapping – 2020:** The existing mapping of intertidal vegetation communities was obtained from DPI through the Fisheries Data Portal accessible here: https://webmap.industry.nsw.gov.au/Html5Viewer/index.html?viewer=Fisheries_Data_Portal
- **Recent high resolution aerial imagery:** A series of high resolution georeferenced aerial images with up to 20 cm horizontal resolution was obtained via the Nearmap image database: (https://www.nearmap.com/au/en).
- **Historic aerial imagery:** Historic aerial images for the property were obtained through the Historical Aerial Photography – Foundation Spatial Data portal accessible here: https://imagery.aerialphotography.fsdf.org.au/

Figure 2.1: Locations of geolocated photographs taken across the site during the field campaign.

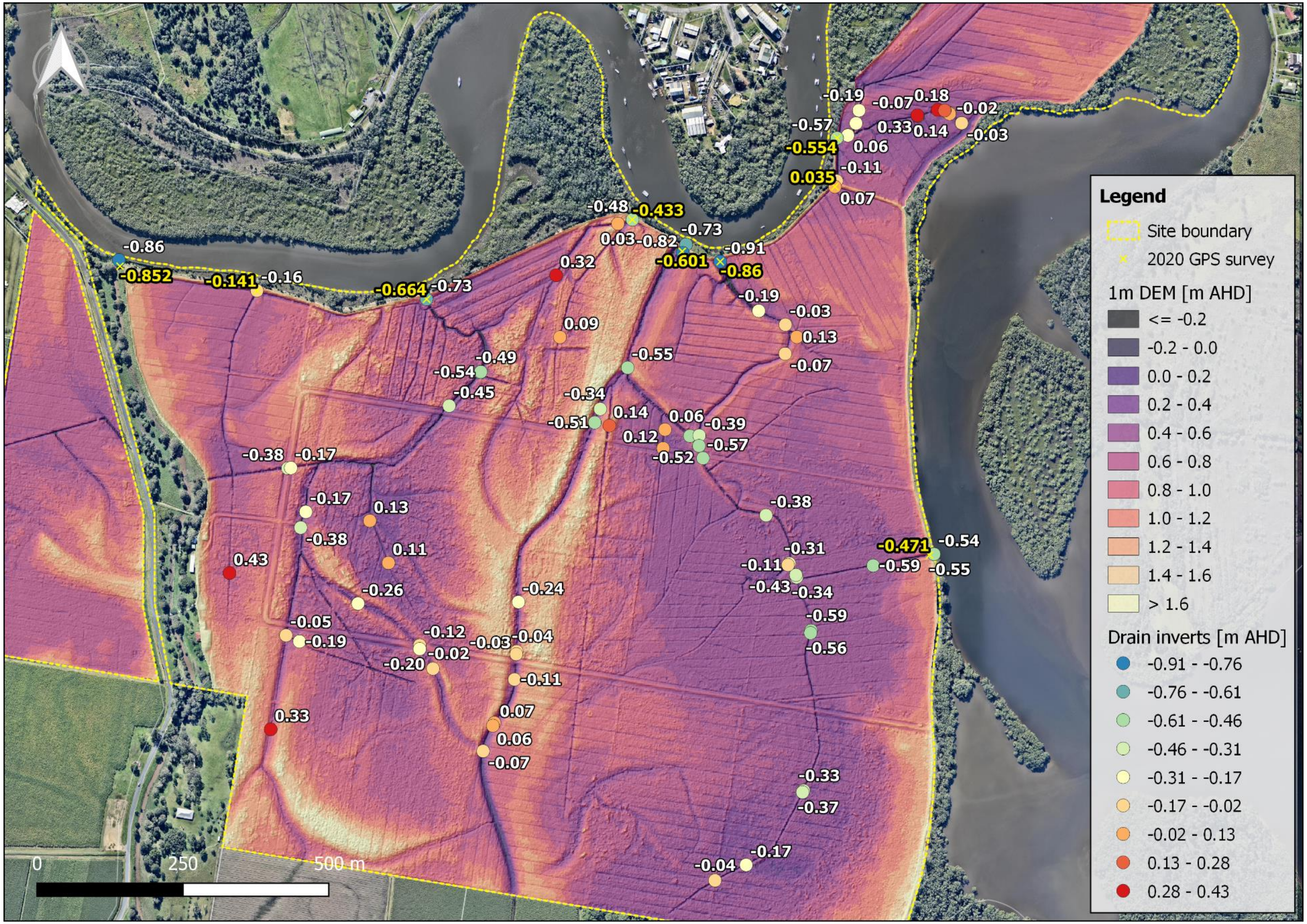

Figure 2.2: Site map showing the location and elevation of survey points collected within drainage channel inverts. The yellow survey points and elevations were collected during fieldwork for a previous project in January 2019.

2.3 Data processing

As small differences in tidal inundation depth can lead to important differences in intertidal vegetation outcomes, accurate ground surface elevation data is necessary to consider tidal restoration opportunities. In this study, the acquired DEM has a horizontal resolution of 1x1 m and a vertical accuracy of ±30 cm. The RTK-GPS system used to collect ground control points has a vertical accuracy of ±1.5 cm. In dense vegetation or grass cover, LiDAR based DEMs can be subject to elevation 'bias', due to the limited penetration of LiDAR beams on the ground surface. As such, RTK-GPS ground control points were used to vertically adjust the DEM.

Figure 2.3 shows a scatterplot of GPS vs DEM elevations. The DEM elevations were extracted from the DEM at the GPS location points. Importantly, only open paddock points that were within a ±30 cm difference were used for this analysis to avoid a bias of the DEM adjustment towards large outliers. The agreement between the DEM and the ground control points was high, with an r^2 of 0.94. However, on average, the DEM was 9.5 cm higher than the selected GPS ground control points. The 'bias' in the DEM was eliminated by vertically adjusting (i.e., lowering) the DEM by -9.5 cm.

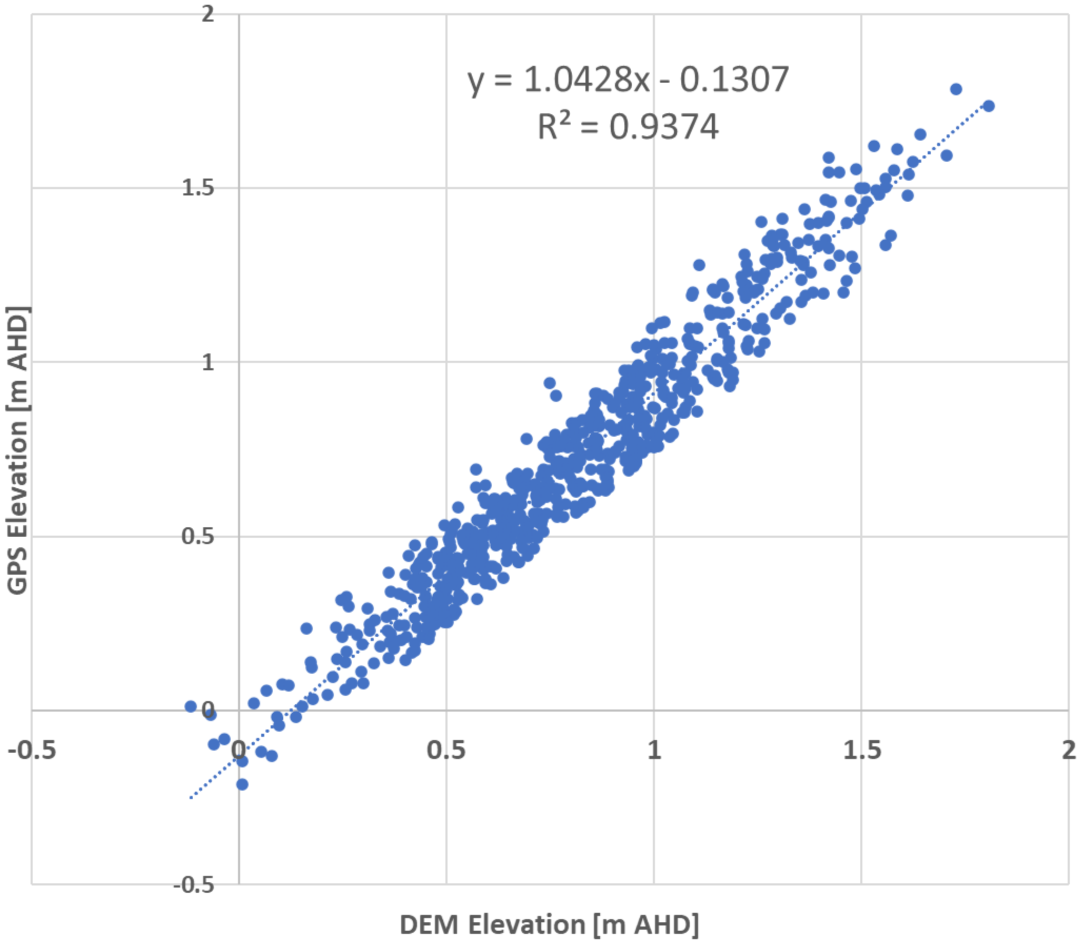

Figure 2.3: Scatterplot of the RTK GPS ground elevations vs. the elevations of the LiDAR derived DEM for all points used to improve the digital elevation model for the site.

3 Site hydrology

3.1 Water balance

To better understand the present-day hydrological functioning of the Duck Creek DPI property, a hydrological water balance model was developed. In this model, losses of water via groundwater infiltration and surface water drainage are modelled as a single constant loss rate. Further, only gains and losses from rainfall and evaporation directly over the site are considered, while runoff entering the site through tributaries is neglected. For simplicity, the water balance was modelled in terms of depth of standing water, independent of the size or shape of the site (i.e., the local topography was not considered). This water balance model is based on the long-term average monthly rainfall and evapotranspiration conditions where the water depth across the site is calculated as the depth at the end of the previous month minus the net difference between average monthly rainfall, evapotranspiration, and infiltration in the current month.

Figure 3.1 shows the long-term monthly average rainfall and evapotranspiration for Ballina, NSW. Between February and August, monthly rainfall typically exceeds monthly evapotranspiration, whereas for the remaining months, evapotranspiration exceeds rainfall. As discussed in detail in BMT WBM (2012), annual rainfall in this area is highly variable. Consequently, the results shown here, which are based on long-term monthly averages, will differ from the actual conditions in any given year.

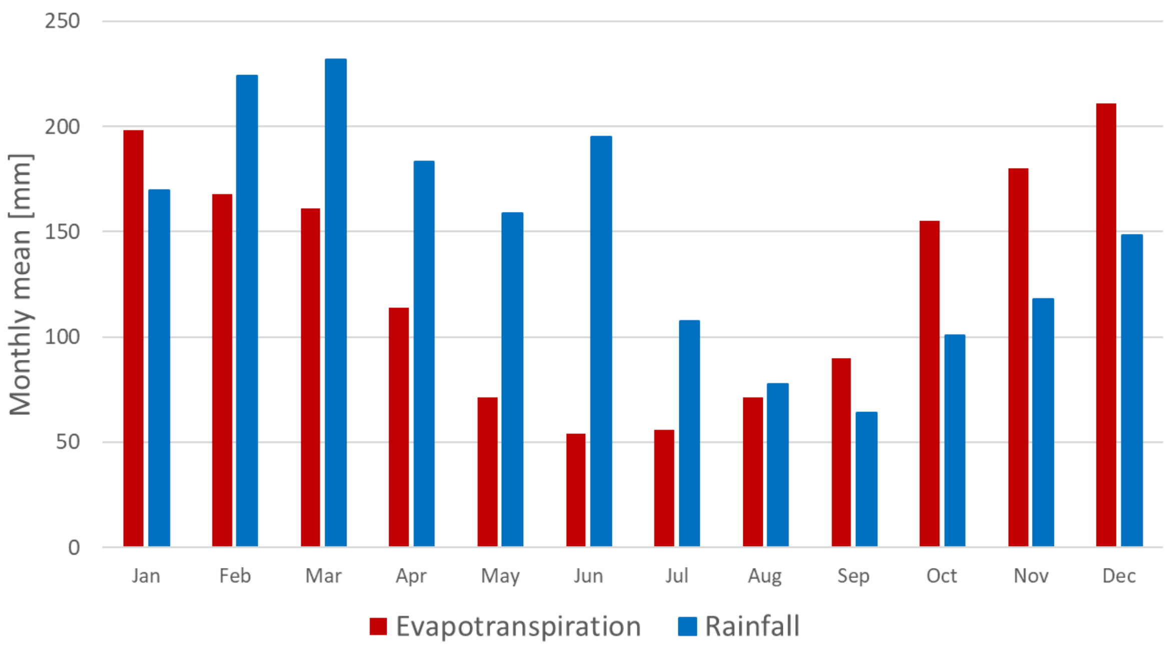

Figure 3.1: Monthly mean evapotranspiration and rainfall for Ballina, NSW.

The water balance modelling results are shown in Figure 3.2. The top panel indicates the depth of inundation that would occur over the site if there were no losses due to groundwater infiltration or drainage, which would be the case for a perfectly sealed flat basin with vertical walls. Over the year, total cumulative rainfall exceeds the total cumulative evapotranspiration, resulting in a net increase of water depth throughout the year.

For the middle and bottom panels, constant loss rates of 47 mm/month and 93 mm/month were applied to respectively account for infiltration and infiltration plus drainage. These loss rates were chosen to demonstrate the importance of infiltration and surface water drainage on the hydrology of the site. With a loss rate of 47 mm/month (less than 2 mm/day), the site would have acted as a seasonal wetland that would have reached peak inundation depths between June and August. These conditions might be representative of the site prior to the extensive drainage works. However, with a combined loss rate of 93 mm/month, the site is efficiently drained, and very minor inundation of 5 cm occurs in June, which is when the difference between average monthly rainfall and evapotranspiration is the highest (around 130 mm). These conditions may be representative for parts of the site that are not efficiently drained.

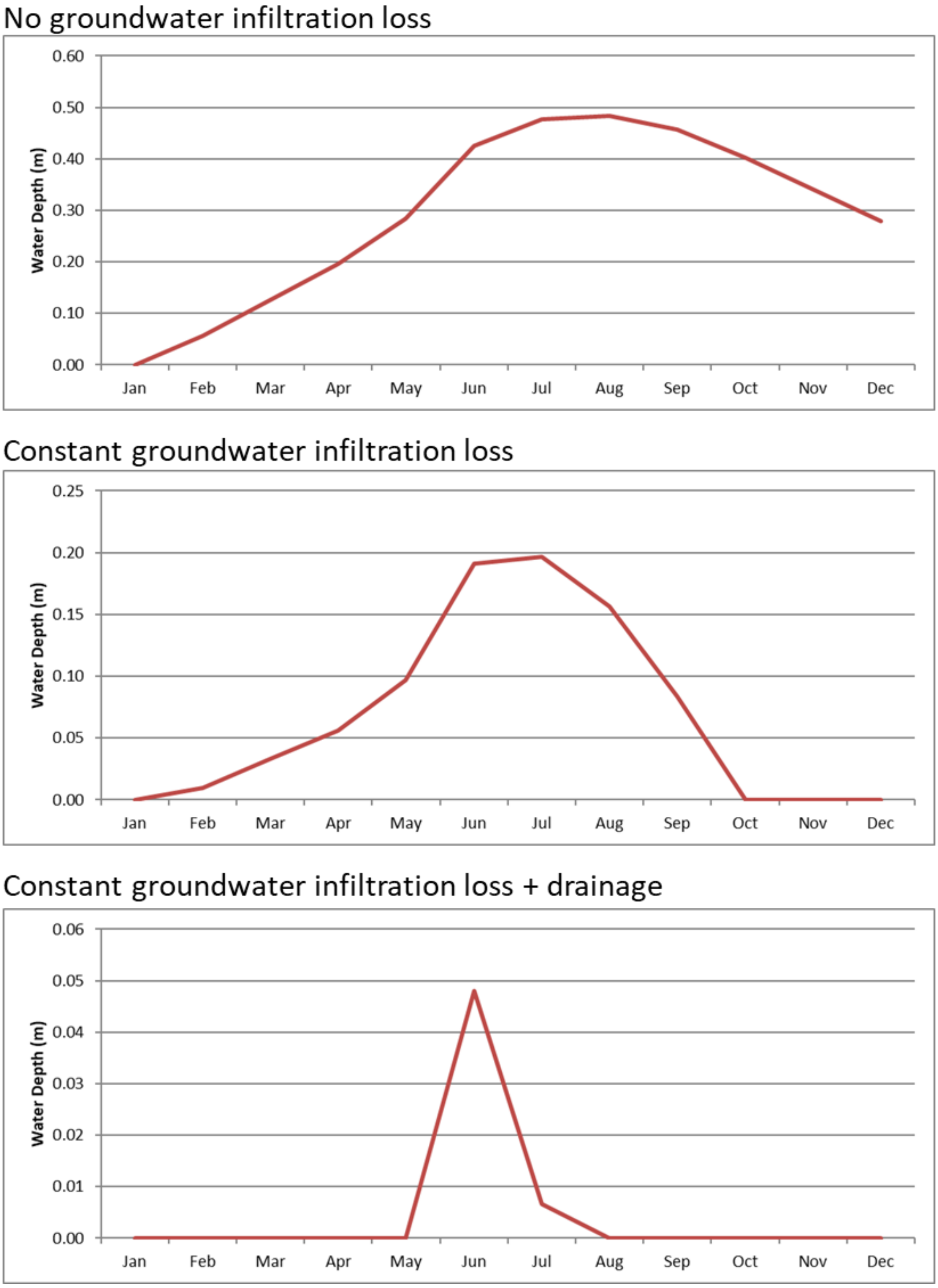

Figure 3.2: Results of the water balance model showing indicative depths of inundation throughout the year based on long-term mean monthly rainfall and evapotranspiration without any infiltration losses (top panel), a constant low infiltration loss of 47mm/month (middle panel), and a high constant loss of 93mm/month due to infiltration and drainage (bottom panel).

