Department of Climate Change, Energy, the Environment and Water

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Avoca Lagoon Processes Study 2022

Technical Report

May 2024

Acknowledgement of Country

The Department of Climate Change, Energy, the Environment and Water acknowledges that it stands on Aboriginal land. We acknowledge the Traditional Custodians of the land and we show our respect for Elders past and present through thoughtful and collaborative approaches to our work, seeking to demonstrate our ongoing commitment to providing places in which Aboriginal people are included socially, culturally and economically.

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Executive summary

The Avoca Lagoon study, commissioned by Central Coast Council, aimed to investigate ecological processes that may be driving the poor water quality grades (NSW Estuary Report Card) and poor recreational health for Avoca Lagoon over the past decade. The study focused on nutrient cycling within the estuary, examining drivers of eutrophication. Key findings include:

Eutrophication and Phosphorus Limitation: The poor water quality grades for chlorophyll indicate that the lagoon is experiencing moderate eutrophication due to elevated nutrient loading. Primary productivity is likely phosphorus-limited, and therefore management strategies should be directed at reducing catchment inputs of phosphorus.

Sediment Dynamics: Avoca Lagoon acts as a net sink for sediments, including particulate nitrogen and phosphorus. This aligns with gradual infilling over the Holocene epoch.

Ammonium: Internal loads of ammonium from sediment fluxes result in a constant supply of bio-available nitrogen. This means that algae in the lagoon are poised to respond to any inputs of phosphorus.

Dredge Hole Impact: The artificially deep basin (dredge hole) traps fine sediments and organic matter, leading to chronic stratification in the lagoon basin, characterized by hypoxia/anoxia and high ammonium concentrations in bottom waters.

Nutrient Recycling: The enhanced nitrogen and phosphorus recycling within dredge hole sediments contributes significantly to lagoon eutrophication.

Benthic Microalgae: The assimilation of bio-available nutrients by benthic microalgae in well-lit sediments represents a significant sink and serves to ameliorate eutrophication. This process represents a valuable ecosystem service in NSW ICOLLs.

Groundwater Influence: Groundwater has high concentrations of ammonium and dissolved organic N and P and seepage from fringing wetlands significantly affects lagoon water quality as it drains below 1m AHD following entrance opening.

Acidification: Despite multiple entrance openings and high rainfall, smartbuoy data showed no evidence of acidification from acid sulfate soils.

Turbidity Drivers: The poor water quality grades for turbidity are driven by significantly higher turbidity in the southern basin of the lagoon. This results from a combination of high suspended solid concentrations in catchment runoff, the trapping of this material in the southern basin, and the subsequent resuspension by wind waves when lagoon water levels are low.

Pathogen Risks: While the study did not focus on pathogens, enterococci counts in samples collected on two occasions during the study period indicated high counts in creeks draining to the northern basin of the lagoon. These preliminary results highlight a need to better understand pathogen sources in Avoca Lagoon and associated risks to ecological and human health.

The current study was undertaken during an above average rainfall year and as such the results of the various experiments and sampling undertaken should be viewed as representative of those climatic conditions. Extended periods of drought during a succession of El Nino years will likely cause shifts in ecosystem processes.

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1 Introduction

The Central Coast Council commissioned the Department of Climate Change, Energy, Environment and Water (previously the Department of Planning and Environment) Estuaries and Catchment team in 2022 to investigate ecological processes that may be driving the poor water quality grades (NSW Estuary Report Card) and poor recreational health for Avoca Lagoon over the past decade.

With a focus on nutrient cycling within the estuary, examining drivers of eutrophication, the study considered all aspects of the nutrient cycle within Avoca Lagoon to investigate the drivers of eutrophication.

The study aimed to be completed in 2022, however as the study required investigation of an opening event to estimate nutrient exports from the lagoon, this was not possible. To mitigate inundation of adjacent wetland areas, the Central Coast Council mechanically opened the lagoon entrance on 14th September 2023, this allowed competition of the study.

1.1 Objective and aims

The main objective of the study is to quantify and understand the influences and inter-relationships between processes within the estuary under a range of conditions and across seasons. These can be grouped together simply as inputs from the catchment (surface and ground water, sewage), internal processes (benthic fluxes, benthic production/respiration), and outputs (entrance breakout).

The aims of the study are summarised by the following research questions:

- What is the magnitude of nutrient and TSS loads entering Avoca Lagoon from the various sub-catchments and how much does sewage contribute to these loads?
- What processes within Avoca Lagoon govern the fate of these loads in different parts of the estuary over the course of a year?
- How does stratification resulting from bathymetry changes due to historical dredging affect the physico-chemical functioning of the estuary?
- What effect do opening events and water level fluctuations have on the nutrient balance of the estuary?
- How do sediment characteristics and sediment-water column fluxes affect water quality behaviour in Avoca Lagoon?

- What are management recommendations related to these processes which drive poor water quality?

1.2 Background

The NSW Central Coast Council is developing a Coastal Management Program (CMP) for coastal lagoons in accordance with the NSW Coastal Management Framework. The CMP will provide strategic and holistic guidance for the management of this section of the coastal zone over the next 5-10 years. Stage 2 of the CMP development process provides an opportunity to address knowledge gaps identified during the scoping stage which will ultimately inform the development of management actions to include in the CMP during stages 3 and 4.

Of significant concern to Council and the community is the ongoing poor ecological and recreational health of Avoca Lagoon. The state-wide Monitoring, Evaluation and Reporting (MER) program indicates persistent very poor turbidity grades and poor-very poor chlorophyll-a grades from the reporting years 2018 to 2023 (Table 1). Similarly, Beachwatch grades have been consistently poor from 2018 to 2022 (Table 2).

Table 1. Ecological Health Report Card grades for Avoca Lagoon between 2018 and 2022 (DPIE, 2023)

Sampling Period	Turbidity	Chlorophyll-a	Overall Water Quality
2018 – 2019	E	D	E
2019 – 2020	E	D	E
2020 – 2021	C	B	B
2021 - 2022	C	B	C
2022 - 2023	D	D	D

Table 2. Beachwatch grades for Avoca Lagoon 2019-2023 (Beachwatch, 2023)

Year	Grade
2019	Poor

2020	Poor
2021	Poor
2022	Poor
2023	Poor

1.2.1 Intermittently closed and open lakes and lagoons

Intermittently closed and open lakes and lagoons (ICOLLs) are the most common type of estuary along the coastline of New South Wales, representing over 60% of the 184 estuaries in the State. ICOLLs are a diverse estuary type due to differences in catchment characteristics, basin morphology and depth, sediment type, fringing habitats and entrance opening regimes. There is growing evidence that ICOLLs differ in their sensitivity to catchment pressures compared with permanently open riverine estuaries (DPIE, 2021). For example, many smaller NSW ICOLLs are predominantly shallow and perched above mean sea level. This has two significant implications: 1) benthic microalgae, seagrasses and macroalgae are the main primary producers due to good benthic light climates, and 2) organic matter and fine sediments are scoured from the system during large entrance breakout events. As a result, the expression of eutrophication in shallow ICOLLs is marked by increases in benthic metabolism (both primary production and respiration), while scouring of sediment organic matter and nutrients during breakout tends to ‘reset’ the system.

Sediment Quality

Sediment quality is a primary driver of benthic processes that can significantly influence water quality. Sediment grain size is driven by the physical energy of a given site: high wind wave and/or tidal current energy will tend to winnow out fine sediments, leaving a predominance of coarser sands, while fine sediments will tend to deposit in more quiescent basins. The distribution of organic matter (quantity and quality) is more complex, driven by a combination of similar physical processes described for fine sediments above and the various sources of organic matter present. These sources include catchment derived material (e.g., leaf litter), phytoplankton detritus, seagrass detritus, and in situ production of benthic microalgae.

Catchment inputs

The inputs of organic matter, nutrients and sediments from catchments during rainfall events significantly influence the processes and ecological health of ICOLLs. Inorganic, bio-available nutrients fuel primary productivity in the immediate post-event period, while particulate nutrients are deposited and remineralised over longer post-event timeframes.

Water Quality

Water quality in ICOLLs is highly dependent on entrance status (i.e. open or closed) and the time elapsed since significant inflows from the catchment. While the entrance remains closed, freshwater inputs accumulate, lowering salinity and raising the water level. Internal processing of material (i.e. organic matter and nutrients) becomes relatively more important the longer the entrance remains closed. Once entrance breakout occurs, a large amount of material is exported to the ocean and oceanic water enters the ICOLL, diluting the residual water remaining in the system until the entrance closes again. This highly dynamic and stochastic behaviour makes the interpretation of water quality data from ICOLLs difficult.

Turbidity

Turbidity in estuaries is an important water quality parameter that determines the availability of light through the water column and at the sediment surface for photosynthetic production by aquatic plants. Turbidity is a measure of light scattered by total suspended solids (TSS) and can be driven by a combination of different factors, including:

- high TSS in catchment inflows
- resuspension of sediments due to tidal currents and/or wind wave energy
- high phytoplankton biomass

During dry periods when catchment inflows are small and dominated by baseflow with low TSS concentrations, the latter two mechanisms are most likely to influence turbidity. In ICOLLs, tidal currents are absent during closed entrance conditions and mostly attenuated by entrance shoals during open conditions. In shallow ICOLLs, wind wave energy can more easily cause bed shear stress to exceed sediment resuspension thresholds.

Stratification and hypoxia

Stratification occurs when stable layers form due to density variation with depth in the water column. Stratification can be caused by temperature (e.g., solar heating of surface water) and/or salinity (e.g., where dense seawater pushes underneath less dense freshwater during flood tides). Stratification impedes mixing of the water column and can lead to the depletion of oxygen bottom waters (hypoxia) where sediment oxygen demand is high. ICOLLs are inherently susceptible to stratification, especially where the central basin extends below mean sea level.

Benthic Processes

Biogeochemical processing of organic matter and nutrients in the sediments (‘benthic processes’) plays a fundamental role in shaping the ecology and health of estuaries, for example, benthic fluxes of nutrients can fuel harmful algal blooms, while consumption of oxygen during the breakdown of sediment organic matter can result in hypoxia in the overlying water. Organic matter deposited in the sediments is broken down by microbes, consuming oxygen and releasing bio-available nutrients to the overlying water. The processing rate (e.g. respiration and nutrient remineralisation) is determined by the amount and quality of organic matter in the sediments, which can be sourced from catchments and/or algae and aquatic plants growing in the waterway (see section above). Where sufficient light penetrates the sediment surface, microscopic algae ('benthic microalgae') can intercept and assimilate nutrients from the sediments and overlying water column, greatly reducing or reversing the flux of bio-available nutrients to the overlying water.

Nutrient Budget

The nutrient budget approach aims to quantify all major terms in the biogeochemical cycles that underpin the ecological function of an aquatic system, including catchment inputs, internal recycling (e.g., benthic fluxes) and exports to the ocean. Nutrient budgets provide an understanding of the relative importance of different pathways and help focus management efforts on areas with the biggest potential environmental outcomes.

Avoca Lagoon

Avoca Lagoon is a small ICOLL located on the NSW Central Coast (Figure 1). Avoca Lagoon is classified as a back dune lagoon, with a catchment and water area of 10.4 and 0.67 km^2 respectively (Roy et al. 2001). Avoca Lagoon has four arms and the main tributary, Saltwater Creek, drains 6.7 km^2 of the catchment (Figure 2, Figure 3). The Avoca Lagoon catchment has undergone increasing urbanisation over the past 70 years, with urban stormwater and sewage overflows blamed for historically poor health assessments. Development of the shoreline has also resulted in the infilling of fringing wetlands and the establishment of assets on land subject to natural flooding when lagoon levels are high. Approximately 46% of the catchment is disturbed, due to urban development (25%) and agricultural activities (21%). The remaining catchment area is forest (46%) and water area (8%) (Cardno Lawson Treloar, 2010). A bridge over the entrance to the southern basin of the lagoon at Avoca Drive has resulted in a restriction of exchange between this basin and the main lagoon.

The entrance to Avoca Lagoon is artificially opened at 2.09m AHD to minimise flooding of low-lying assets in the catchment. The degree of drainage in the lagoon depends on factors including the