3.2 Tides

The tidal behaviour of an estuary is dynamic and affected by several factors, including the entrance state, river inflows, and geomorphic adaptations within the estuary (Khojasteh *et al.,* 2021). These factors often lead to differences in tidal elevations as the tidal wave propagates within the estuary. These effects can include amplification, dampening and a loss of symmetry. As a result of these complexities, it is important to obtain tide water level observations that are as close to the area of interest as possible.

As shown in Figure 1.1, there is a permanent tide gauge (Byrnes Point) located less than 1 km from the eastern boundary of the property along a wide and unvegetated section of the estuary. Due to the proximity between the property and this gauge, this gauge and the corresponding tidal planes were deemed to be representative of the local tidal boundary conditions along the eastern side of the property. The northern side of the property is connected to the main estuary via Emigrant Creek at a maximum distance of about 2 km from the Byrnes Point tide gauge. Minor modifications to the tidal wave could occur over this distance but these were neglected for the purpose of this assessment. Due to this site configuration, the available tide boundary data complies with the highest standard for characterising tidal boundary conditions outlined in the Blue Carbon Method (CER, 2022).

Table 3.1 shows the tidal planes that have been derived for the Byrnes Point permanent tide gauge using tidal constituent analysis as part of the "OEH NSW tidal planes analysis 1990-2010 harmonic analysis" (Couriel *et al.,* 2012). In this report, tidal planes and ranges are derived for tide gauges for a period of 20 individual years from July 1st 1990 to June 30th 2010 inclusive.

The Highest High Water Solstices Springs (HHWSS) at Byrnes point is 0.926m AHD. The Mean Sea Level (MSL) is 0.015 m AHD. The mean tidal range is 0.855 m, while the maximum tidal range is 1.718 m.

Table 3.1: Annual average tidal planes (1991-2009) for the Byrnes Point permanent tide gauge (source; Couriel *et al.,* 2012).

Tidal Planes	Elevation
HHWSS	0.926
MHW	0.442
MSL	0.015
MLW	-0.413
ISLW	-0.791

3.3 Future sea level rise

White *et al.* (2014) completed an analysis of tidal gauges across Australia and found that the average rate of rise in relative sea levels between 1966 – 2010 in Australia was +1.4 mm/year and had accelerated to +4.5 mm/year between 1993 – 2010. The rate of sea level rise is expected to continue to accelerate over the next century (Nerem *et al.,* 2018). Coastal estuaries are amongst the most vulnerable areas to sea level rise due to the proximity to the ocean and anthropogenic development (Khojasteh *et al.,* 2021).

Coastal floodplain areas, such as the Duck Creek site, are susceptible to sea level rise as changes in sea levels and hence tidal levels, will intensify factors that currently contribute to flooding, reduced drainage efficiency, and changes to inundation extent/duration. Detailed information on how climate change will likely impact estuaries in NSW can be found at:

http://estuaries.wrl.unsw.edu.au/index.php/climate-change/

For the purpose of this assessment, the following time periods and corresponding increases in sea level were adopted in line with the Coastal Floodplain Prioritisation Study undertaken by Rayner *et al.* (2022):

- Present day (PD (~2020);
- Near future (NF) (~2050); and
- Far future (FF) (~2100).

Sea level rise scenarios were based on scenarios from Glamore *et al.* (2015). The adopted changes in mean sea level relative to 2020 for these periods have been detailed in Section 11 of the Methods report of the Coastal Floodplain Prioritisation Study (Rayner *et al.,* 2022) and are represented in Table 3.2 below.

Table 3.2: Adopted sea level rise scenarios based on the future mean sea level (MSL) relative to present-day (2020)

Time period	Adopted change in MSL relative to 2020 (m)
PD – Present day (circa 2020)	0
NF – Near future (circa 2050)	+0.16
FF – Far future (circa 2100)	+0.67

3.4 Drainage network and catchment delineation

For the assessment of blue carbon opportunities across the Duck Creek property, it is critical to understand the current surface water hydrology of the site. Figure 3.3 provides an overview of the current hydrological functioning of the property, detailing the boundary of all drainage catchments, the drainage channel network, and the flow direction of all drainage channels. All major drainage channels, their respective flow directions and hydraulic infrastructures were manually mapped based on available aerial imagery, the DEM, on-site inspection, GPS-surveyed channel invert elevations, and geolocated photographs. Based on this mapping, seven drainage catchments have been identified that drain surface water into the main estuary via a total of eight tidal floodgates. Further, three small tributaries have been identified that deliver surface water runoff into the property from the adjacent land areas. The map also details the high number of culverts and cattle crossings that are part of the drainage network. The majority of cattle crossings over drainage channels are made up of earth and gravel infill and one or more culverts (e.g., see photos 3 and 8 in Figure 1.6). Some of the delineated drainage catchment boundaries are uncertain, due to the extremely flat nature of the terrain. The hashed areas in Figure 3.3 are areas that are currently fully tidally connected to the main estuary. Importantly, only areas that are currently not tidally connected to the main estuary due to a tidal barrier are eligible under the Blue Carbon Method (CER, 2022), which includes the identified drainage units.

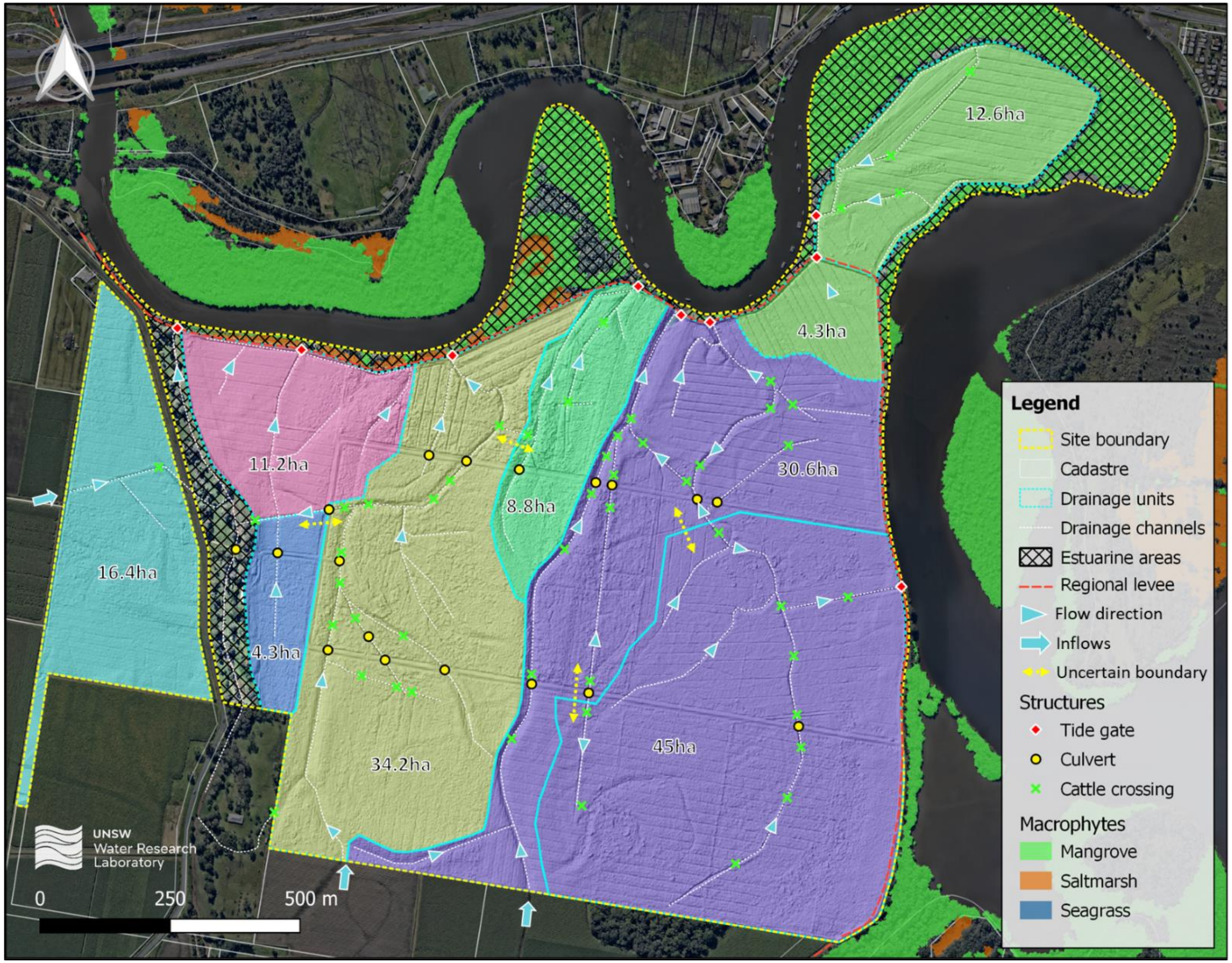

Figure 3.3: Present day hydrological functioning of the site detailing major drainage channels and flow directions, drainage catchment boundaries, inflows to the site, and all relevant hydraulic infrastructures.

4 Blue carbon feasibility assessment

4.1 Blue carbon method summary

The Blue Carbon Method enables eligible sites to be developed for Australian Carbon Credit Units (ACCUs) via the establishment of intertidal 'blue carbon' habitats.

Under the Blue Carbon Method, tidal restrictions are removed or modified to enable tidal inundation of land, leading to the establishment of intertidal vegetation communities (i.e., seagrasses, mangroves, saltmarsh, and supratidal forests) (CER, 2022). Carbon is sequestered and stored within the vegetation and soils, and emissions are avoided by introducing tidal flows and changing existing land cover types, leading to the creation of ACCUs that can then be sold on carbon markets (see Figure 4.1). The Blue Carbon Method considers the existing greenhouse gas balance of the site, with ACCUs generated based on the net change resulting from the project activities.

The blue carbon method involves a detailed assessment through multiple steps (Figure 4.2), however, the critical components that determine the physical feasibility and initial eligibility of a site are:

1. General project eligibility and land eligibility requirements.
2. Hydrological assessment and mapping (i.e., are the local conditions (salinity and tidal range) suitable for the establishment of blue carbon habitats?).
3. Calculation of carbon abatement potential using the Blue Carbon Accounting Model (BlueCAM) to inform the ACCU generation potential of the site.

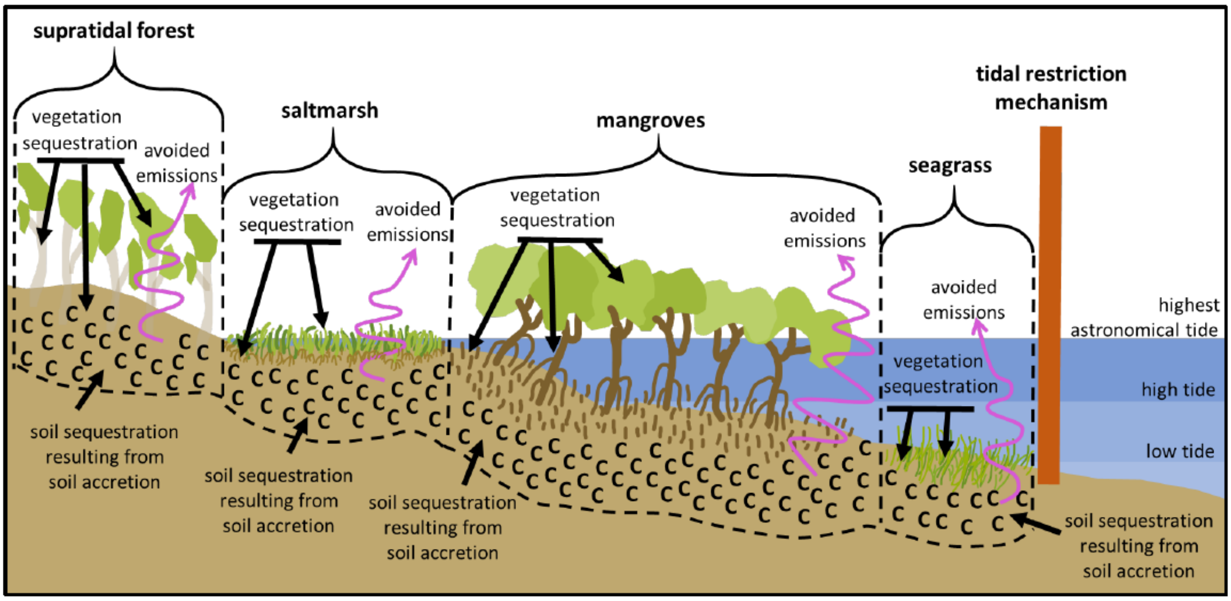

Figure 4.1: Carbon sequestration and emissions avoidance covered by the blue carbon method (illustrative only) (source; CER, 2022)

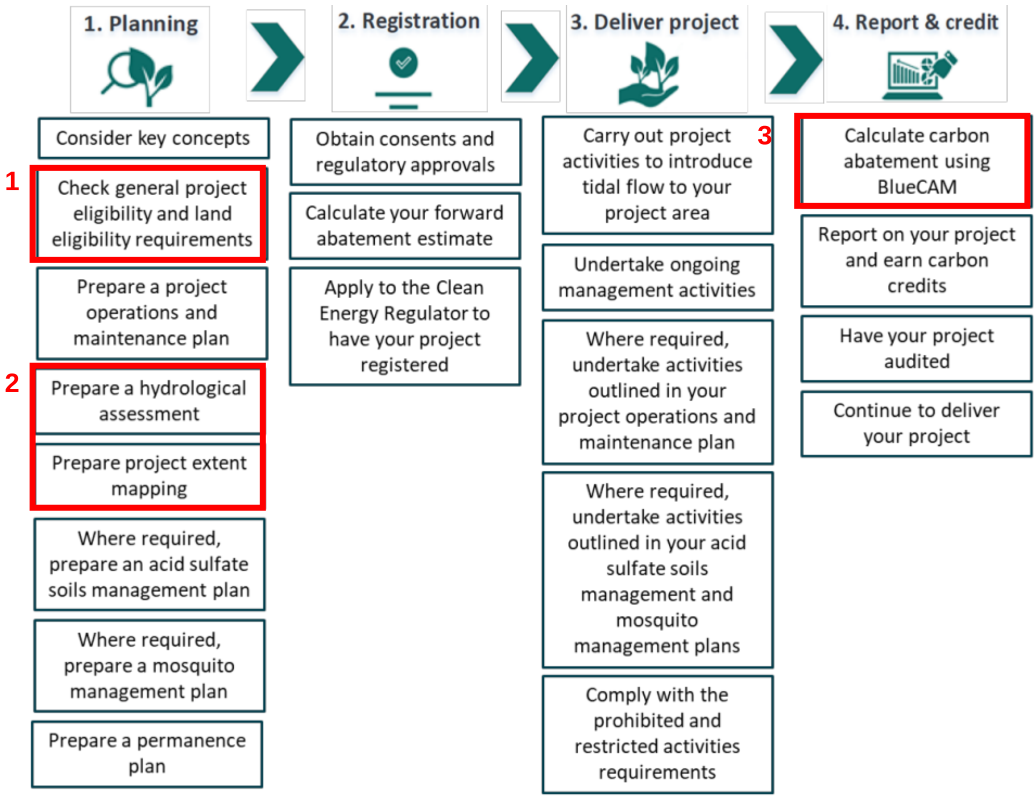

Figure 4.2: Key steps involved in a blue carbon project (critical feasibility components highlighted in red) (source: CER, 2022)

4.2 General eligibility

4.2.1 Tidal barriers

A key requirement for a property/site to be eligible under the blue carbon method is the presence of existing tidal barrier(s). This can be in the form of floodgates, weirs, or levees, which currently restrict connectivity of tidal waters to upstream land. Barriers that restrict or exclude tidal flows must have been in place for seven years prior to commencement of the project and must have been legally installed/constructed. The presence of tidal flow restricting structures is a critical criterion to the eligibility of the project to be registered under the Blue Carbon Method. All drainage catchments identified across the property, and shown in Figure 3.3, are situated behind tidal gates, a farm levee, or the regional flood levee and, as such, are eligible under the Blue Carbon Method.

4.2.2 Land use and tenure

The entire study site was gazetted as an experimental farm in 1894 and is Crown Land managed by DPI for the purpose of an experimental farm (NSW Government, 1894). The eligibility (or non-eligibility) of Crown Land for registration of projects under the Blue Carbon Method is not explicitly stated in the Blue Carbon Method and it is recommended that further clarification is obtained from the CER in this regard.

4.3 Predicting vegetation outcomes

To estimate the potential blue carbon vegetation distribution that would result from partial or full tidal introduction across different parts of the site, GIS-based inundation modelling (i.e., bathtub modelling) of tidal inundation was used. The vegetation class resulting from different levels of tidal inundation were predicted using the Standard Tidal Position Index (STPI) for blue carbon habitats in subtropical eastern Australia, as provided in the Blue Carbon Method (CER, 2022). The STPI method is illustrated in Figure 4.3. It uses the HAT and the MSL to establish elevation ranges corresponding to different types of intertidal blue carbon vegetation.