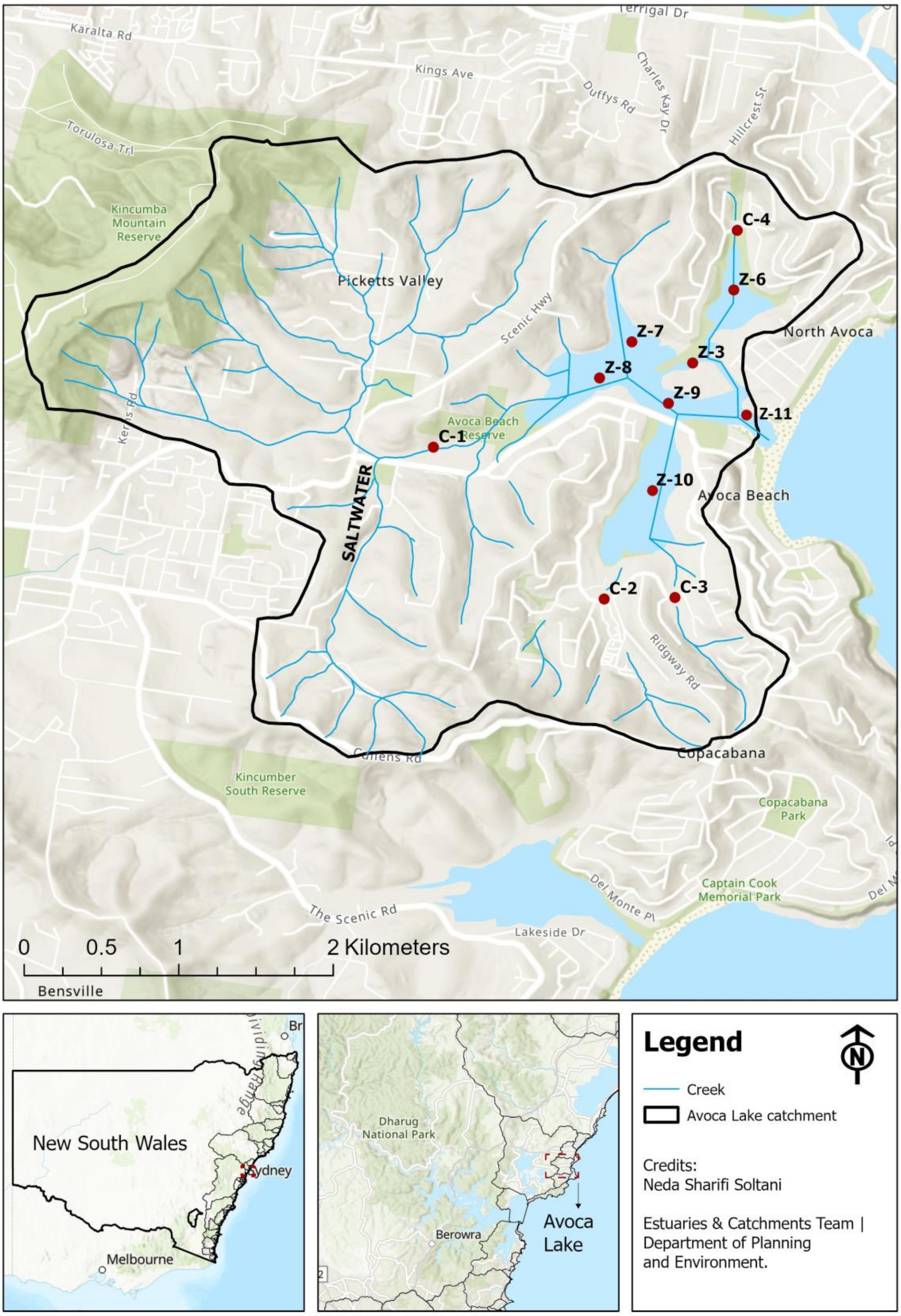


Figure 1. Location map of Avoca Lagoon showing current study sites

Figure 2. Aerial image of Avoca Lagoon from 1954. Courtesy of Ben Cuerel, Central Coast Council

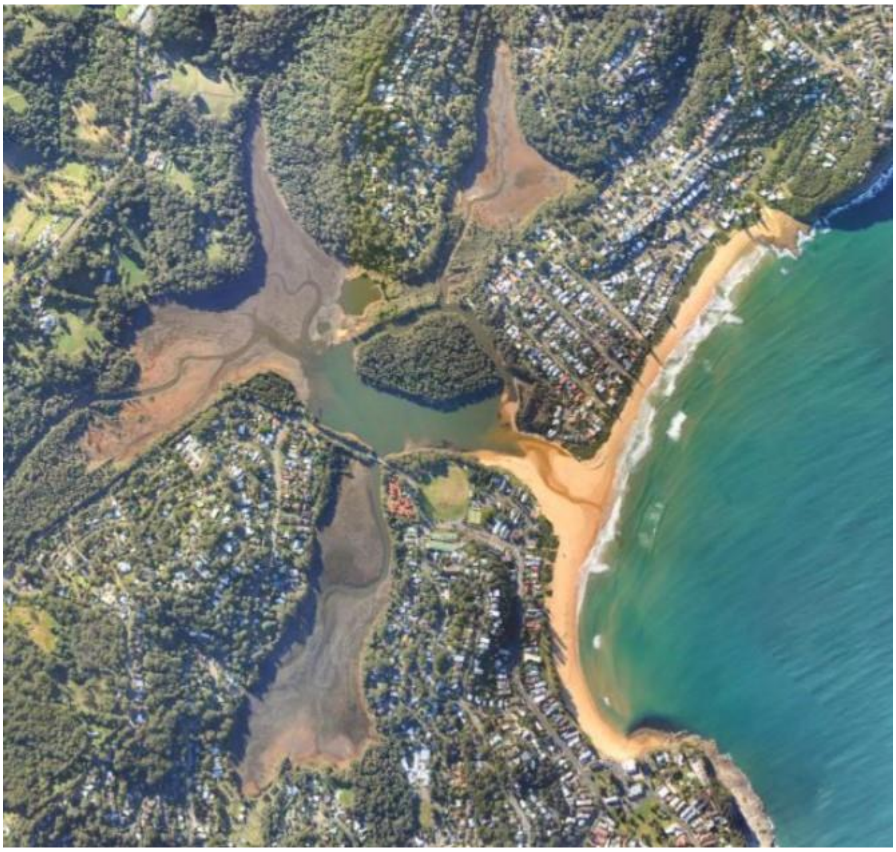


Figure 3. Aerial image of Avoca Lagoon from 2012 clearly showing the dredge hole in the central basin (Nearmap, 2024)

water level prior to opening, rainfall in the catchment and resultant streamflow at the time of opening, and ocean conditions (i.e., wave heights, tide, and storm surge). The lagoon entrance is opened about 3 times a year on average.

In its natural state, Avoca Lagoon was shallow and perched entirely above mean sea level (Figure 2). Dredging of the central basin between the early 1980s and 1994 resulted in the creation of a deep basin extending up to 3m below mean sea level (Figure 3). These historical works have changed the morphology and distribution of sedimentary environments, hydrology and the benthic light climate. Although there seems to be little data available on the actual extent of the dredging, it has been previously estimated that the extent of dredging is 10%, or 7.5 ha, of the bed surface with levels taken to between -2 to –4 m AHD, equating to around 100,000 m^3 (Cardno Lawson Treloar, 2010).

As part of the study, we estimated the hypsometry of Avoca Lagoon before the dredging to make a clear comparison with the current hypsometry. This was done by identifying several un-dredged points in the 1954 image and extracting data for those locations in the post-dredge bathymetric dataset. The locations chosen are within the narrow channels and in the shallows. The points in the channel are estimated to be +0.25m AHD, with the shallows being about +0.7m AHD. This suggests that the lagoon sat entirely above 0m AHD. In the pre-dredge image, the channels appear to be of uniform darkness, so we have assumed this means a uniform depth in the channels (Figure 2).

The post-dredge hypsometric curve that we have developed suggests that approximately 20% of the lagoon area was dredged. There is a dramatic difference between the bathymetry and subsequently the volume of the lagoon following dredging (Figure 4).

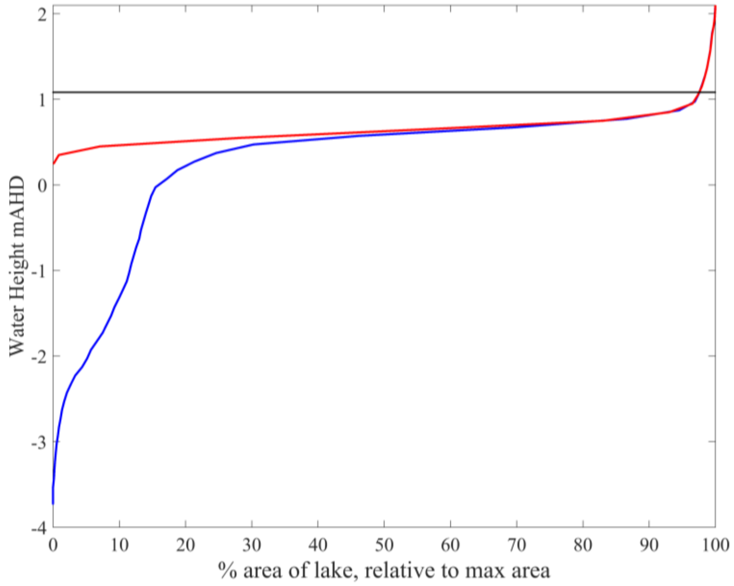


Figure 4. Hypsometry of Avoca Lagoon currently (blue line) and estimated for prior to dredging works (red line)

* The black line represents the long-term average lagoon height over the last decade (1.12m AHD)

2 Methodology

2.1 Study approach

The methodology for this study used a combination of routine monitoring, in situ physicochemical loggers, event sampling, seasonal benthic process measurements, and once-off surveys (Table 3).

Table 3. Summary of study methods

Approach	Sampling detail	Objective	Frequency
Routine monitoring	Grab samples for physico-chem, nutrients, Total suspended solids (TSS) and chlorophyll at sites representing key functional zones within the lagoon	Characterise broad trends in water quality during the study period	Monthly
In situ water quality buoy	A multi-depth buoy located in the central basin measuring physico-chemical water quality in the surface and bottom waters at 30min time intervals. See Avoca Lake study | NSW Environment and Heritage	Characterise the dynamics and drivers of stratification and hypoxia in the central basin of the lagoon	Continuously
Event-based sampling	Flow-weighted sampling of nutrients and TSS in main catchment inflows during runoff events and initial effects on receiving waters	Quantify the inputs of nutrients and TSS to the lagoon from the catchment	Four events between January – August 2022

Approach	Sampling detail	Objective	Frequency
Benthic process measurements	Benthic flux incubations of sediment cores from each lagoon zone to measure benthic metabolism and nutrient fluxes	Quantify the contribution of benthic fluxes to the internal recycling of nutrients in the lagoon	February, June, and October 2022
Sediment survey	Survey of sediment quality (carbon, nitrogen, grain size, stable isotopes)	Characterise the distribution of sediment carbon and nitrogen in the lagoon to inform the interpretation of benthic process measurements	In drain audit study (2019) and during benthic process measurements (see previous, above)
Breakout event sampling	High-frequency sampling of water velocity, water quality and radon before and during a breakout event	Quantify the export of material from the lagoon during a typical entrance breakout event. Quantify the post-event input of shallow groundwater seepage to the lagoon.	September 2023

2.2 Location and sites

Routine monthly sampling was completed at Zones 3, 9 and 10, including bottom water sampling in the central basin (Z-9). Event based sampling was completed at the four creek sites (C-1 – C-4) and around the lagoon in response to rainfall events (Table 4). Six sites were also sampled for benthic cores as part of our benthic process measurements (Table 4).

Table 4. Site locations of the study

Site code	Latitude	Longitude	Site name	Sample type
C-1	-33.46467	151.41574	Saltwater Ck	Event
C-2	-33.47351	151.42567	Round Drive West	Event
C-3	-33.47342	151.42979	Round Drive East	Event
C-4	-33.45205	151.43341	NW Ck	Event
Z-3	-33.45980	151.43073	Island Channel	Routine
Z-6	-33.45553	151.43320	Northern basin	Event/Cores
Z-7	-33.45855	151.42727	North western basin	Event/Cores
Z-8	-33.46065	151.42540	South western basin	Event/Cores
Z-9	-33.46213	151.42940	Central basin	Routine/Event/Cores
Z-10	-33.46720	151.42840	Southern basin	Routine/Event/Cores
Z-11	-33.46210	151.43391	Lagoon entrance	Cores

2.3 Multi-depth smartbuoy

An automated water quality buoy and logger (smartbuoy), nicknamed 'Beatrice', provided a live stream of physico-chemical data from the surface and bottom of the water column. The smartbuoy was anchored within the Avoca Lagoon's deep basin to monitor the presence and magnitude of stratification (Figure 5). Pumps at the surface and the bottom of the water column activate every half hour, and sensors within the solar-powered logger would measure stabilised readings of temperature, conductivity/salinity, dissolved oxygen, turbidity, pH, chlorophyll a, CDOM (colour) and phycocyanin and send them to a cloud-based dashboard in real time and stored on the instrument.

Figure 5. Beatrice the smartbuoy, a telemetered water quality buoy on Avoca Lagoon (Nov 2021)

2.4 Routine water quality monitoring

Routine monthly sampling was carried out at three zones within Avoca Lagoon during the study period following DPE MER protocols (OEH, 2016). These sites were Z-3, Z-9 and Z-10 (Figure 1). Data was collected both in situ and sub samples were collected for later analysis from a bucket filled with water from the top 1m beside a drifting canoe and from water pumped from the bottom of the water column close to the sediment surface.

2.5 Event-based sampling

Creek samples were collected at sites C-1 – C-4 during rainfall events across the study period, both manually and using automated water sampling equipment (ISCOs). Where possible, creek flows were measured using Sontek flow meters. Duplicate samples for analysis of Enterococci concentration were collected during two of the runoff events at sites C-1 – C-4 as well as another unnamed ephemeral creek (C-5) which flows into the eastern section of the northern basin (east of Z-6 – Figure 1). During the same events, samples were also collected from the receiving waters at Z-6, Z-8 and Z-10.

Samples were strategically collected around four rainfall events which resulted in runoff to estimate event mean concentrations (EMCs) of nutrients and TSS entering the lagoon in surface water from the catchment. Dates for these event sampling trips are as follows (Table 5).

Table 5. Rainfall events which were sampled during the study period

Date	Details
18/01/2022	Three creeks (baseline and event) and lagoon sampled before, during and after event
2/02/2022	Two creeks sampled (baseline and event). No lagoon samples
21/02/2022	Four creeks sampled (baseline and event). Lagoon sampled before and during event
22/08/2022	Saltwater Creek sampled (baseline and event) and lagoon sampled during event

2.6 Benthic metabolism and sediment-water nutrient fluxes

Field Collection

Benthic metabolism and sediment-water nutrient flux incubations were undertaken in late February, June and October 2022. On each occasion, three random sediment cores were collected from five shallow sites within the zones of Avoca Lagoon (Figure 1) – Z-6 (core at Site 1), Z-7 (core at Site 2), Z-8 (core at Site 3), Z-10 (core at Site 4) and Z-11 (core at Site 5,) and at three sites adjacent to Z-9 in the main basin (cores = Basin 1, Basin 2, Basin 3).