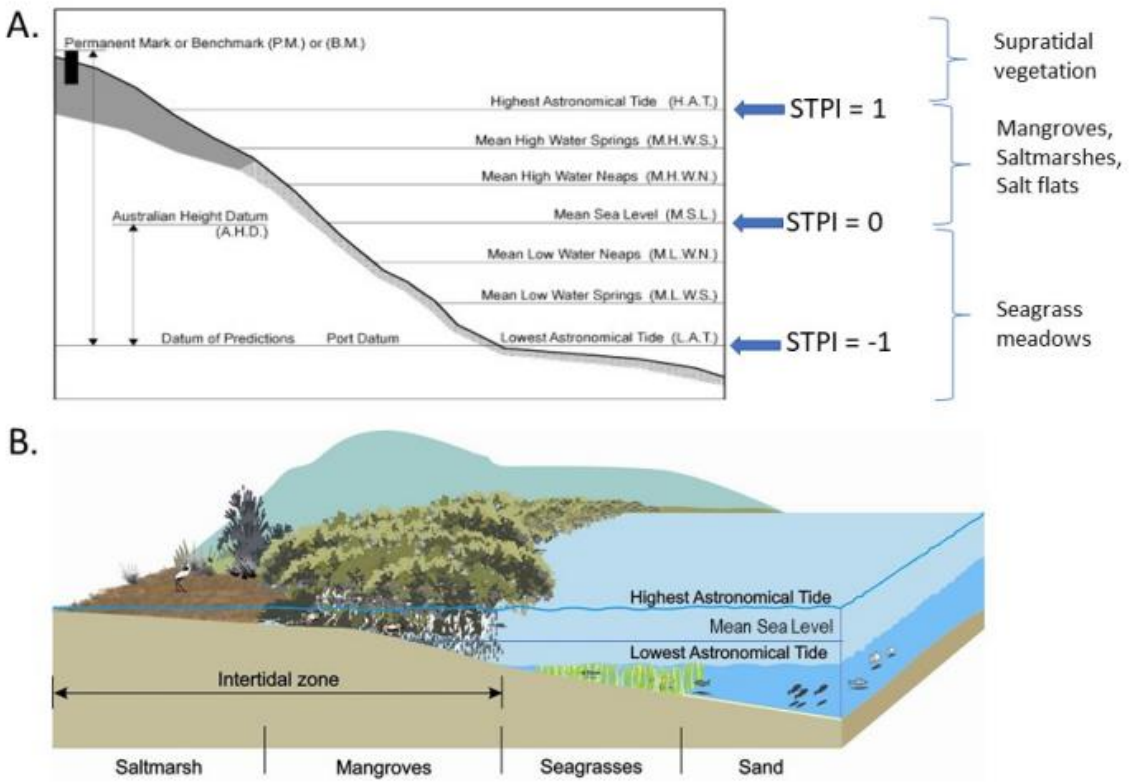

Figure 4.3: Conceptual diagram illustrating the standard tidal positioning index method for linking tidal planes with intertidal vegetation communities (source; CER, 2022).

Table 4.1 outlines the STPI for each habitat type, where 0 is local mean sea level, and 1 is the HAT, or HHWSS. Based on local tidal planes from the Byrnes Point tide gauge (Table 3.1), the upper and lower elevation for each vegetation class can be established. The elevation ranges for the various vegetation classes are shown in Table 4.1 for the following scenarios.

- Present day – assuming no tidal attenuation;
- Present day – assuming 25 cm attenuation in the HAT;
- Near future sea level rise of 16 cm – assuming no attenuation; and
- Far future sea level rise of 67 cm – assuming no attenuation.

For this assessment, tidal inundation across the property is modelled using a bathtub approach that does not account for hydraulic constraints and losses. The extent of inundation corresponding to the HAT and the Mean High Water (MHW) is shown in Figure 4.5 and Figure 4.6, respectively. These maps illustrate that the majority of the site has an elevation between MHW and HAT.

Due to the known shortcomings of the bathtub inundation modelling approach, a 'plausible range' approach was adopted here. This approach assumes that depending on the degree of hydraulic connectivity that is created for a given tidal introduction opportunity via removal of levees and the construction of pilot channels or enlarged culverts, a tidal attenuation of between 0 to 25 cm may occur across the activated area. As such, the 'no attenuation' and the '25 cm HAT attenuation' scenarios provide a likely upper and lower boundary of tidal inundation extent, which can guide the choice of appropriate tidal introduction works to either achieve an increase or reduction of tidal flow conveyance. Due to the simplified nature of this approach, a full hydrodynamic modelling and implementation design study may be required to better identify potential onsite implementation options, predict intertidal vegetation outcomes, or assess impacts to stakeholders.

To ensure that the STPI method leads to accurate vegetation outcomes, the elevations of existing blue carbon vegetation communities along the outer perimeter of the property were surveyed with the RTK-GPS. Figure 4.4 shows the results of this survey, indicating that the STPI-based elevation ranges match the existing vegetation communities. Due to the tidally disconnected nature of the drained paddock, the saltmarsh communities inside the levee have lower downslope elevations than STPI model predictions. As such, these vegetation communities inside the drained paddock are not representative of the tidal boundary regime. Apart from those survey points, there is reasonable agreement between the bottom elevation of existing vegetation communities and the STPI model. One explanation for the slight differences is that established and mature mangrove and saltmarsh communities can survive in tidal conditions that deviate from those required for recruitment and establishment of plants. Kumbier *et al*. (2021) provides further details for consideration.

Based on the STPI-based vertical elevation ranges for each habitat type (Table 4.1), and the property land elevation, the potential extent and distribution of each habitat type can be estimated. Figures 4.7, 4.8, 4.9, and 4.10 show the distribution of the different blue carbon vegetation types across the property for the four tidal inundation scenarios. All inundation and vegetation maps were generated using the GIS/bathtub modelling approach, which does not account for dynamic tidal processes related to volumes, velocities, and timing of tidal flows. These dynamic processes are partially accounted for by the '25 cm HAT attenuation' scenario but this assessment should be treated as a first-pass estimate of tidal restoration opportunities and vegetation outcomes onsite. If further detailed information regarding costs, risks or benefits are required, additional hydrodynamic investigations may be useful.

Table 4.1: Standard tidal positioning index and corresponding minimum and maximum water levels for different blue carbon vegetation classes and water level scenarios. All values are derived from the Byrnes Point gauge tidal planes (see Table 3.1).

	Standard tidal positioning index		Water levels (m AHD)							
			No attenuation		25 cm attenuation in HAT		16 cm of near future sea level rise		67cm far future sea level rise	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Tall mangrove	0	0.37	0.02	0.35	0.02	0.26	0.18	0.51	0.69	1.02
Scrub Mangrove	0.37	0.73	0.35	0.68	0.26	0.5	0.51	0.84	1.02	1.35
Saltmarsh	0.73	1	0.68	0.93	0.5	0.68	0.84	1.09	1.35	1.6
Supratidal forest	1		0.93		0.68		1.09		1.6	

Notably, there is a substantial shift in vegetation type from saltmarsh and mangroves towards coastal upland forest if the HAT is attenuated by 25 cm. However, the near future sea level rise of 16 cm leads to an expansion of mangroves and a reduction in coastal upland forest. Further, a far future sea level rise of 67 cm leads to a 'drowning' out of mangroves in large parts of the property since water levels may be too deep for mangroves to establish. However, tidal restoration of these areas in the next few decades might provide those ecosystems sufficient time to establish and maintain pace with sea level rise via vertical accretion. The balance between sea level rise and vertical accretion is complex and depends on a variety of biological and geomorphological factors as discussed in the relevant scientific literature (including examples such as Marx *et al.,* (2020); Rayner *et al.,* (2021); Rogers *et al.,* (2014); Saintilan *et al.,* (2018); and Schuerch *et al*., (2018)).

Figure 4.4: RTK GPS surveyed elevations of existing intertidal vegetation communities at the Duck Creek site.

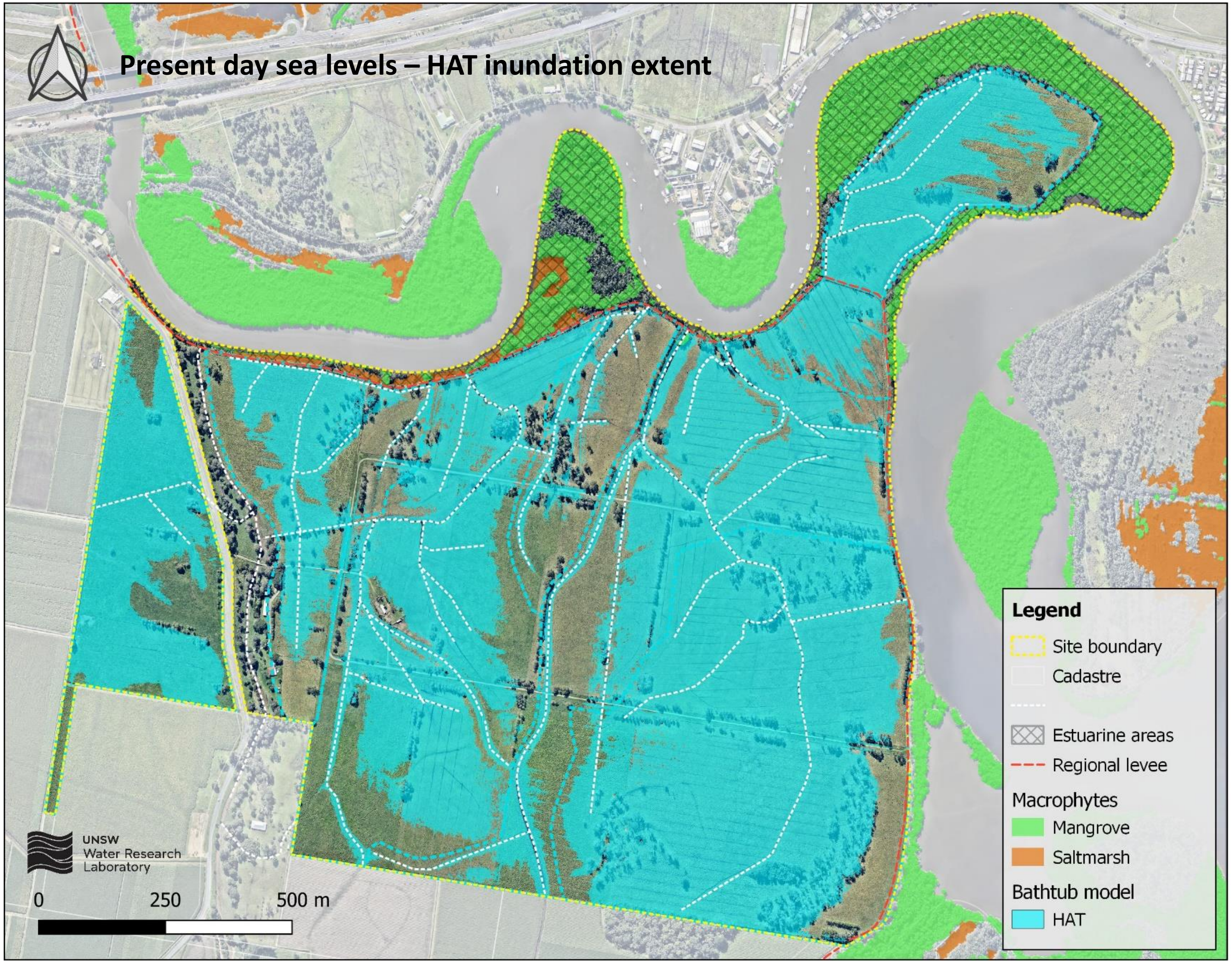

Figure 4.5: Site map showing areas that are lower or equal to the highest astronomical tide of 0.93 m AHD. Clear areas are above 0.93 m AHD.

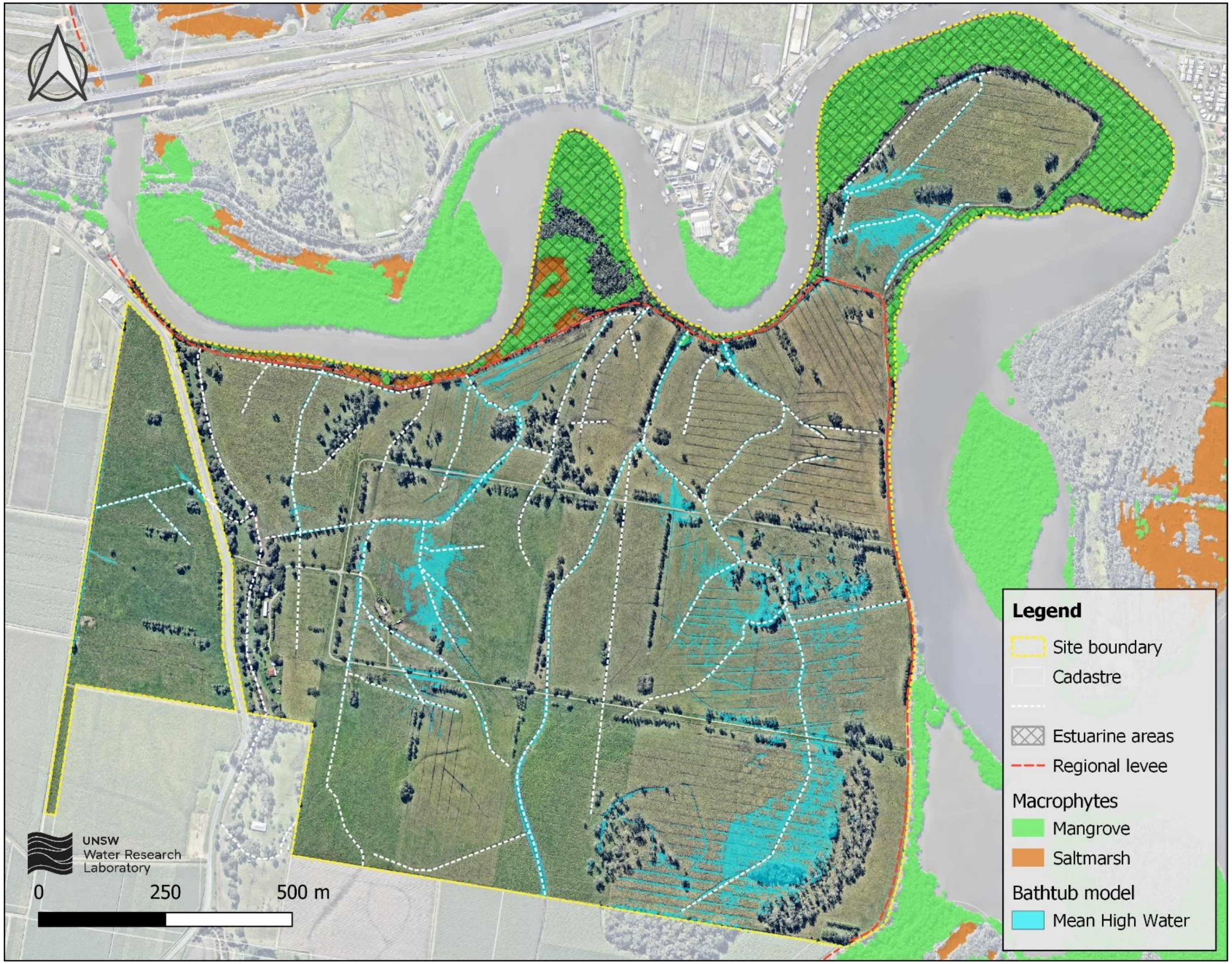

Figure 4.6: Site map showing areas that are lower or equal to Mean High Water (0.44 m AHD).

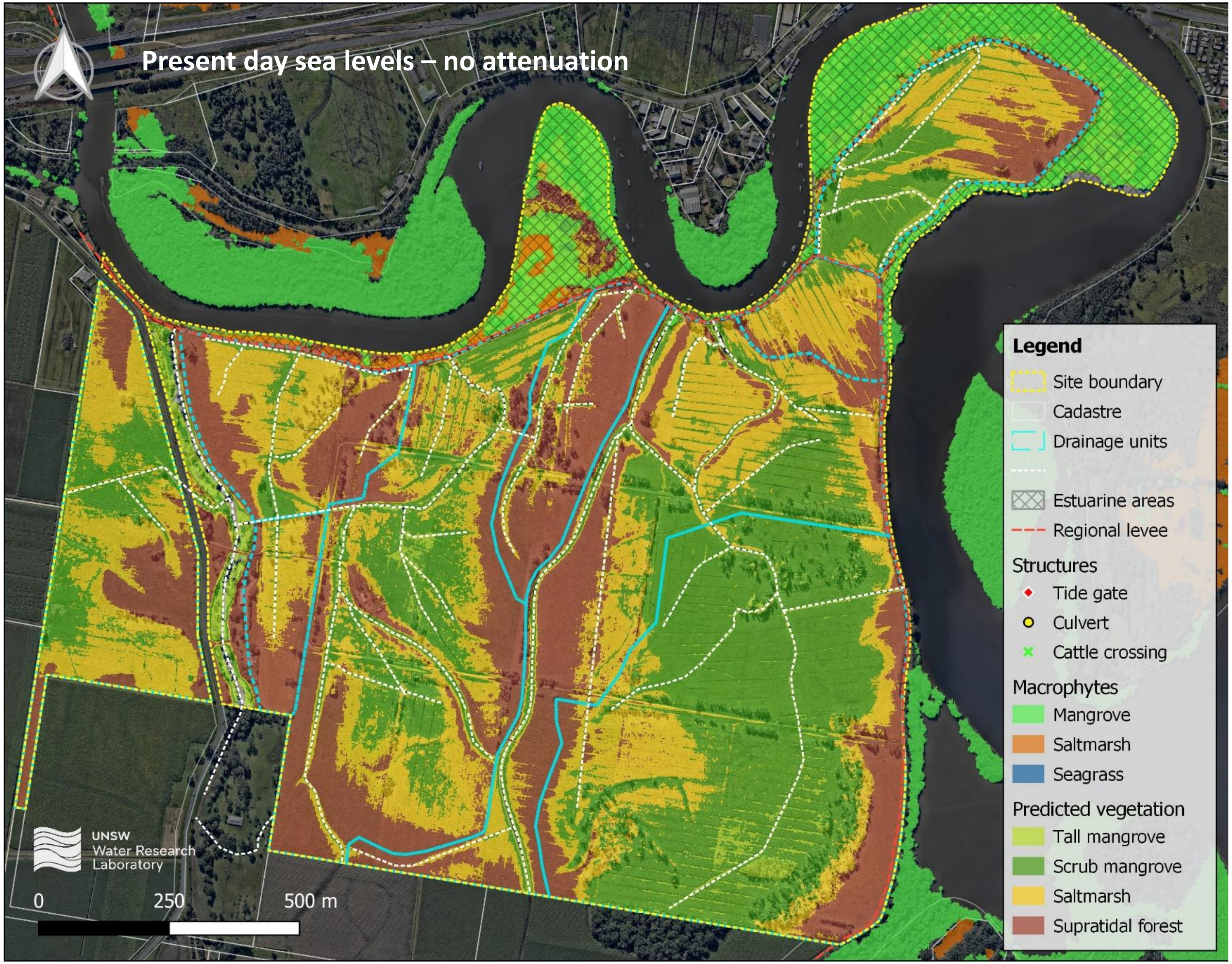

Figure 4.7: STPI-based blue carbon vegetation outcomes without tidal attenuation.