Samples were collected using transparent polycarbonate cores (diameter: 90mm; height: 500mm) from a water depth of approximately 1 metre at the shallow sites and were pushed into the sediment by hand to a depth of 200mm. Samples from the deeper basin were collected in 2-3.5m depth (depending on lagoon height) and were collected using a pole corer operated from a small dinghy. The sediment level was then adjusted using foam spacers to produce a water column height of approximately 250mm above the sediment surface. Cores were sealed at both ends and returned to shore. Sufficient water (200-300L) was also collected from the lower water column of shallow and basin areas of the lagoon for the respective incubation chambers. Sediment cores and water were gently transported to a laboratory for incubation.

Laboratory sediment incubation

Sediment cores were placed into respective incubation chambers (shallow and basin) which had been filled with site water and were being kept at constant *in situ* temperatures by re-circulating water via a thermostatically controlled pump (Figure 6). Cores were left uncapped and allowed to exchange freely with the ambient water being gently circulated around the chambers.

During this time, the top of each core was fitted with a perspex O-ring sealed cap that had a central port to allow insertion of a YSI ProOBOD dissolved oxygen and temperature probe, and small intake and out-take tubes on either side of the probe. The tubes allow water to enter and leave cores during initial flushing and collection of water samples during the incubation. To prevent stratification, water in the cores was gently mixed by a magnetic stirring bar attached suspended within individual cores. The bars were triggered at a frequency of ~40 revolutions per minute by magnets mounted on a rotating arm in the incubation chamber. During “dark” incubations chambers were covered to exclude all light.

In “light” incubations, cores were illuminated using a 1000 W high-pressure sodium bulb suspended directly above the centre of the chamber. Cores were incubated at 200-300 µE light intensity which was similar to the minimum light intensity measured using a LI-COR 192 underwater quantum sensor at 0.5 m depth in the middle of the day at all sites. In this study, we have assumed that light-saturated production of Benthic Macro Algae (BMA) occurs at light intensities roughly equal to 300-µE $m^{-2}.s^{-1}$ meaning that BMA were incubated at, or close to, their maximum autotrophy potential at these light intensities (Sundbäck & Jönsson, 1988; Rizzo, Lackey, & Christian, 1992).

At the commencement of the incubation (time zero), all cores were capped with and sampled as follows:

- Dissolved oxygen concentrations and internal water temperature were measured with a YSI ProOBOD dissolved oxygen and temperature probe
- Inorganic nutrients: a 25mL water sample was withdrawn from the sample port using a syringe. Samples were passed through a 0.45 µm glass filter (Sartorius®) into 30mL V-bottom vials and immediately frozen.
- Cores and blanks were then checked to ensure no gaseous headspace was present, isolated from the flushing system and sealed. They were then incubated in the chambers and similarly sampled approximately four hours later.

Figure 6. Photograph of a core incubation chamber set up at the laboratory

2.7 Sediment properties

The analyses of %N, %C, $\delta^{15}N$ and $\delta^{13}C$ of sediment samples were carried out at Monash University. Sediment samples for carbon were weighed into silver capsules, acidified using HCl on a hotplate at ~60°C, and then encapsulated into tin capsules. Samples for nitrogen were weighed and encapsulated in tin capsules. All samples were analysed on an ANCA GSL2 elemental analyzer interfaced to a Hydra 20–22 continuous-flow isotope ratio mass spectrometer (IRMS; Sercon Ltd., UK). The precision was +/-0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$ (SD; n=5). To ensure the accuracy of the isotopic results, internal standards (i.e., ammonium sulfate, sucrose, gelatine and bream) were run concurrently with the sediment samples. These internal standards have been calibrated against internationally recognised reference materials (i.e., USGS 40, USGS41, IAEA N1, USGS 25, USGS 26 and IAEA C-6). All results were provided relative to the stable isotopic ratio of Vienna Pee Dee belemnite standard for carbon and the air standard for nitrogen.

2.8 Benthic metabolism and sediment-water nutrient flux calculations

Oxygen (O_2), inorganic nutrient (NH_4^+, NO_x, DIP), DON, DOP and dinitrogen (N_2) flux rates ($\mu mol.m^{-2}.hour^{-1}$) were determined as the difference between the final and initial concentrations in the water column after 4 hours incubation (light or dark) as calculated in Equation (1):

$$Fx = \frac{(Cf - Ci) x V}{A x t} \text{ .... Equation (1)}$$

where;

Fx = flux of oxygen or inorganic nutrient species ($\mu mol.m^{-2}.hr^{-1}$)

Cf = final concentration (μM)

Ci = initial concentration (μM)

V = volume of water (l)

A = surface area (m^2)

t = incubation time (h)

For oxygen, benthic community respiration (BCR) and net primary production (NPP) rates were determined from the dark and light incubations respectively. Benthic gross primary production (GPP) for each ICOLL was then calculated by the following formula:

GPP = NPP-BCR .... Equation (2)

For practical reasons, we have assumed that BCR in the light equalled BCR in the dark, recognising that light-enhanced respiration is acknowledged to occur in most autotrophs (Raven & Falkowski, 1999). Net benthic metabolism (NBM) and net sediment-water nutrient flux rates for each core were calculated by averaging hourly flux rates obtained during light and dark incubations.

2.9 Export Event

A mechanical opening of Avoca Lagoon was performed by council staff on the 14th September 2023 due to the persistence of high water levels and the attendant risk to low lying assets due to flooding. An intensive monitoring campaign prior to and during the opening event was carried out to quantify the flows, water level and water quality in the basins of the lagoon, particularly the main basin. The aims of this sampling campaign were to:

- Quantify the export of nutrients and suspended sediments from the lagoon
- Characterise spatial and temporal variation in lagoon hydrodynamics

- Investigate the influence of groundwater seepage on water quality

Water quality

Hourly water quality samples for nutrient and TSS analysis were collected using an automated sampling device (ISCO) moored at the telemetered smartbuoy site.

Groundwater seepage

Groundwater influence at the smartbuoy site was measured at 15-minute intervals using the radon tracer method (Maher et al. 2013, 2015, 2019).

Hydrodynamics

The hydrodynamic measurements started at 5:30am on 14th September 2023 and continued until about 4:30pm that day, followed by measurements the following morning. The flow measurements were taken using a M9 doppler current profiler near the smartbuoy (near Z-9, Figure 1). The M9 profiling instrument floats from a secured line from an anchored boat. All profiling measurements at the buoy were within a 5 m radius area and can be treated as a single point time-series measurement.

Pre-opening

Before the mechanical opening of the entrance, the flows in the main basin were measured to establish the initial or baseline flow magnitudes and directions.

Vertical current velocity profiles were measured at various sites around the lagoon using an M9 ADCP.