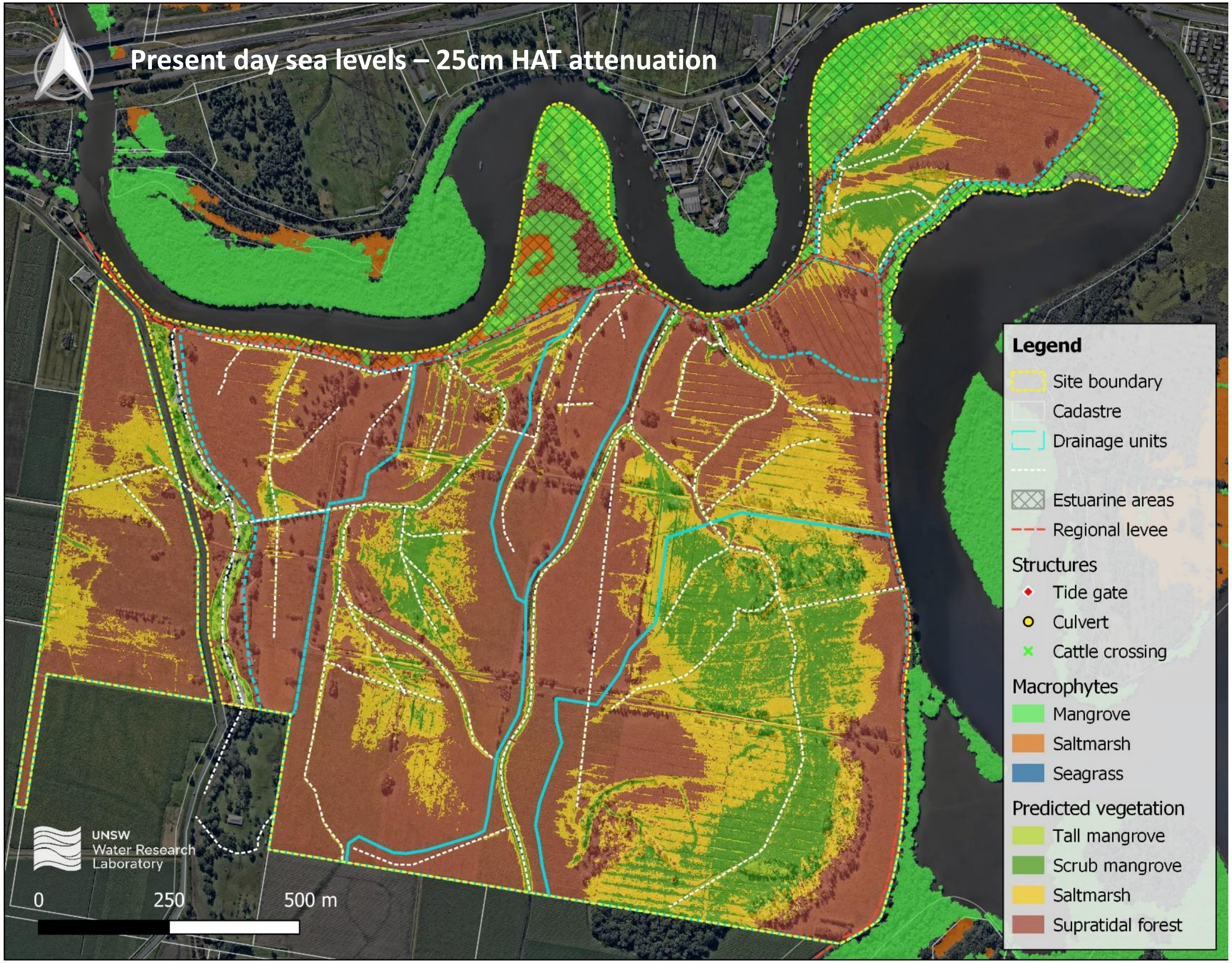

Figure 4.8: STPI-based blue carbon vegetation outcomes with 25 cm attenuation in the highest astronomical tide.

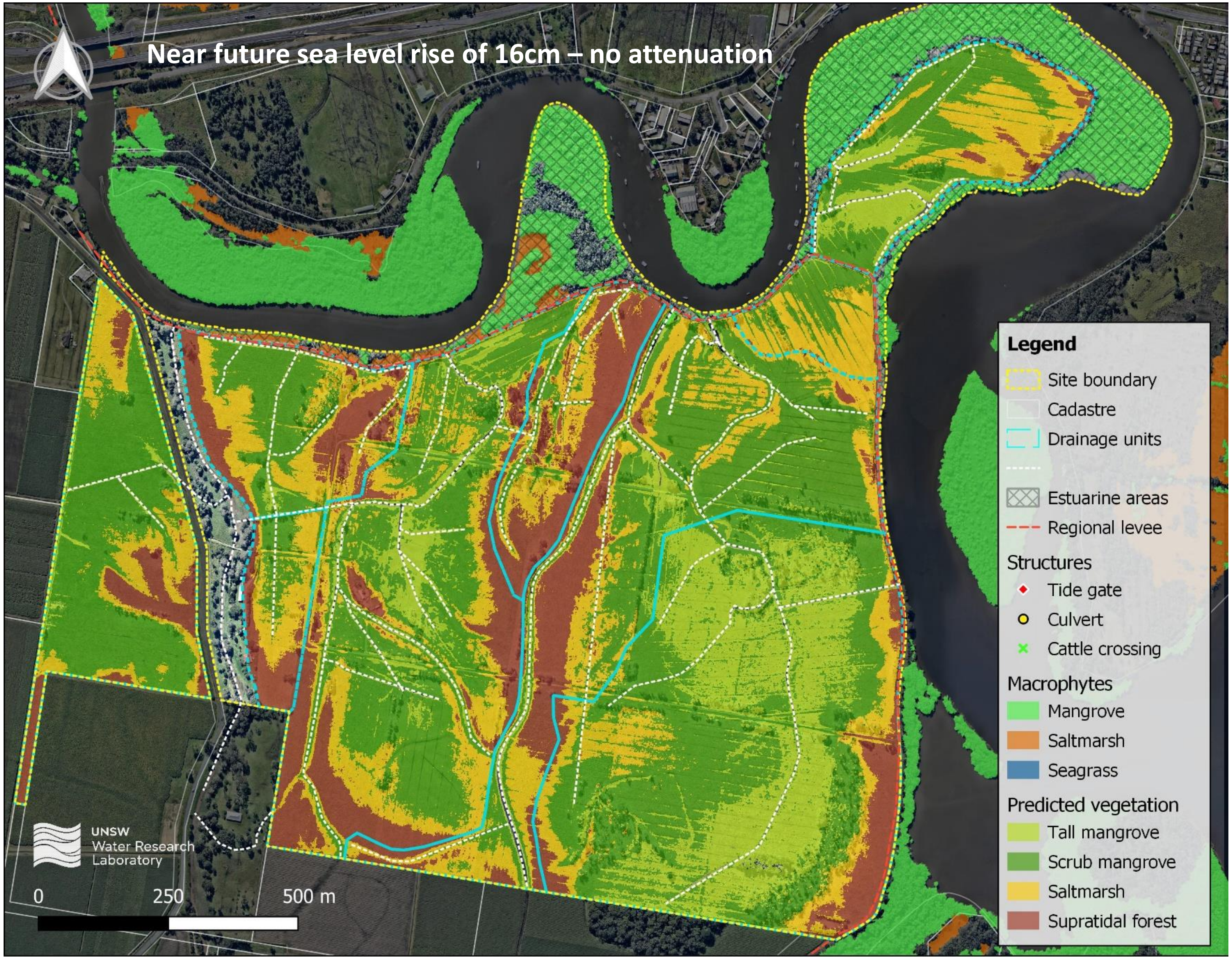

Figure 4.9: STPI-based blue carbon vegetation outcomes for 16 cm of near future sea level rise – no attenuation.

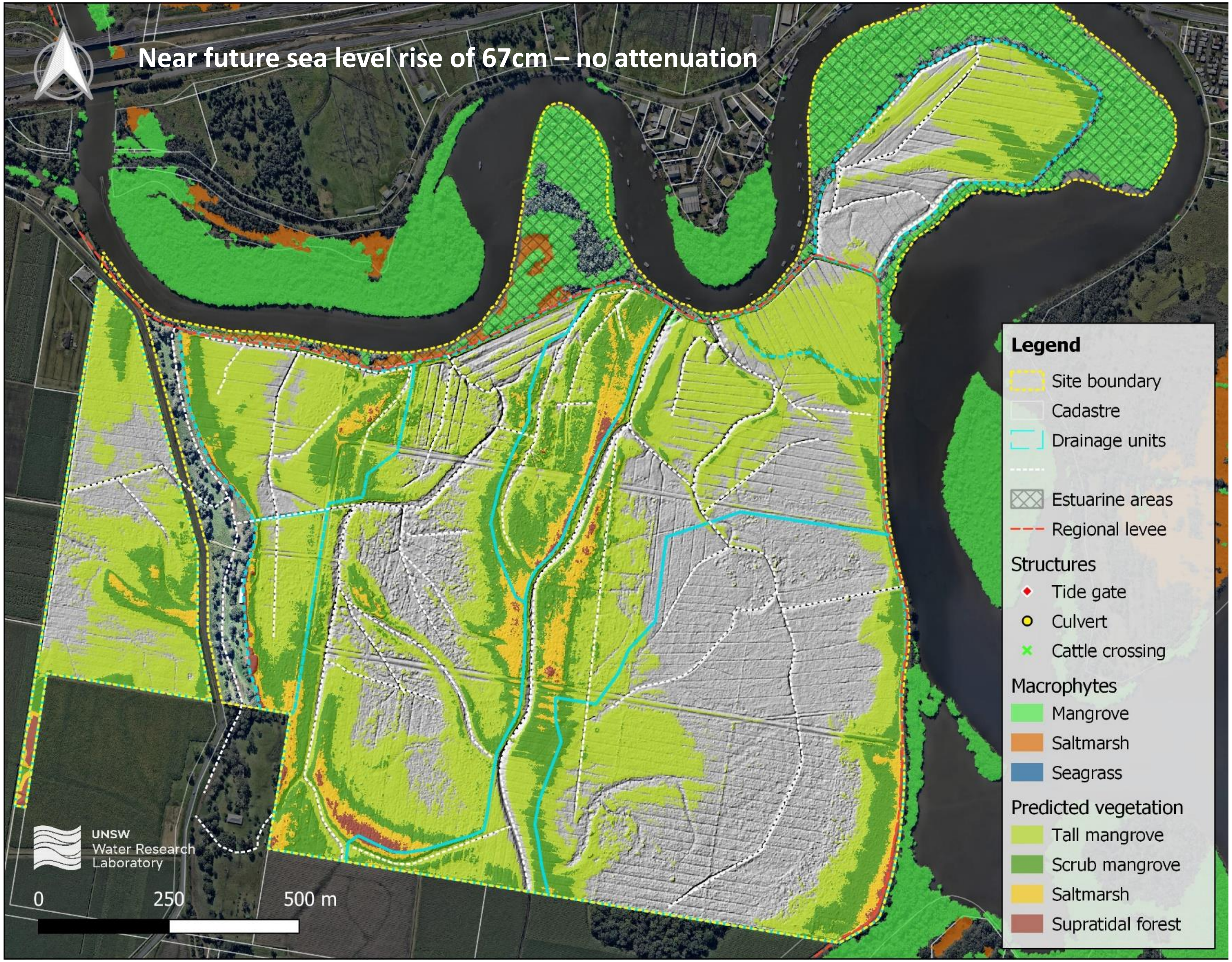

Figure 4.10: STPI-based blue carbon vegetation outcomes for 67 cm of far future sea level rise – no attenuation.

4.4 Developing tidal restoration opportunities

The previous chapters established a detailed understanding of the current hydrological functioning as well as current and future blue carbon opportunities at the Duck Creek site. In this section, a preliminary set of biophysically feasible tidal restoration opportunities is introduced. Maintaining the existing land cover and use of the site (or an area within the site) in its current state will hereafter be referred to as the baseline scenario. In addition to the baseline scenario, a range of potential tidal restoration configurations (or blue carbon opportunities) exist for the property. To facilitate this assessment, it was necessary to narrow down these options to feasible opportunities.

As illustrated in Figure 4.11-A, tidal restoration opportunities generally follow a spectrum ranging from minimal modifications of the existing infrastructure to significant modifications and engineering works (Sadat-Noori *et al.,* 2021). While larger interventions may have larger costs, they may also potentially lead to larger returns, in terms of the restored area or lower ongoing costs. Figure 4.12 illustrates a range of possible on-site implementation options for all tidal restoration projects. When designing tidal restoration projects, it is important to consider that both the modification of existing infrastructure as well as the desired level of tidal inundation that can be achieved (i.e., removal of levees, size and shape of culverts, pilot channels). Note that several other options exist (beyond Figure 4.12) that may be relevant for the Duck Creek site.

In addition to these hydrological and engineering considerations, different blue carbon implementation options and configurations may also lead to different ecosystem service outcomes (e.g., nutrient removal, fisheries productivity, recreational values, cultural values, biodiversity) (Figure 4.11-B). Often trade-offs exist between these ecosystem services and outcomes should be carefully considered when adopting a given option. For instance, the creation of blue carbon wetlands via tidal introduction may conflict with the existing use of cattle farming, since restored areas can no longer be used for grazing or feed production. Further, some shorebirds prefer extensive mudflats over saltmarsh and mangrove areas for foraging (Lloyd Environmental, 2019), however, mudflats produce limited blue carbon returns.

A key objective of this study was to identify ways to reinstate tidal flows and develop blue carbon opportunities on suitable parts of property, while continuing to use other areas for agricultural purposes, until sea level rise constraints impact those operations. For this assessment, only the biophysical and technical feasibility of blue carbon, risks to neighbouring properties, and a limited set of constraints related to the existing cattle farming operation were considered. At Duck Creek, the core farming areas that contain significant farming infrastructure, including sheds and stock yards, are on high ground above the HAT, located south of farm roadways and west of the Pimlico Road. These areas are also adjacent to neighbouring properties. Apart from those areas, other areas of the site were considered in the blue carbon feasibility assessment, even if they are in competition with the requirements of the current and near future cattle farming operation. This was done to provide a full suite of biophysically feasible tidal restoration opportunities for the property. These options are intended to inform the current and future management of the site by decision makers.

Based on these factors and considerations, five current or near future tidal restoration opportunities were identified for the property (Figure 4.13). Another blue carbon opportunity, but one that would limit farming opportunities was also identified for the site. This sixth opportunity could be implemented when sea level rise constrains the viability of farming for cattle production at the site. This opportunity has high biophysical feasibility but also contains areas of high ground, which may be incompatible with the current and/or future farming operations. Overall, these options provide a 'staged' and flexible tidal restoration plan, where different areas of the site could be individually or subsequently 'activated' via tidal introduction.

The five current or near future tidal restoration Blue Carbon Opportunities, as detailed in Figure 4.13 are:

1. The Point Paddock,
2. North-East Paddock,
3. East Paddock north section,
4. Central Paddock north section, and
5. North-West Paddock north section.

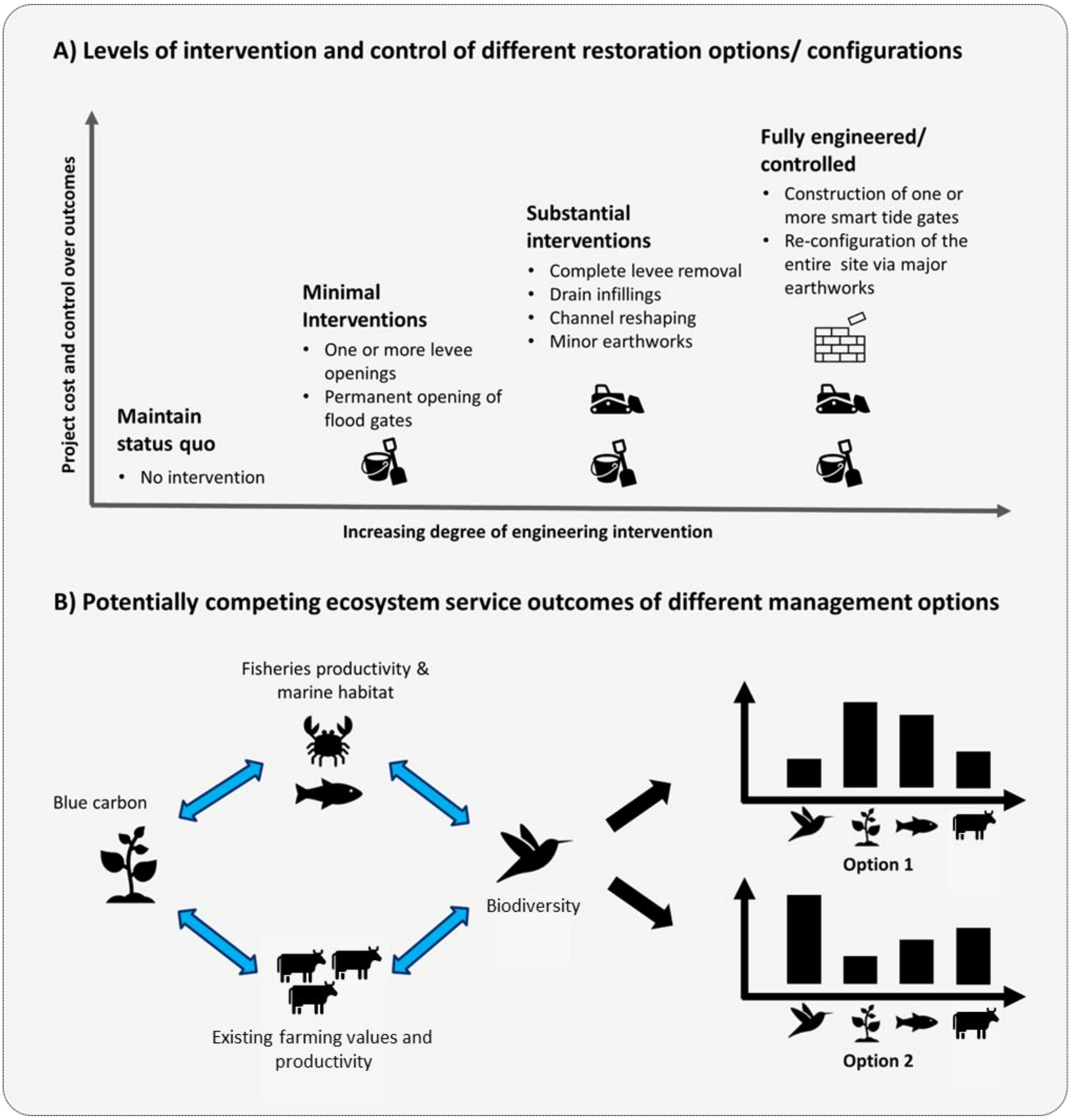

Figure 4.11: Schematic illustrating (A) different levels of engineering intervention for different tidal restoration opportunities and (B) considerations regarding ecosystem services derived from different tidal restoration opportunities (source: Heimhuber *et al.,* 2022).

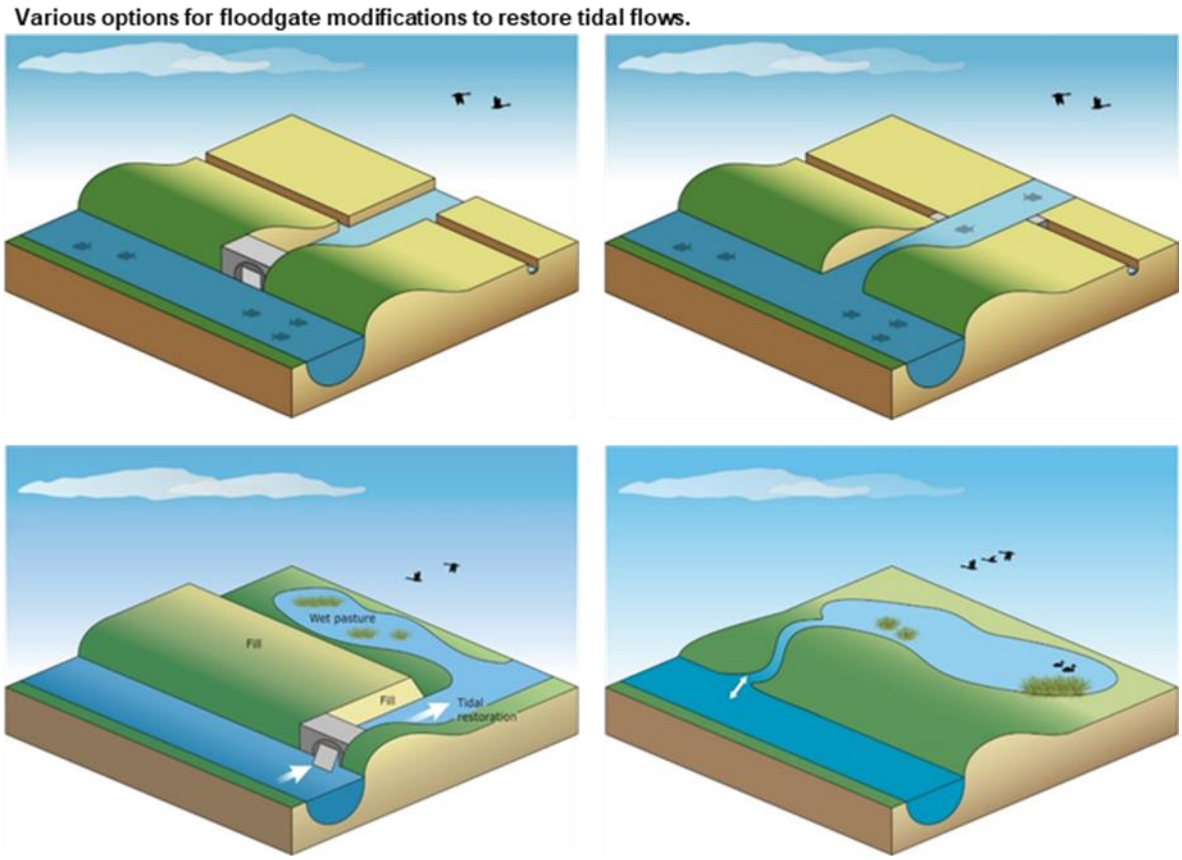

Figure 4.12: Schematic illustrating potential engineering interventions to partially or fully restore tidal inundation to the drained floodplain areas.

Figures 4.14, 4.15, 4.16, and 4.17 detail the five tidal restoration opportunities, showing the HAT and 25 cm attenuated HAT inundation extents and one possible set of recommended engineering interventions for each option. Opportunity 5 is shown together with Opportunity 4 (Figure 4.17) since tidal restoration of this area without tidal restoration of the East Paddock – northern segment (Opportunity 4) is not recommended. This is due to the high degree of connectivity between these two areas, which used to be covered by a large backswamp wetland. Opportunity 4 is shown in isolation (Figure 4.16) as it is directly adjacent to Opportunity 1 and 2 and could be used to create a sizable and connected blue carbon wetland complex consisting of Opportunity 1, 2 and 4, without significantly impacting existing access roads and farming operations.

Importantly, the engineering interventions outlined here represent one of many implementation configurations. Final option selection should take into consideration social, economic, and environmental considerations. The final selected option would also require detailed engineering design studies before commencing the registration of an area under the Blue Carbon Method.

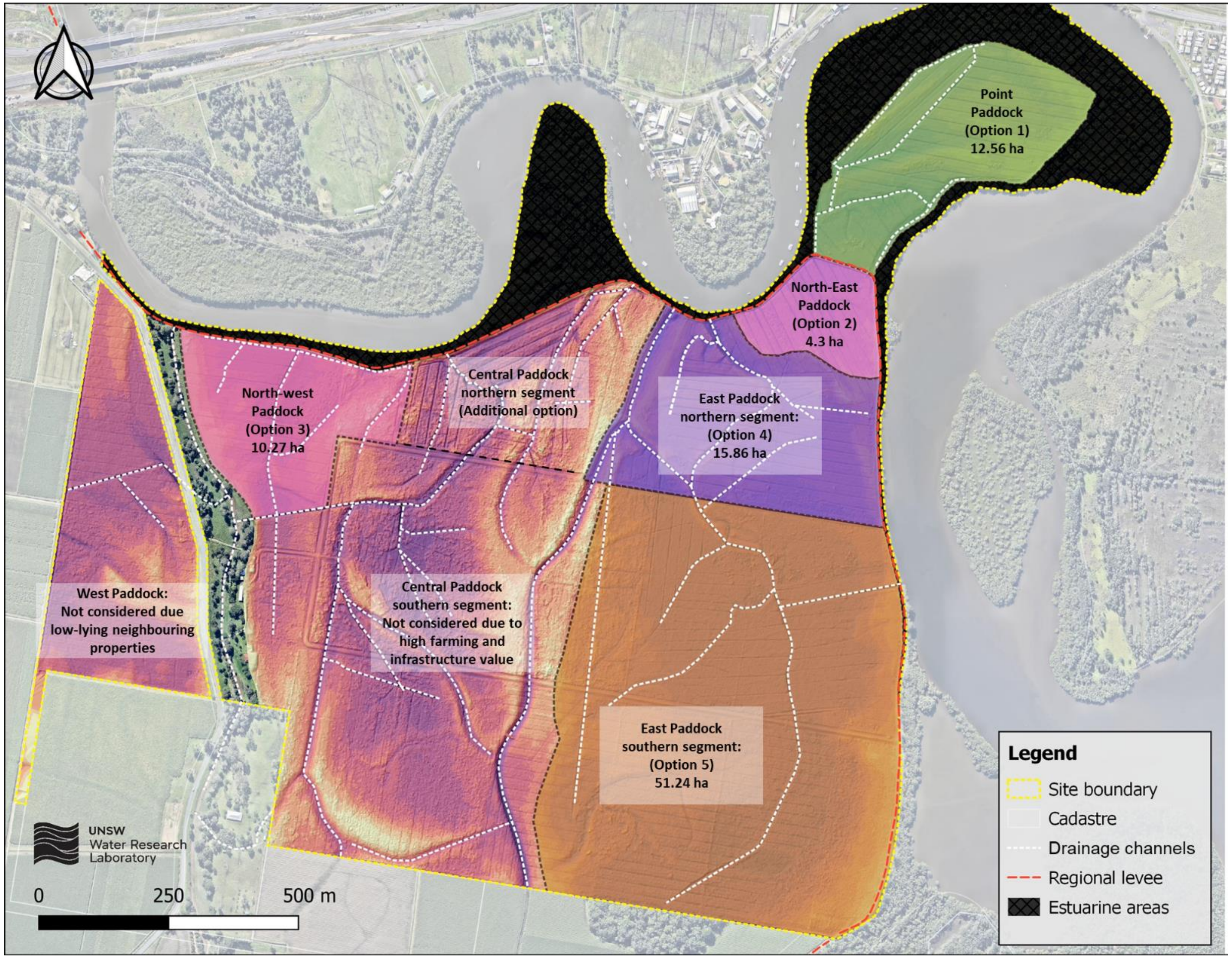

Figure 4.13: Locations of the potential tidal restoration opportunities (coloured areas) and areas not considered for tidal restoration (Central Paddock – southern segment and West Paddock).

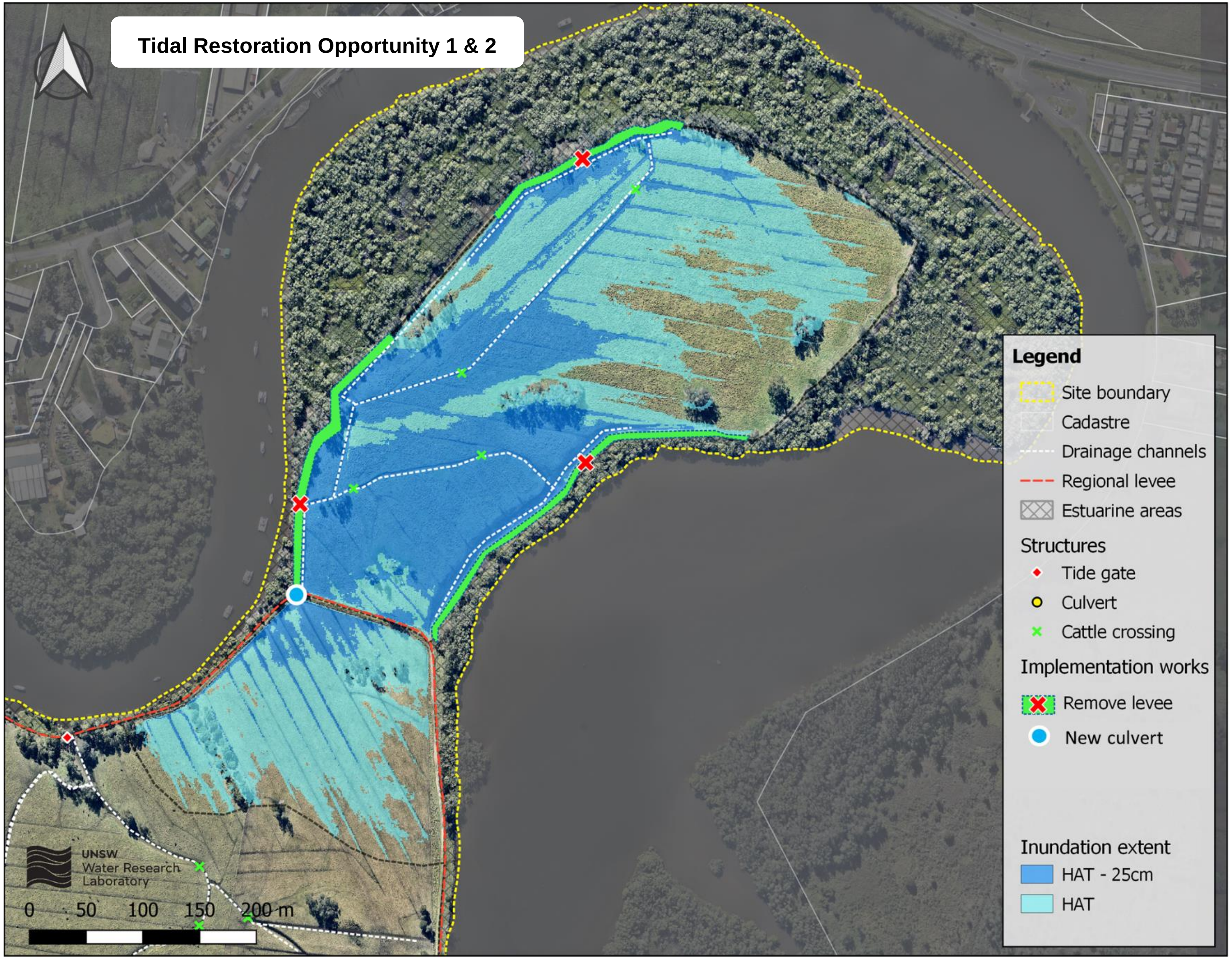

Figure 4.14: Map showing tidal restoration Opportunities 1 and 2 and potential onsite modifications.

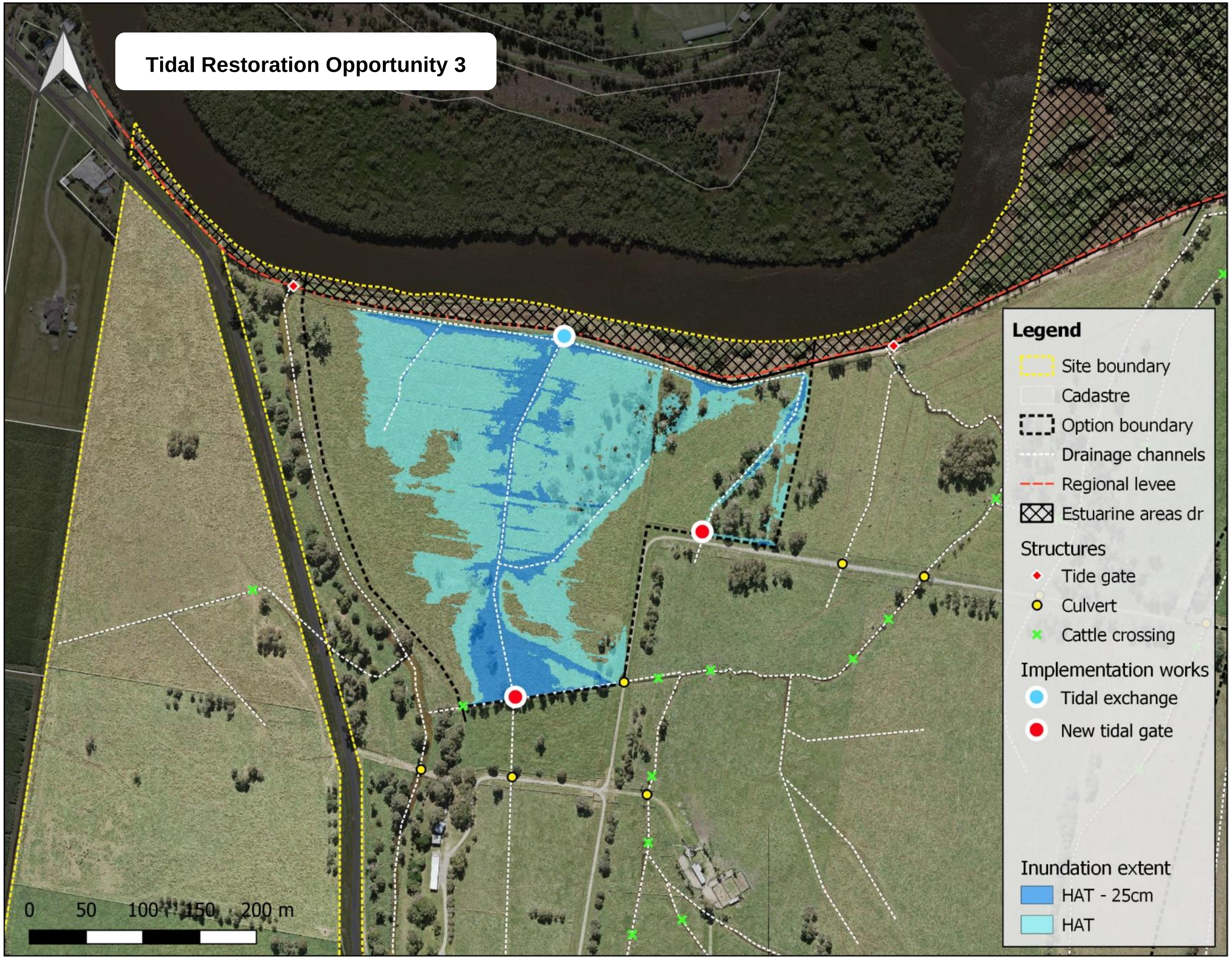

Figure 4.15: Opportunity 3 map showing potential tidal restoration outcomes and possible onsite modifications.