2.10 Nutrient budget

Nutrient budgets for Avoca Lagoon were developed to compare the relative magnitude of catchment input loads, internal benthic flux loads and export loads during periods of entrance closure terminated by entrance breakout.

Catchment input loads were estimated for each of the three event sampling campaigns by integrating flow-weighted nutrient concentrations for each sub-catchment (section 3.5) with estimated flows. Total inflows for each event were estimated by calculating the change in lagoon volume over the duration of the event:

$$\text{Total inflow}_{t0\text{ - }t1} = (\text{water level}_{t1} - \text{water level}_{t0}) \times \text{lagoon area}$$

Inflows from individual sub-catchments were estimated by multiplying the total inflow by the ratio of the sub-catchment area to total catchment area. Each of the sampled events had similar rainfall totals, water level rises (0.12m) and estimated inflows. Catchment input loads for the three events were averaged to provide an event mean load for a 0.12m water level rise. These loads were then scaled to a total load for the budget periods (i.e., period of entrance closure) by:

$$\text{Total load}_{\text{budget}} = \text{event mean load}_{0.12} \times (\text{lagoon level rise}_{\text{budget}} / 0.12)$$

Internal loads due to benthic nutrient fluxes were estimated by scaling the net daily fluxes at sites within each zone to the area of the zone and multiplying by the number of days in the budget period. Benthic fluxes from the relevant season were used for each budget.

Export loads for each budget period were estimated by scaling the measured export loads from the September 2023 entrance opening event to the entrance opening at the end of each budget period. This was done using the relative differences between water level drop during the September 2023 event ('measured') and the budget event:

$$\text{Export}_{\text{budget}} = \text{Export load}_{\text{measured}} \times (\text{water level drop}_{\text{budget}} / \text{water level drop}_{\text{measured}})$$

2.11 Meteorological and lagoon data

Rainfall data from 2019 until present and lagoon heights were accessed through the KISTERS Web Portal of Manly Hydraulics Laboratory (MHL) Avoca Lagoon station website (Manly Hydraulics Laboratory, 2023). Long term rainfall data for Avoca Beach Bowling Club were also accessed through the BOM Climate Data Online webpage (Bureau of Meteorology, 2023). Some wind and solar data from the Wyong weather station was also accessed through the BOM Climate Data Online webpage. From August 2022, we deployed an Atmos 41 all-in-one weather station (Meter Group®, USA) which provided meteorological data thereafter.

2.12 Indicators/Parameters

Physico-chemical parameters

A YSI EXO2 multiparameter water quality sonde was used to log physico-chemical water quality in situ. Depth profiles were also logged at Z-3 and Z-9, where depth allowed for a worthwhile data log to occur. These sampling trips aided in verifying readings from Beatrice.

Nutrients

Nutrients were subsampled from a bucket of water collected from the top 1m of water in the lagoon or from creek flows during event-based sampling. On each sampling occasion, a single 30mL vial was filled with unfiltered water using a syringe for total nitrogen (TN) and total phosphorus (TP) analysis. Two 30mL vials were subsequently filtered through 0.45µm syringe-filters (Minisart®) for the analysis of ammonia, NOx and FRP/SRP/phosphate and for total dissolved nitrogen (TDN) and phosphorus (TDP), respectively. Upon collection, the samples were immediately placed in a cool esky and transferred ASAP to a freezer at -18°C in the vehicle.

The samples remained stored at -18°C until being despatched to external laboratories for analysis. Standard methods shown in Table 6 were used for the determination of nutrient concentrations within samples (APHA, 2012).

Chlorophyll-a

Chlorophyll-*a* samples were kept cool and dark in an esky until being filtered upon return to the laboratory. A known volume of sample was filtered under vacuum through a 0.45µm glass fibre filter paper and frozen until analysis. Concentrations were determined by fluorometry following 24-hour extraction in 95% acetone solution following method 10200H (APHA, 2012).

Total suspended solids

Total suspended solids (TSS) samples were also collected from the bucket and kept cool and dark until being refrigerated at 4°C upon return to the laboratory. Analysis was completed in-house following standard methods 2130B and 2540D (APHA, 2012).

Enterococci

Duplicate samples were collected in sterilised 200mL plastic jars and kept cool and dark in an esky to be transported to the local Central Coast Council laboratory at the Kincumber sewage treatment plant.

Table 6. Methods used in nutrient analyses.

Test ID	Methods used during testing	Units	PQL*
NH_4^+	APHA Method 4500 – NH_3 H	µg NH_3-N.L^{-1}	2
NO_x	APHA Method 4500 – NO_3 F (Modified)	µg NOx-N.L^{-1}	1
DIP	APHA Method 4500 – P F	µg PO_4-P.L^{-1}	1
TN & TDN	APHA Method 4500 - NO_3 F (Modified) + (Autoclave Persulfate Digestion)	µg N-N.L^{-1}	80
TP & TDP	APHA Method 4500 – P F + (Autoclave Persulfate Digestion	µg P-P.L^{-1}	3
DON	DON = TDN - (NO_x + NH_4^+)	µg N-N.L^{-1}	N/A
DOP	DOP = TDP - (DIP)	µg P-P.L^{-1}	N/A
PN	PN = TN - TDN	µg N-N.L^{-1}	N/A
PP	PP = TP - TDP	µg P-P.L^{-1}	N/A

3 Results and Discussion

3.1 Rainfall and lagoon openings

Annual rainfall was well above the long-term average (1366 mm) in 2022 with March, February and April being particularly wet months that year (Table 7).

Table 7. Annual rainfall statistics for Avoca Lagoon 2018-2023 (Bureau of Meteorology, 2023).

	2018	2019	2020	2021	2022	2023
January	22.2	77.2	110.2	128	75.8	76
February	153.6	89.2	404.6	106.6	397.6	138
March	109.6	288.8	263.6	469.2	562	62
April	44.2	52.6	78.2	13.2	279.2	168
May	23.4	22.4	155.2	52.8	170.2	47
June	260.2	171.8	83.8	85.4	13.2	14
July	17.2	36.4	207.4	71.8	199.4	57.5
August	11.8	193.6	52.2	72.8	48.2	70.5
September	63	108.6	50.2	48.4	138.4	12.5
October	207	66.6	269.2	66.2	194	37
November	135.4	25.2	36.2	203.4	27.8	88
December	51	3	183.4	193.4	65.6	61
Annual Total	1098.6	1135.4	1894.2	1511.2	2171.4	831.5

Rainfall was generally above long-term averages during the study period, with the exception of June 2022 and the last three months of 2022 (Figure 7).