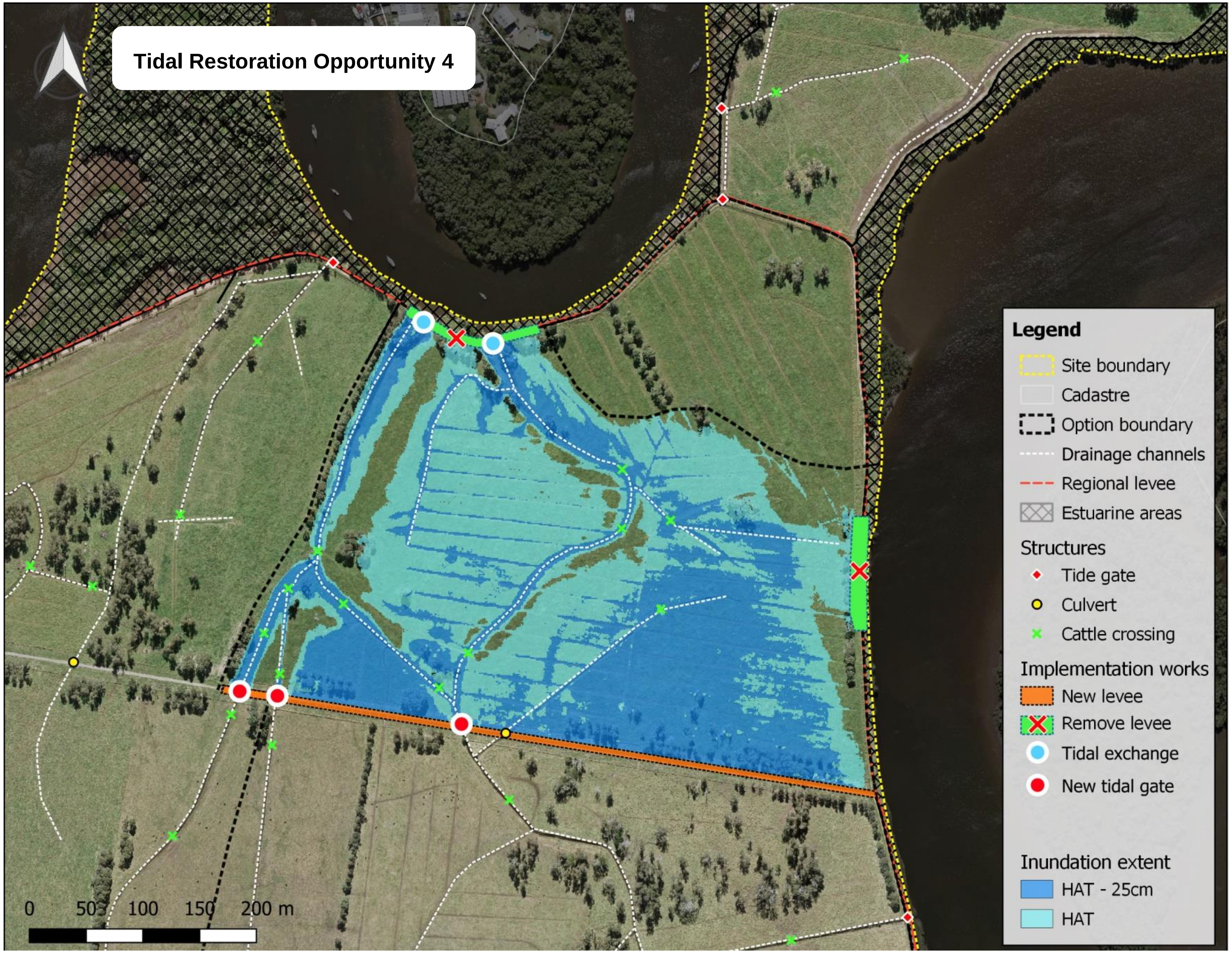

Figure 4.16: Opportunity 4 map showing potential tidal restoration and onsite modifications.

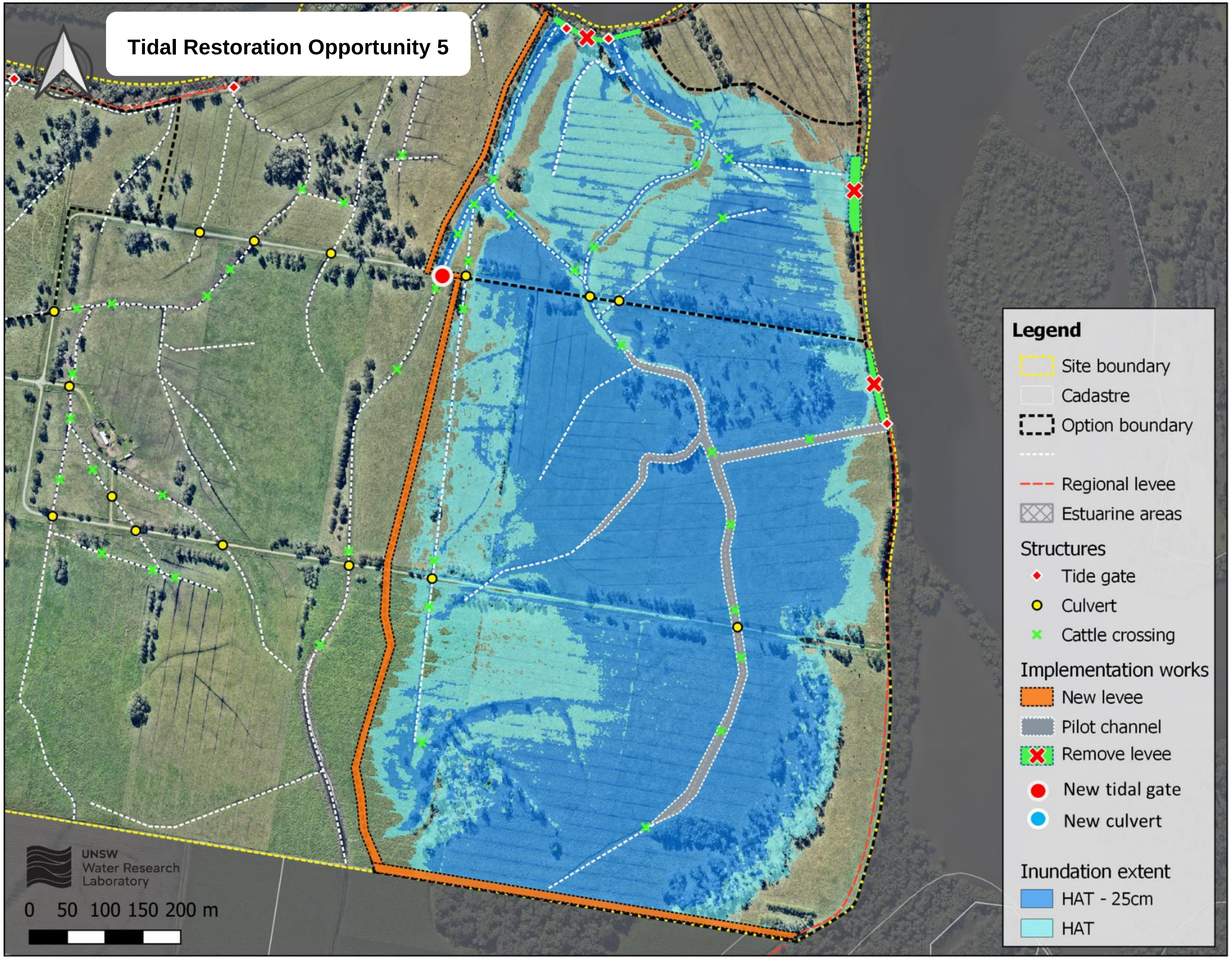

Figure 4.17: Opportunity 5 map indicating potential tidal restoration and associated onsite modifications.

4.5 Carbon abatement estimation

To estimate the carbon abatement potential, vegetation areas are divided into Carbon Estimation Areas (CEA). Each CEA considers the future and existing vegetation type and land-use within each CEA. The carbon abatement of each CEA is estimated using BlueCAM (CER, 2022). BlueCAM uses data from each CEA to compare what exists at the project baseline to the end of the reporting period (as short as 1 year but not longer than 5 years) to determine the carbon abatement from a project. Different values and coefficients are used in the calculation depending on the region/area within Australia, with subtropical values used in this assessment. Further information is provided in the BlueCAM technical overview (CER, 2022). BlueCAM calculates emission abatements in tonnes CO_2 equivalent (CO_2-e), which accounts for all greenhouses gases; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from soils and waterbodies (CER, 2022). Methane and nitrous oxide have global warming potentials 25 and 298 times respectively that of CO_2 (CER, 2022).

BlueCAM considers:

- The project permanence period (25 or 100 years).
- Emissions (e.g., fuel for traveling to and from the site) generated during project activities (none assumed for the purposes of this assessment).
- Emissions avoided or generated due to land use change/transition.
- Carbon sequestration for above and below ground vegetation biomass.
- Carbon sequestered in soil.

The carbon abatement potential for the study site was estimated using BlueCAM using a permanence period of 100 years. For this assessment, ‘grazing’ was used as the baseline land-use across all areas of the property. Due to this uniform baseline land use, it was not necessary to map CEAs within each restoration opportunity. Instead, each vegetation class within each restoration option can be considered a CEA (i.e., see Figures 4.7, 4.8, 4.9, and 4.10). The detailed mapping of CEAs is a reporting requirement for blue carbon projects and should be undertaken at the relevant stage.

Table 4.2 details the emissions avoided, and carbon sequestered for each tidal restoration opportunities shown in Figure 4.13. For this assessment, it is assumed that areas that are too high for saltmarsh to establish (i.e., areas above the HAT), would promote coastal upland forest growth after tidal introduction and the exclusion of livestock. For the 25 cm attenuated HAT scenario, some of the areas identified as saltmarsh or mangroves in the ‘no attenuation’ scenario may become partially replaced by coastal upland forest, due to the lower extent of HAT into the site. As a result, the net abatement amount of the different tidal restoration options is largely a function of the size of the restoration option area. Due to the higher amount of carbon sequestered in the sediment and biomass of coastal upland forest compared to saltmarsh, the 25 cm attenuated HAT scenario resulted in higher total carbon abatement amounts for Restoration Opportunities 1-4 compared to the ‘no attenuation’ scenario. This is illustrated in the net carbon abatement amounts achieved per hectare for the different restoration options. The minimum net abatement amount per ha of 80.7 t CO_2-e/ha was obtained for the North-East Paddock under the no attenuation scenario. The maximum net abatement amount per ha of 143.9 t CO_2-e/ha was obtained for the same area under the 25 cm attenuation scenario. On average, the five identified core restoration opportunities had a net abatement of 97.0 t CO_2-e/ha for the no attenuation scenario and 110.5 t CO_2-e/ha for the 25 cm attenuation scenario. The total amount of net carbon abatement achievable across the five core restoration opportunities, which cover a combined area of 94.23 ha, is 5,239.7 t CO_2-e.

Table 4.2: Predicted blue carbon vegetation outcomes for all rehabilitation opportunities and corresponding BlueCAM carbon abatement results. All outcomes are provided for the 'HAT no tidal attenuation' and a '25 cm attenuated HAT' scenario. The spatial distribution of the associated vegetation outcomes is provided in Figures 4.7 - 4.8.

				STPI method vegetation outcomes [ha]							
	Opportunity code	Total area [ha]	Tidal (HAT) attenuation [cm]	Tall Mangrove	Scrub Mangrove	Saltmarsh	Supratidal Forest	Reporting period emissions avoided (t CO_2-e)	Reporting period C sequestered in vegetation and soil (t CO_2-e)	Net abatement amount (t CO_2-e)	Net abatement per unit area (t CO_2-e/ha)
Point paddock	1	12.6	0	0.7	4.4	4.6	2.9	-68.4	1,703.1	1,208.9	96.3
			25	0.3	2.2	2.6	7.5	-68.4	2,101.3	1,507.5	120.0
North-east paddock	2	4.3	0	0.0	0.4	2.6	1.3	-23.4	494.1	347.2	80.7
			25	0.0	0.1	0.4	3.9	-23.4	856.5	618.9	143.9
North-west paddock	3	10.3	0	0.1	1.3	4.6	4.3	-55.9	1,363.6	966.7	94.1
			25	0.1	0.3	1.1	8.9	-55.9	1,956.3	1,411.3	137.4
East-paddock northern segment	4	15.9	0	0.4	6.0	6.7	2.8	-86.4	1,956.8	1,381.2	87.1
			25	0.2	1.0	5.2	9.5	-86.4	2,433.9	1,739.0	109.6
East-paddock southern segment	5	51.2	0	2.0	30.6	11.1	7.6	-279.2	7,358.5	5,239.7	102.3
			25	0.6	15.7	16.3	18.6	-279.2	7,224.7	5,139.4	100.3
Areas 1-5 combined	-	94.2	0	3.2	42.7	29.5	18.9	-513.4	12,876.1	9,143.7	97.0
			25	1.2	19.2	25.5	48.4	-513.4	14,572.7	10,416.1	110.5

4.6 Risks and other considerations

Factors to be considered in a project application are detailed in CER (2022). Risks associated with ASS and connectivity to neighbouring properties are discussed in the following sections. Other factors not covered in this preliminary assessment include, but are not limited to, local and state regulations, ongoing maintenance, social considerations, historical inundation patterns, mosquito health risks, indigenous inputs, or economic returns. Further, detailed engineering is required to confirm the location, design specifications, and legality of any proposed works. It is worth noting that the introduction of tidal flows to the identified restoration areas may be subject to various approvals and development controls as per Table 4.3.

4.6.1 Acid sulfate soils

ASS present a risk to project activities onsite. In Chapter 1.1, it was established that the property has a high risk of ASS. Several of the core samples detailed in Figure 1.8 indicated high acidity risks onsite and a variable spatial distribution. As such, further ASS investigations would be required depending on the on-ground works proposed.

4.6.2 Managing risks to neighbouring properties

Table 4.4 provides a summary of the five identified restoration opportunities at Duck Creek along with a qualitative rating and description of associated risks. A possible onsite configuration including engineering modifications is also provided for each opportunity. Due to the configuration of the Duck Creek DPI property, the risk to neighbouring properties stemming from the current or near future opportunities (Opportunity 1-4) is low. These options are fully contained within the property and do not have boundaries with adjacent properties. However, these four opportunities may pose risk to some of the existing farming values of the baseline areas, particularly by permitting tidal surface and ground waters into existing freshwater grazing areas.

GIS bathtub modelling of potential tidal inundation indicated that activation of Opportunity 5 (East Paddock – southern segment) might result in tidal connectivity to adjacent properties to the south of the study site (Figure 4.17). A new levee at this southern property boundary might be sufficient to manage this risk by fully containing tidal flows within this area. However, it is important to consider that impacts may not be limited to surface waters and may also result from elevated groundwater levels and salinity intruding into the adjacent property, as well as altered drainage of the adjacent paddocks.

Mitigation of inundation risks to neighbouring properties may be achieved by maintaining agricultural use on the property between blue carbon opportunities and neighbouring paddocks. Based on the proximity to neighbours, undertaking Opportunity 5 would require:

- Agreement from neighbouring landholders for the project to proceed (this is likely required for all tidal introduction areas with a boundary to a neighbouring property).
- Participation of neighbouring landholders in the project application.
- Construction of infrastructure to limit connectivity (i.e., levee) and maintain drainage (i.e., new culverts/floodgates)

Table 4.3: NSW regulatory approvals (CER, 2022)

Approval	Administering body
Coastal protection works consent	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels
Development approval in coastal wetlands and littoral rainforest planning zones	Department of Planning, Industry and Environment; Local Governments
Local Environment Plan, State Environmental Planning Policies, development controls	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels
Consent for demolition works	Local Governments, Regional Planning Panels
Category 1 Remediation Work Needing Consent (SEPP 55)	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; NSW Environment Protection Authority
Development on Crown Land	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; Crown Lands
Development consent	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; Department of Primary Industries - Fisheries
Permit to dredge or conduct reclamation work; or permit to cut, remove, damage or destroy marine vegetation on public water land or an aquaculture lease, or on the foreshore of any such land or lease; or any activity that obstructs or alters tidal flows to marine vegetation in a protected area; or permit to: (a) set a net, netting or other material, or (b) construct or alter a dam, floodgate, causeway or weir, or (c) otherwise create an obstruction, across or within a bay, inlet, river or creek, or across or around a flat	Department of Fisheries
Development consent and/or permission to harm Aboriginal objects or declared Aboriginal places	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; National Parks and Wildlife Service
Demolishing or removing State or Local non-Aboriginal Heritage Items	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; NSW Heritage Council
Development consent and/or water use approval, water management work approval or activity approval under Part 3 of Chapter 3 of the Water Management Act 2000	Department of Planning, Industry and Environment; Local Governments; Regional Planning Panels; Water NSW; Natural Resources Access Regulator
Permit to harm marine vegetation (in course of works)	Department of Planning, Industry and Environment; Department of Primary Industries
Approval to clear threatened or endangered flora or fauna	Department of Planning, Industry and Environment – Environment Energy and Science; Local Governments; Regional Planning Panels; Local Land Services
Consent to undertake work in marine park or aquatic reserve	Department of Primary Industries
Development consent for the disturbance of acid sulfate soils	Dept. Planning, Industry and Environment; Local Governments; NSW EPA

Table 4.4: Summary table of identified tidal restoration opportunities, risks, and potential engineering works.

Opportunity	Area [ha]	Net abatement (t CO2-e)	Timing and Qualitative rating of risk	Recommended engineering works
Opportunity 1 Point Paddock	12.6	1,209	Current or near future opportunity. Very low risk. This area is located on the estuary side of the regional flood levee and isolated from the rest of the property. Activating this area may influence groundwater salinity near the boundary with the North-east Paddock.	This area could be fully activated via removal of existing earth levees (or parts thereof). If needed, spoil could be used to fill and shorten constructed drains in the paddock.
Opportunity 2 North-East Paddock	4.3	347	Current or near future opportunity. Low risk. This area is fully contained within the property and hydrologically constrained by a natural ridge. Activating this area may influence groundwater salinity near the boundary with the East Paddock North Section.	This area could be partially activated by removing the existing tidal flap. Full activation would likely require a new, larger culvert although this expense could be avoided if opportunities C1, C2 and C3 were implemented. Together Opportunities B, C1, C2 and C3 could enable realignment of the regional levee to the existing northern east-west farm roadway.
Opportunity 3 North-West Paddock	10.3	967	Current or near future opportunity. Low risk. This area is fully contained within the property, but minor modifications and earthworks may be required to contain extreme tide levels within this area. Activating this area may influence groundwater salinity near the boundary with the margin of the Central Paddock.	This area could be partially activated by removing the tidal flap on the existing culvert. Full activation would likely require a new, larger culvert although this expense could be avoided if opportunities C1, C2 and C3 were implemented. Together Opportunities B, C1, C2 and C3 could enable realignment of the regional levee to the existing northern east-west farm roadway. Culverts upstream of the area would need to be equipped with floodgates.
Opportunity 4 East Paddock Northern Segment	15.9	1,381	Current or near future opportunity. Low to medium risk. This area is fully contained within the property but there is a high degree of connectivity to the large basin to the south (Opportunity 5) and significant modifications and earthworks may be required to fully contain tidal flows. Activating this area may influence groundwater salinity near the boundary with the East Paddock Southern Section.	This area could be partially activated by removing the tidal flaps on the existing culverts. Full activation would likely require a new, larger culvert or this expense could be avoided if opportunities B, C1, C2 and C3 were implemented. Together this could enable realignment of the regional levee to the existing northern east-west farm roadway.
Opportunity 5 East Paddock Southern Segment	51.2	5,240	Distant future opportunity Medium to high risk in current or near future, risk reduced in distant future due to natural impact of sea level rise on neighbouring properties. This area borders	This area could be partially activated by removing the tidal flap on the existing large culvert. Full activation would require partial removal of the existing earth levee and the creation of pilot channels for enhanced

Opportunity	Area [ha]	Net abatement (t CO2-e)	Timing and Qualitative rating of risk	Recommended engineering works
			the neighbouring coastal forest and sugarcane fields at the southern end and a new levee may be required to fully contain tidal flows within the property boundary. Activating this area may influence groundwater salinity beyond the blue carbon estimation area into the neighbouring property to the west and south.	tidal conveyance. Relocation of the regional levee might be necessary. It would be also necessary to create a levee at the southern part of the site.
Opportunity C2 Central Paddock Northern Segment	11.6	Not calculated	Current or near future opportunity. Low to medium risk. This area is fully contained within the property but there is a high degree of connectivity to the large central basin to the south. Significant drainage modifications and earthworks would be required to fully contain tidal flows to this area. Activating this area may influence groundwater salinity into the adjacent property areas.	This area could be partially activated by removing the tidal flaps on the existing culvert. Full activation would likely require a new larger culvert or partial removal of the existing earth levee although this expense could be avoided if opportunities B, C1, C2 and C3 were implemented. Together this could enable realignment of the regional levee to the existing northern east-west farm roadway. At this site it may be necessary to establish a corridor between drains south of the proposed realigned levee through C2 to the current floodgate outlets aware of the increasing drainage constraint posed by sea level.

5 Design of a monitoring and reporting program

5.1 Monitoring program general design considerations

Monitoring of the tidal restoration process is required to ensure that the desired and/or predicted blue carbon and co-benefit outcomes are achieved on-site. As shown in Figure 5.1, it is recommended that pre- and post-restoration monitoring is an integral part of any adaptively managed tidal restoration project.

Adaptive management is an iterative process whereby on-ground actions are adjusted to maximise the alignment between observed outcomes and restoration targets/objectives. Ecosystem responses such as the establishment of different blue carbon vegetation communities post tidal introduction are difficult to accurately predict. This means that on-ground outcomes can differ substantially from the initial estimates. Further, risk factors may emerge that were not anticipated as part of the hydrologic assessment. Through adaptive management, these uncertainties or 'unknowns' are managed via on-ground management strategies or through the implementation of (new) on-ground actions.

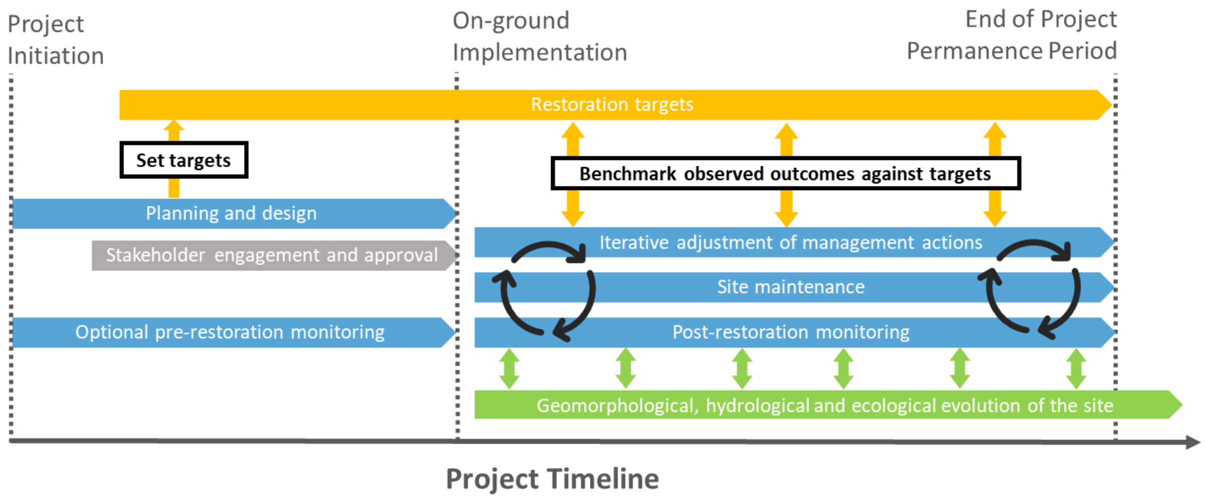

Figure 5.1: Schematic illustrating the adaptive management process for tidal restoration projects (source; Heimhuber *et al*., 2022)

In an adaptive management approach, specific restoration targets are set early in the project planning and design phase. Key targets for blue carbon restoration projects may include (but are not limited to):

- blue carbon vegetation distribution and extent
- carbon accrual/sequestration levels
- meeting surface/groundwater quality objectives and nutrient reduction thresholds
- achieving a specific hydrological regime, such as high and low tide levels or hydroperiods
- reduced acid flux
- counts of target species (e.g., migratory shorebirds)
- species richness and diversity measures
- limiting disturbance to existing habitat
- avoiding inundation of adjacent properties during king tides or flood events

- site visitors (e.g., eco-tourism)
- community education outcomes
- specific geomorphological changes and/or adaptations (e.g., channel deepening or infilling)

Following the selection of restoration targets, a well-designed monitoring program should observe changes in the hydrological, ecological, and geomorphological outcomes and evolution of the restoration site and include relevant indicators of:

- hydrology,
- water quality,
- vegetation changes and extent, and
- biodiversity, including fish assemblages and avifauna.

These observations can then be benchmarked against the previously defined restoration targets to ensure that the site is developing in-line with the predicted outcomes.

A field monitoring program is used to verify whether key targets are being met. It is recommended that the site is monitored prior to the implementation of the tidal restoration activity to establish the eco-hydrological baseline from which improvements can be assessed (ideally one year or more). Figure 5.2 illustrates how the appropriate scope and frequency of a monitoring program depends on the site complexity and the risks associated with the tidal inundation, as well as other factors, such as habitat requirements of threatened species.

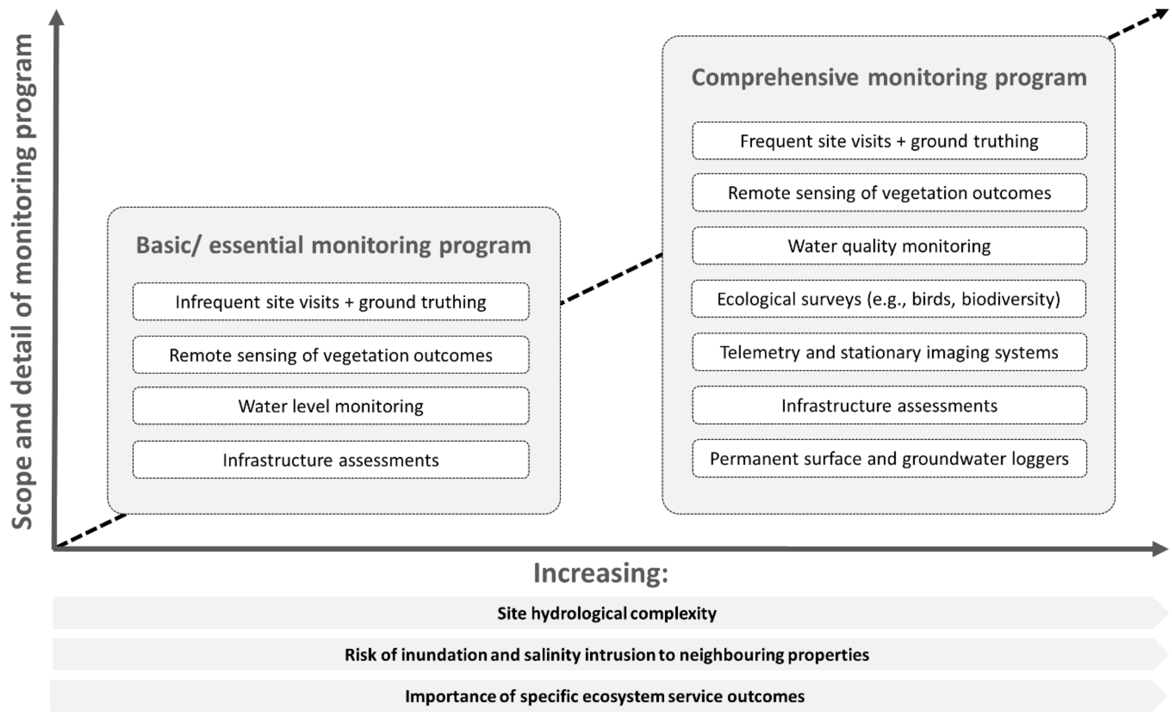

Figure 5.2: Scope and frequency of a monitoring program for tidal restoration activities (source; Heimhuber *et al.,* 2022).

If the hydrologic assessment and on-ground implementation are led by robust data and suitable modelling, major changes to ongoing management actions are often minimal or not required. This should be considered on a project and site basis. Funds can be allocated to ongoing monitoring and maintenance - e.g., onsite morphological changes may require mechanical interventions, such as deepening or widening of channels, raising of levees, which can incur significant costs.

5.2 Monitoring program for the Point Paddock

Based on discussions with DPI, the Point Paddock (Opportunity 1) was identified as the opportunity with the highest priority for on-site implementation and registration as a blue carbon project with the CER. This chapter provides a preliminary monitoring program design for a possible tidal restoration project focusing on the Point Paddock. Importantly, the exact nature and design of the monitoring program cannot be finalised at this stage, as it depends on various factors, including but not limited to the available budget, current and future research projects and collaborations, stakeholder needs, and evolving policies around co-benefit and biodiversity markets. As such, the recommended monitoring activities should be treated as preliminary guidance. Depending on the available budget and other aforementioned factors, a suitable monitoring program can then be finalised.

The monitoring and reporting requirements for projects registered under the Blue Carbon Method are largely limited to mapping the established blue carbon vegetation at the end of each reporting period (as short as 1 year but not longer than 5 years) via appropriate remote sensing/GIS tools supported by ground truthing of vegetation classes, where required (CER, 2022). However, for the Duck Creek DPI property, it is recommended that a more comprehensive and scientifically rigorous eco-hydrological monitoring program is considered. This will help to quantify the blue carbon and co-benefit outcomes of the tidal introduction activities and to better communicate these benefits with stakeholders, including the public. Further, the data will enable novel scientific investigations into the evolution of sites from drained grazing lands to blue carbon ecosystems. Lastly, a thorough assessment of the ecological values of the site before and after tidal introduction is recommended. This will ensure that biodiversity and other co-benefits can be quantified in addition to blue carbon ACCUs, as is the case in Queensland under the Land Restoration Fund (QLD Department of Environment and Science, 2020).

The recommended monitoring program for the Point Paddock is focused on the hydrological evolution of the site and the resulting blue carbon vegetation outcomes. Figure 5.3 details the recommended layout of the hydrological monitoring setup, while Table 5.1 provides a summary of all proposed monitoring activities. The hydrological monitoring consists of ten conductivity temperature depth (CTD) loggers deployed across the site at various depths (ground and/or surface water depending on location and monitoring goal). CTD loggers have a design life of around 5 years and require regular maintenance and recalibration (2-3 times per year).

The monitoring objectives of the CTD loggers differ across the deployment sites. Two loggers are recommended on the estuary side of the existing levee to accurately quantify the tidal and salinity boundary regime along the perimeter of the Point Paddock. This is recommended because the Byrnes Point permanent tide gauge does not measure salinity and to quantify the local tidal boundary regime more accurately. In addition, it is recommended that six CTDs are deployed across the paddock as shallow piezometers. The placing of these CTDs is done strategically to capture the salinity and hydroperiod for different blue carbon vegetation classes (i.e., mangroves, saltmarsh, and coastal upland forest). Lastly, a minimum of two CTDs are recommended within groundwater piezometers on the dry side of the regional flood levee to monitor potential salinity intrusion into this area resulting from tidal activation of the Point Paddock. Note that a transact array approach as noted in Glamore and Indraratna (2009) has been shown to provide accurate mapping of salinity intrusion in tidal restoration environments.

To facilitate high-resolution mapping of vegetation outcomes and changes over each blue carbon reporting period, it is recommended that aerial drone surveys are completed at regular intervals. Due to the temporal changes in vegetation cover, drone flights should be conducted at least twice per year. The distribution of different blue carbon vegetation classes can be mapped on a multispectral drone imagery either manually or using appropriately trained image classification algorithms (i.e., using ground truth data collected in the field as training data). It is critical that this mapping is undertaken by an expert with the relevant expertise as the resulting blue carbon vegetation distribution at the end of each reporting period forms the basis for the calculation of carbon abatement amounts via BlueCAM and the amount of ACCUs that will be received (CER, 2022). Recent examples of this research can be found in Lanceman *et al.* (2022).

In addition to the loggers and drone surveys, two high resolution stationary cameras are recommended at strategic locations that overlook areas of the paddock (see Figure 5.3). These cameras are highly effective for monitoring and capturing the eco-hydrological evolution of the site, which is useful for education and community engagement purposes. Footage and data from these cameras can also be used to monitor and visualise vegetation changes, tidal and extreme water levels, and the use of the restored site by shorebirds.

As stated in Table 5.1, it is recommended that telemetry is used to access the data in near-real time from some or all of the loggers and the stationary cameras into an online data portal and warehouse. This will ensure that all project managers and stakeholders have access to the monitoring data at all times and that the data is securely archived. In addition, the datafeeds can be used for educational and community engagement purposes as well as for research. Further, the live video and photo footage from the stationary cameras is particulary useful for monitoring (and responding to) any potential unforseen events occuring at the restoration site such as tresspassing, cattle incursions, or failure of infrastructure.

In addition to this suggested hydrologic monitoring program, it is recommended that ecological surveying of biodiversity, including vegetation, freshwater and estuarine fish, meiobenthic communities, birds, invertebrates, and other fauna is undertaken prior to and at regular intervals after tidal introduction (see Table 5.1 for further details). Rod surface elevation tables (RSETs) are also recommended to track sedimentation across the site with tables deployed inside/outside the Point Paddock and in adjoining locations that may potentially be restored in the future (Cahoon *et al.,* 2002). It is also recommended that an aboriginal cultural heritage survey, detailed monitoring of carbon sequestration and a mosquito survey is undertaken. These additional surveys will help to establish the baseline ecological and cultural values of the site and to accurately quantify all co-benefits. Further, these assessments will ensure that impacts to existing environmental and farming values from tidal restoration can be comprehensively assessed, considered, and mitigated, where appropriate.

Finally, there is a growing body of science that is focused on developing indicators that best represent ecosystem services before and after tidal restoration. It is recommended that an expert workshop is held to determine the latest scientific advice regarding these indicators and whether reference sites should be established. The approach noted in the Society of Ecological Restoration's *National standards for the practice of ecological restoration in Australia* (SERA, 2017) highly recommends the use of reference sites, denoting monitoring conceptual approaches and progress evaluation tools that should be considered for the site.

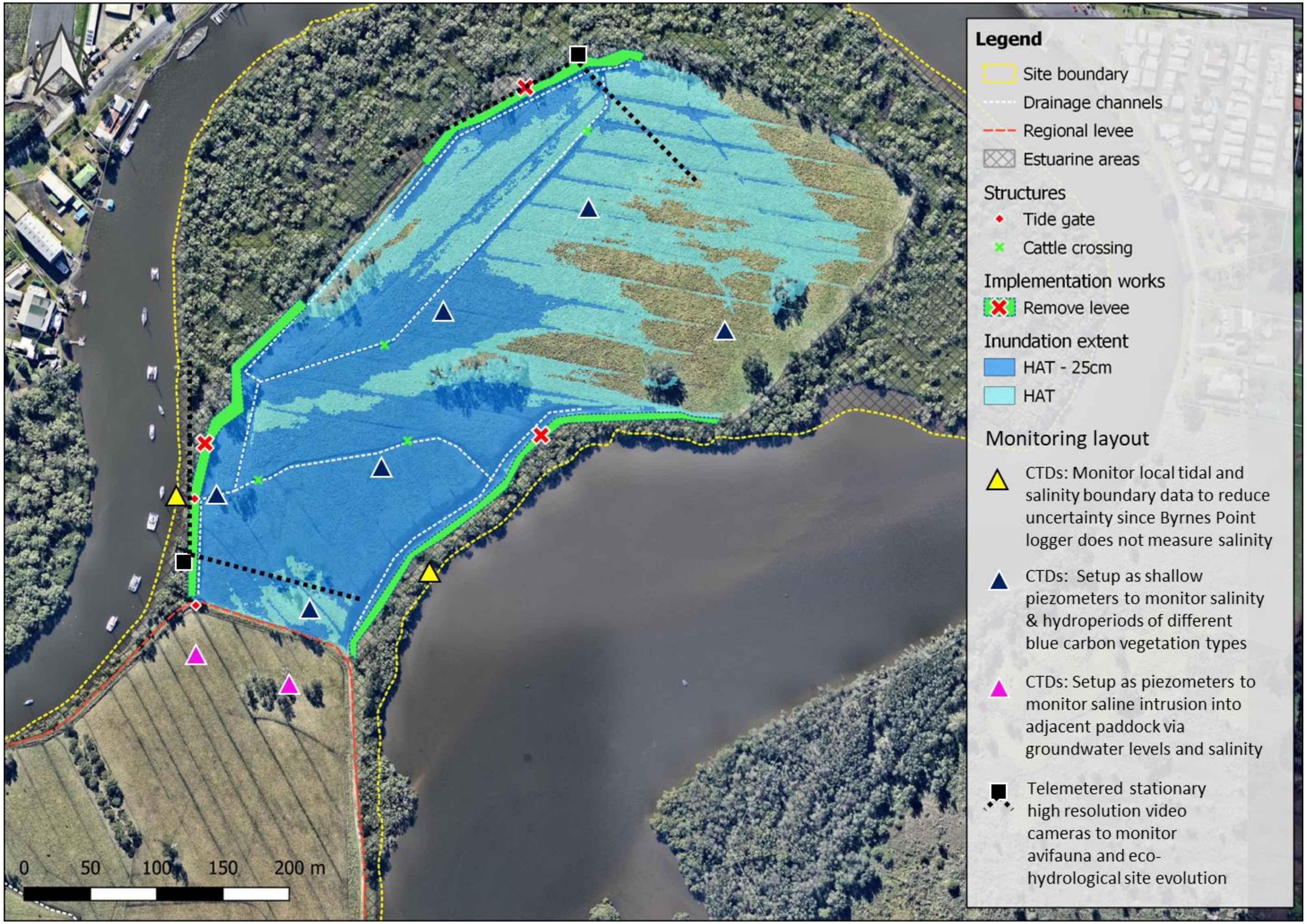

Figure 5.3: Potential hydrological monitoring program.