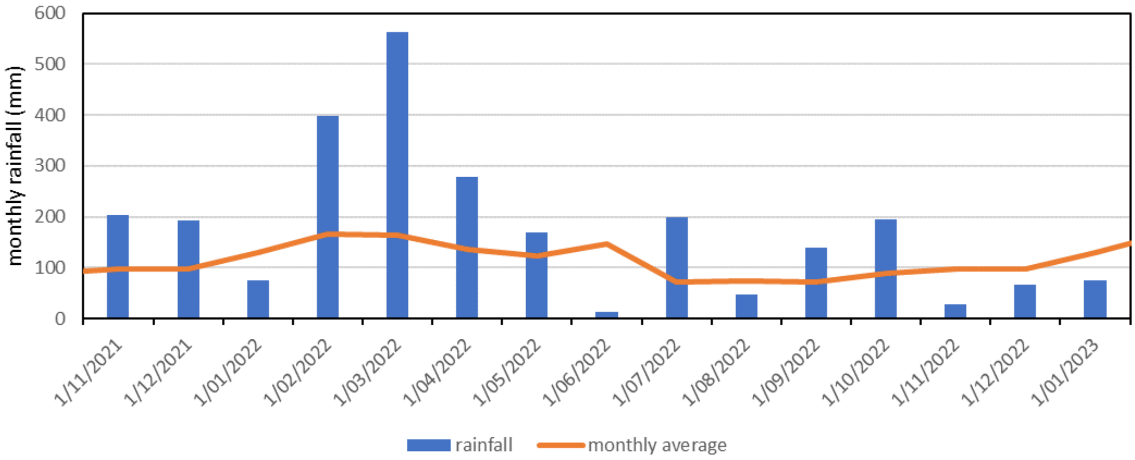


Figure 7. Monthly rainfall at Avoca Beach during the study period (source BOM)

Avoca Lagoon was artificially opened to the ocean due to the water level reaching the trigger threshold (2.09m AHD) four times during the study period. In between these artificial opening events, there were several other occasions when the lagoon opened naturally to the ocean without reaching the trigger threshold (Figure 8). Hence there were twelve opening events during the study period which included long periods where the lagoon entrance was in a semi-open state, filling up on high tides.

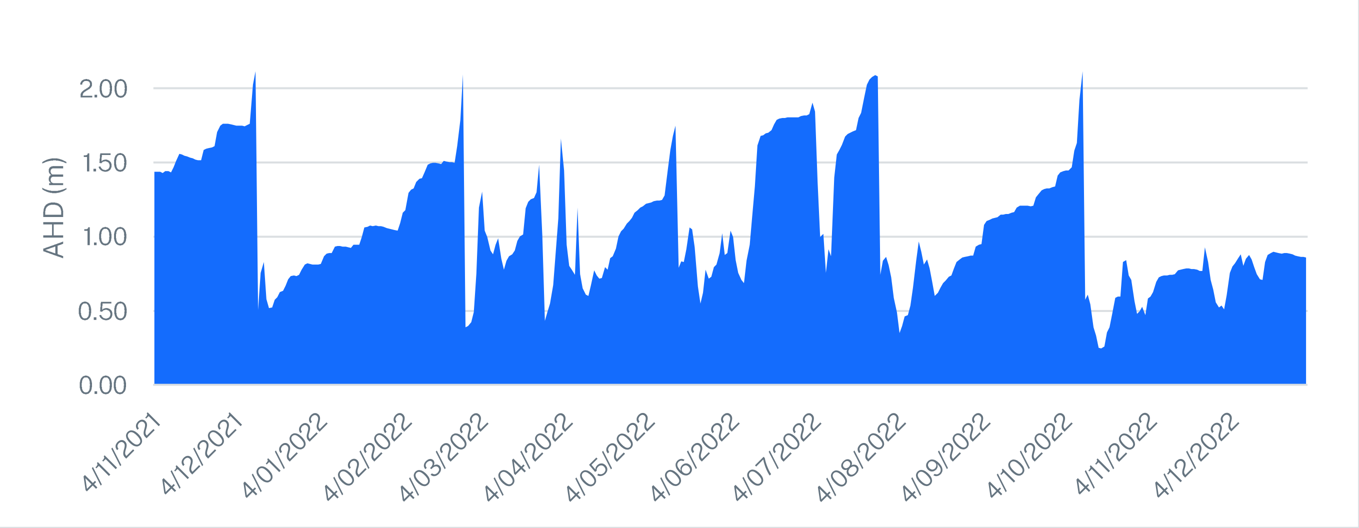


Figure 8. Avoca Lagoon water height during the study period (Manly Hydraulics Laboratory, 2023)

3.2 Water Quality

During the study period from November 2021 until December 2022, a range of sampling trips to Avoca Lagoon was undertaken. Half of these trips were planned around routine monitoring trips that occur monthly for the Central Coast estuary monitoring program. Samples were taken around the entire lagoon for event-based monitoring and during seasonal sediment core collection. Water quality buoy servicing trips also provided an opportunity to collect surface and bottom water (BW) samples at Z-9 (BW-9 samples). A table has been provided to summarise the samples collected at lagoon sites (Table 8). This table does not include creek samples, samples from benthic core incubations, or samples collected in 2023 as part of continued monitoring or the export event sampling in September 2023.

Table 8. Summary of sampling completed in Avoca Lagoon during the study period

Site	Physico-chemical	Chlorophyll a	Nutrients	TSS
Z-3	13	10	14	11
Z-6	9	0	8	6
Z-7	9	0	8	6
Z-8	9	0	8	6
Z-9	24	15	23	17
BW-9	21	15	15	1
Z-10	20	10	20	17
Z-11	3	0	1	0
Total	108	50	97	64

The study period was characterised by periods of freshwater inflows during extended entrance closure causing a decrease in lagoon salinity in surface waters interspersed with entrance opening events which caused a rapid increase in salinity (Figure 9). The salinity of bottom water in the dredge basin remained relatively stable throughout the study period indicating a long residence time of this body of water (Figure 9, Table 9). Dissolved oxygen in surface waters was mostly undersaturated (~80-90%) indicating that the lagoon is net heterotrophic (Table 9) – see the section below for a more detailed description of dissolved oxygen dynamics.

Turbidity and chlorophyll a, which the estuary reports cards are based upon, were consistently higher at Z-10 compared to surface waters at Z-9, especially during the summer months (Figure 9) - see section below for more details. Turbidity was also high at the other shallow zones (Z-6, Z-7 & Z-

8, Table 9) well exceeding the trigger value of 4.2 NTU for back dune lagoons (OEH, 2016). Chlorophyll a was consistently higher in the bottom waters of the main basin – Z-9 (Figure 9).