Table 5.1: Proposed monitoring program for the Point Paddock (Opportunity 1). See Figure 5.3 for recommended location of loggers and cameras.

Monitoring activity	Equipment and/or expertise required	Outcome of monitoring activity	Research opportunity?
Monitor tidal and salinity boundary regime	2 CTDs deployed on the estuary side of the levee. Expert consultant required for deployment and maintenance.	The Byrnes Point tide gauge does not measure salinity so local boundary data will help reduce uncertainty.	Yes
Monitor hydroperiod and salinity across the tidally restored paddock as the key factors that determine blue carbon vegetation outcomes	6 CTDs deployed across the paddock at strategic locations. Expert consultant required for deployment and maintenance.	Shallow piezometers will identify salinity levels and hydroperiods in areas of different elevation and distance to the estuary for which different blue carbon vegetation classes are expected. The number of CTDs deployed across the paddock could be reduced in case of budget constraints.	Yes
Monitor salinity intrusion on the landward side of the regional flood levee	2 CTDs deployed as piezometers behind the regional flood levee. Expert consultant required for deployment and maintenance.	These piezometers will provide accurate data on the salinity intrusion into the paddock on the landward side of the regional flood levee that might result from tidal introduction to the Point Paddock.	Yes
High resolution vegetation mapping	Multispectral drone flights should be conducted twice per year. One or two pre-restoration drone surveys are also recommended.	High resolution land cover mapping focusing on blue carbon vegetation outcomes before and after tidal restoration of the site. Accurate mapping of blue carbon vegetation outcomes before and after each reporting period is critical as it is the basis for calculating carbon abatement of the project via BlueCAM (CER, 2022).	Yes. Consider research collaborations and obtaining suitable research grants to undertake and finance this work.
Continuous video and imagery footage across the site via stationary cameras.	Two telemetered surveillance cameras mounted on poles at strategic locations around the paddock. Expert consultant required for deployment and maintenance.	These cameras will provide footage of the eco-hydrological evolution of the site, which is highly effective for education and community engagement purposes. Footage can be used to monitor and visualise vegetation changes,	Yes. Consider research collaborations and obtaining suitable research grants to undertake and finance this work.

Monitoring activity	Equipment and/or expertise required	Outcome of monitoring activity	Research opportunity?
		extreme water levels and the use of the restored site by avifauna.	
Online data dashboard and data warehouse	Expert consultant is required to setup the online dashboard and warehouse	The data dashboard will display and store all telemetered data in a single location. All CTDs and stationary cameras can be linked to the data dashboard and warehouse via telemetry, but this will incur additional cost for each logger. The data dashboard and warehouse will facilitate the dissemination of data and the communication of outcomes with all stakeholders and the public.	Unlikely
Survey of ecological baseline and rehabilitation outcomes	Gather ecological data on biodiversity, including freshwater and estuarine fish, birds, meiobenthic communities, invertebrates, and other fauna before and after tidal introduction using appropriate survey methods (continuously at regular intervals). Requires specialist ecological consultant or research group	Continuous ecological surveys will provide critical data to: • quantify all co-benefits including those that might be monetizable in the future. • inform the development of an ecological values assessment • enable before-after-control-impact experimental design • inform the Environmental Impact Assessment (if required).	Yes. Consider research collaborations and obtaining suitable research grants to undertake and finance this work.
Aboriginal cultural heritage survey	Undertake before tidal introduction. Requires specialist consultants.	This survey will identify all aboriginal cultural heritage that might be present across the site and needs to be considered before introducing tidal flows.	Possibly
Detailed on-ground vegetation surveys	Use ecological survey techniques for detailed assessment of vegetation community health and assembly (e.g., quadrants). Requires specialist ecological consultants or research groups.	On-ground vegetation surveys are recommended to develop a detailed understanding of the vegetation changes occurring on the site after the introduction of tidal flows. This data can further be used as ground-truth for the remote sensing-based mapping of blue carbon vegetation outcomes.	Yes. Consider research collaborations and obtaining suitable research grants to undertake and finance this work

Monitoring activity	Equipment and/or expertise required	Outcome of monitoring activity	Research opportunity?
Carbon sequestration and greenhouse gas balance	Use soil cores, surface elevation tables and Feldspar markers to accurately quantify the baseline soil carbon and blue carbon sequestration after introduction of tidal flows. Requires specialist consultants or research groups.	Although the measurement of soil carbon accumulation is not a requirement of the Blue Carbon Method, it is recommended to accurately monitor the accumulation of blue carbon across the paddock. This will provide important information about the actual carbon sequestration rates and data with high value for scientific research.	Yes. Consider research collaborations and obtaining suitable research grants to undertake and finance this work
Rod surface elevation table (RSET)	Previously undertaken installation and analysis. Requires specialist consultants or research groups	RSETs measure sediment elevation in shallow water wetland systems. The RSET makes it possible to partition change in sediment elevation over time.	Yes
Mosquito survey & management plan	Undertake appropriate surveys before and after tidal introduction. Requires specialist ecological consultants or research groups.	One of the risks of tidal restoration activities is that they might lead to increased mosquito abundance. Pre- and post-intervention monitoring is therefore recommended to quantify these impacts accurately and to respond appropriately if required.	Possibly

6 Summary

This study represents a first-pass assessment of the blue carbon feasibility at the 192 ha DPI research station at Duck Creek, Pimlico. The main goal of this assessment was to investigate whether all or parts of the property are suitable for the establishment of blue carbon ecosystems (i.e., seagrass meadows, saltmarsh, mangroves, and supratidal forests) via introduction of tidal flows, and whether those areas would be eligible for receiving ACCUs under the CER's Blue Carbon Method. Even though blue carbon feasibility was mostly assessed based on biophysical factors, constraints stemming from the existing use of the site for cattle farming were considered for the identification of blue carbon options.

This preliminary analysis revealed that most of the property is biophysically suitable for the creation of blue carbon ecosystems via appropriate tidal introduction works. Due to the drained nature of the property and a sequence of tidal floodgates, all biophysically suitable areas are eligible for registration under the Blue Carbon Method. Based on this finding, an analysis was undertaken to identify sub-sections of the property that are suitable for consideration. The project assumed a staged implementation strategy due to current and future farming constraints and sea level rise.

Five unique areas were identified as particularly suitable for registration as blue carbon projects under the Blue Carbon Method now and over the coming decades, covering a combined area of 94.2 ha (see Figure 4.13). For each of these five areas, GIS-based geospatial modelling of tidal inundation depth and extent was used in conjunction with the STPI method of the Blue Carbon Method to estimate the likely blue carbon vegetation outcomes (type and distribution). Further, one possible (and preliminary) onsite configuration was provided for each tidal introduction opportunity.

This preliminary analysis showed that registration of the five identified tidal introduction opportunities under the Blue Carbon Method would result in a net carbon abatement of between 9,144 to 10,416 t CO_2-e. Importantly, these estimates are based on vegetation outcomes predicted via the STPI method and geospatial modelling. The actual ACCUs that a given project will receive depends on the on-site extent and distribution of different blue carbon vegetation classes that establish in response to tidal introduction. This actual extent and distribution will likely differ from the first-pass estimates provided here, possibly resulting in significant differences between the estimates provided and the net carbon abatement amount (i.e., number of ACCUs) accrued over the lifetime of the project.

Based on discussions with DPI, the 12.6 ha Point Paddock (Opportunity 1) was identified as the option with the highest priority for on-site implementation. This option would result in a net carbon abatement of between 1,209 to 1,508 t CO_2-e. This paddock is fully contained on the open estuary side of the regional flood levee and full tidal introduction could be achieved via removal of the surrounding earth levee in two or three strategic locations. This means that there is essentially no risk to neighbours associated with this tidal introduction activity, apart from the potential increase in groundwater salinity intrusion into the paddock on the landward side of the regional flood levee. Consequently, this area represents a comparatively low-risk and low-complexity opportunity for registration as a project under the Blue Carbon Method. As such, a detailed monitoring program was designed for this option, focusing on capturing the eco-hydrological evolution of this paddock from its current state into a blue carbon ecosystem.

The 4.3 ha North-East Paddock on the landward side of the regional flood levee adjacent to the Point Paddock was identified as another low-risk and low-complexity blue carbon opportunity. This area currently drains into the Point Paddock via a floodgate-equipped culvert and could be partially tidally activated by permanently opening the floodgate. A new larger culvert might be required to achieve full tidal flushing for this area, but such detailed hydraulic design considerations were beyond the scope of this assessment. This area is contained within a natural ridge line with an elevation above the HAT, which suggests that the risk of unwanted tidal flows intruding into adjacent property areas is low.

Tidal introduction Opportunities 3, 4 and 5 cover areas of 10.3, 15.9 and 51.2 ha respectively and all have a direct boundary with Emigrant Creek along the regional flood levee. While a degree of tidal flushing could be achieved in these areas by opening the existing floodgates, it is likely that additional engineering modifications (including the creation of pilot channels for Opportunity 5) would be required to achieve a high degree of tidal flushing. These three options are generally more complex than Opportunity 1 and 2 and new levees, floodgates or a relocation of the regional flood levee would be required to contain tidal flows within these areas. Due to these complexities, detailed hydrodynamic and engineering design studies are required before Opportunities 3, 4 and 5 can be considered for registration under the Blue Carbon Method.

As emphasized throughout this report, this blue carbon feasibility assessment is based on geospatial modelling of tidal inundation. Bathtub inundation modelling does not account for the complexities of tidal inundation over vast intertidal areas related to volume, velocities, and timing of flows. Such dynamic factors can lead to significant attenuation and modification of tidal flows as they spread across large flat areas, which in turn can lead to different blue carbon vegetation outcomes than what would be predicted via a bathtub model. Due to the known shortcomings of this approach, a 'plausible range' approach was adopted here. In this approach, 'no attenuation' and '25 cm HAT attenuation' tidal inundation scenarios are used to characterise the likely upper and lower boundary of tidal inundation extent resulting from tidal introduction. The resulting inundation envelope can be used as first-pass guidance for designing tidal introduction works. Importantly, large paddocks such as Opportunity 5 might experience tidal attenuation of more than 25 cm in the most upstream areas. Due to the shortcomings of a bathtub inundation modelling approach, hydrodynamic modelling and implementation design studies may be required where added detail is needed.

Another important consideration for developing a staged blue carbon implementation strategy for the property is future sea level rise. For this assessment, the impacts of 16 cm and 67 cm of near (~2050) and far (~2100) future sea level rise on the blue carbon feasibility of the property were assessed. This analysis showed that due to the very flat and low-lying nature of the property, even minor increases in the mean sea level of 16 cm would lead to comparatively large increases in tidal inundation extent and large changes in the blue carbon vegetation outcomes. Under 67 cm of sea level rise, large parts of the property are forecast to become too low for the establishment of mangroves and may transition to mudflats or seagrass habitat. These findings suggest that it would be advantageous to introduce tidal flows into the corresponding areas within the next decade as this would ensure that blue carbon ecosystems can establish, mature, and potentially keep pace with sea level rise.

In summary, this assessment provided a suit of biophysically feasible and eligible (under the Blue Carbon Method) tidal introduction options across the DPI Duck Creek property. This assessment was based on a high-quality dataset and undertaken in accordance with the highest assessment standards outlined in the Blue Carbon Method (CER, 2022). While further hydrodynamic and engineering design studies may be required, this assessment should provide a foundation to develop a staged blue carbon implementation strategy for the property. Any blue carbon implementation strategy should consider a long-term management horizon and carefully weigh the risks and benefits of the provided tidal introduction options against the existing values of the cattle farming operation. To this end, a detailed assessment of the financial and ecological values of the existing use of the property is recommended.

7 References

BMT WBM, 2012. Cumbalum Ridge Inundation Investigation for and Adjacent Properties, prepared by WBM.pdf.

Cahoon, D., Lynch, J., Perez, B., Segura, B., Holland, R., Stelly, C., Stephenson, G and Hensel, P. (2002) High Precision measurements of wetland sediment elevation. The rod surface elevation table. Journal of Sedimentary Research. 72 (5) https://doi.org/10.1306/020702720734.

CER, 2022. Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022. Australian Government Clean Energy Regulator. URL https://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Vegetation-methods/tidal-restoration-of-blue-carbon-ecosystems-method (accessed 7.12.22).

Couriel, E., Alley, K., Modra, B., 2012. OEH NSW tidal planes analysis 1990-2010 harmonic analysis MHL2053, 491.

DFSI Spatial Services, 2021. Elvis - Elevation and Depth - Foundation Spatial Data, NSW Department Finance, Services and Innovation. URL https://elevation.fsdf.org.au/ (accessed 3.13.19).

Glamore, W. and Indraratna, B. (2009) Tidal forcing groundwater dynamics in a restored coastal wetland: Implications of saline intrusion. Australian Journal of Earth Sciences. 56,1. https://doi.org/10.1080/08120090802541911

Glamore, W.C., Rahman, P.F., Cox, R.J., Church, J.A., Monselesan, D.P., 2015. Sea Level Rise Science and Synthesis for NSW NSW Office of Environment and Heritage' s Coastal Processes.

Heimhuber, V., Ruprecht, J., Glamore, W., 2022. A best-practice framework for planning, implementing and managing tidal restoration of blue carbon ecosystems (under review). Restor. Ecol.

Khojasteh, D., Glamore, W., Heimhuber, V., Felder, S., 2021. Sea level rise impacts on estuarine dynamics: A review. Sci. Total Environ. 780, 146470. https://doi.org/10.1016/j.scitotenv.2021.146470

Kumbier, K., Hughes, M.G., Rogers, K., Woodroffe, C.D., 2021. Inundation characteristics of mangrove and saltmarsh in micro-tidal estuaries. Estuar. Coast. Shelf Sci. 261, 107553. https://doi.org/https://doi.org/10.1016/j.ecss.2021.107553

Lloyd Environmental, 2019. Hydrological Options Assessment for Avalon Coastal Reserve - Final Report.

Marx, S., Knight, J., Dwyer, P., Child, D., Hotchkis, M., and Zawadzki, A. (2020) Examining the response of an eastern Australian mangrove forest to changes in hydro-period over the last century. Estuarine and Coastal Shelf Science. 241, 31. https://doi.org/10.1016/j.ecss.2020.106813

Naylor, S., Chapman, G., Atkinson, G., et al., 1998. Guidelines for the Use of Acid Sulfate Soil Risk Maps, 2nd ed., Department of Land and Water Conservation, Sydney.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci. https://doi.org/10.1073/PNAS.1717312115

NSW Government (1894) 1894, New South Wales Government Gazette (Sydney, NSW : 1832 - 1900), 27 April, p. 2654. , viewed 05 May 2023, http://nla.gov.au/nla.news-page13193505

QLD Department of Environment and Science, 2020. Land Restoration Fund Co-benefits Standard.

Rayner, D., Glamore, W., Grandquist, L., Ruprecht, J., Waddington, K., Khojasteh, D., 2021. Intertidal wetland vegetation dynamics under rising sea levels. Sci. Total Environ. 766, 144237. https://doi.org/10.1016/j.scitotenv.2020.144237

Rayner, D.S., Harrison, A.J., Tucker, T.A., Lumiatti, G., Rahman, P.F., Juma, D., Waddington, K., Glamore, W.C., 2022. Coastal Floodplain Prioritisation Study – Background and Methodology.

Rogers, K., Saintilan, N., Woodroffe, C.D., 2014. Surface elevation change and vegetation distribution dynamics in a subtropical coastal wetland: Implications for coastal wetland response to climate change. Estuar. Coast. Shelf Sci. 149, 46–56. https://doi.org/10.1016/j.ecss.2014.07.009

Sadat-Noori, M., Rankin, C., Rayner, D., Heimhuber, V., Gaston, T., Drummond, C., Chalmers, A., Khojasteh, D., Glamore, W., 2021. Coastal wetlands can be saved from sea level rise by recreating past tidal regimes. Sci. Rep. 11, 1–10. https://doi.org/10.1038/s41598-021-80977-3

Saintilan, N., Rogers, K., Kelleway, J.J., Ens, E., Sloane, D.R., 2018. Climate change impacts on the coastal Wetlands of Australia. Wetlands. https://doi.org/10.1007/s13157-018-1016-7 WETLANDS

SERA Standards Reference Group (2017) National Standards for the Practice of Ecological Restoration in Australia. Second Edition. Society of Ecological Restoration Austraslia. https://www.seraustralasia.com/standards/National%20Restoration%20Standards%202nd%20Edition.pdf

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561, 231–234. https://doi.org/10.1038/s41586-018-0476-5

Stone, Y., Ahern, C., Blunde, n B., 1998. Acid Sulfate Soils Manual 1998. Acid Sulfate Soils Advisory Committee. Wollongbar, NSW, Australia.

Tulau, M.J., 2011. Lands of the richest character: agricultural drainage conservation and policy change : an environmental New South Wales, Australia : development, of backswamp wetlands on the North Coast of history. Southern Cross University, Lismore, NSW.

White, N.J., Haigh, I.D., Church, J.A., Koen, T., Watson, C.S., Pritchard, T.R., Watson, P.J., Burgette, R.J., McInnes, K.L., You, Z.J., Zhang, X., Tregoning, P., 2014. Australian sea levels-Trends, regional variability and influencing factors. Earth-Science Rev. 136, 155–174. https://doi.org/10.1016/j.earscirev.2014.05.011