Table 9. Means (±std error) of relevant physico-chemical parameters measured in Avoca Lagoon during the study period

Site	N*	Temp (°C)	DO (%sat)	Sal (psu)	pH (pHu)	Turb (ntu)
Z-3	13	21.6 (1.4)	89.2 (1.7)	23.5 (2.5)	7.7 (0.1)	4.3 (0.6)
Z-6	9	21.3 (1.9)	91.9 (3.5)	14.5 (2.8)	7.5 (0)	12.6 (2.3)
Z-7	9	21 (1.9)	88.4 (2.5)	18.7 (3.1)	7.5 (0.1)	16.2 (5)
Z-8	9	21.5 (1.9)	87.3 (3.6)	18.6 (3.2)	7.5 (0.1)	13 (2.3)
Z-9	24	21.1 (1.1)	88.8 (1.3)	22.6 (1.8)	7.7 (0.1)	4.6 (0.7)
BW-9	21	21.8 (0.8)	53.8 (6.9)	30.9 (1.1)	7.7 (0.1)	9 (0.9)
Z-10	20	21.5 (1.2)	89.2 (1.9)	21.7 (2.2)	7.6 (0.1)	14 (1.5)

Dissolved organic nitrogen (DON) dominated total nitrogen concentrations (~55%), with equal contributions from dissolved inorganic and particulate forms (19% and 26% respectively, Table 10). In contrast, particulate phosphorus (PP) dominated total phosphorus concentrations (~77%), with dissolved organic and dissolved inorganic forms contributing 17% and 6% respectively.

The molar ratio of bio-available nitrogen to phosphorus was considerably more than 16 (the Redfield ratio) during the study period indicating that pelagic productivity in Avoca Lagoon is phosphorus limited (Figure 10). Particulate N and P were significantly correlated, with a mean molar ratio of 16 (= Redfield ratio) indicating that these particulate forms are associated with phytoplankton biomass (Figure 11).

Table 10. Mean (±std error) concentrations (µg.L^{-1}) of nitrogen and phosphorus at seven monitoring sites in Avoca Lagoon (figure 1) during the study period.

Site	NH_4^+	NO_x	DON	PN	TN	PO_4	DOP	PP	TP
Z-3	79 (22)	25 (7)	267 (42)	107	478 (42)	1 (0.1)	3 (0.7)	12 (1.2)	15 (1.5)
Z-6	31 (11)	28 (10)	404 (59)	202	666 (104)	2 (0.5)	8 (2.7)	34 (10.4)	45 (12.5)
Z-7	83 (29)	17 (6)	302 (49)	139	541 (69)	1 (0.2)	3 (0.6)	20 (2.9)	23 (3.2)
Z-8	86 (30)	19 (7)	289 (48)	106	500 (72)	1 (0.7)	3 (0.7)	19 (2.2)	23 (2.8)
Z-9	69 (15)	27 (6)	263 (26)	76	435 (34)	1 (0.3)	3 (0.4)	12 (1.1)	16 (1.3)
BW-9	269 (69)	23 (6)	200 (30)	115	606 (92)	6 (2.5)	4 (0.7)	17 (2)	27 (3.8)
Z-10	124 (28)	27 (6)	293 (34)	143	587 (56)	1 (0.5)	4 (0.5)	18 (1.7)	24 (1.8)

Note: sites Z-3, Z-6, Z-7, and Z-8 were only sampled during events. BW-9 = bottom water (deep basin). NH_4^+ = ammonium; NO_x = nitrate+nitrite; DON = dissolved organic nitrogen; PN = particulate nitrogen; TN = total nitrogen; DIP = dissolved inorganic phosphorus; DOP = dissolved organic phosphorus; PP = particulate phosphorus; TP = total phosphorus.

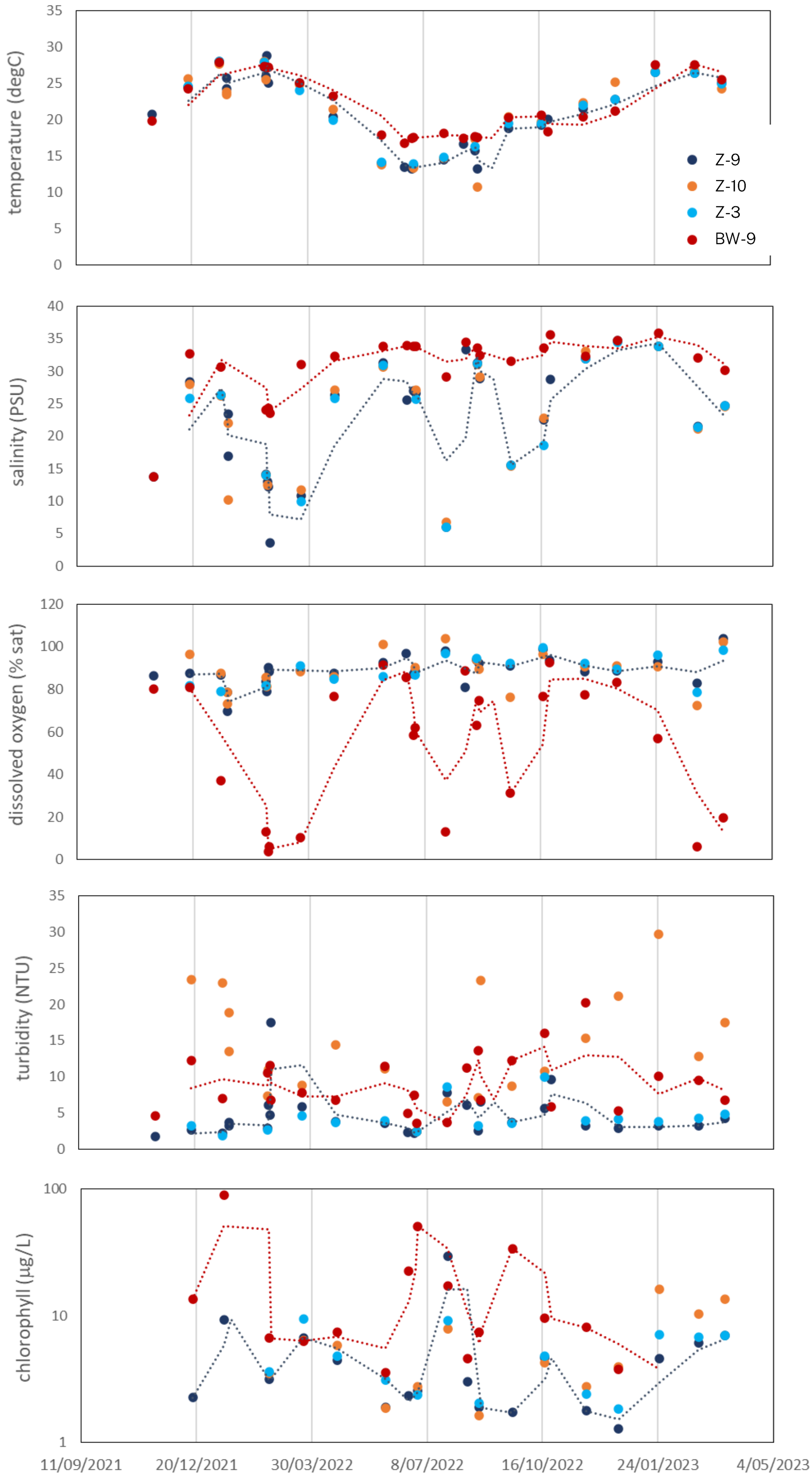


Figure 9. Physicochemical water quality and chlorophyll in Avoca Lagoon during the study period.

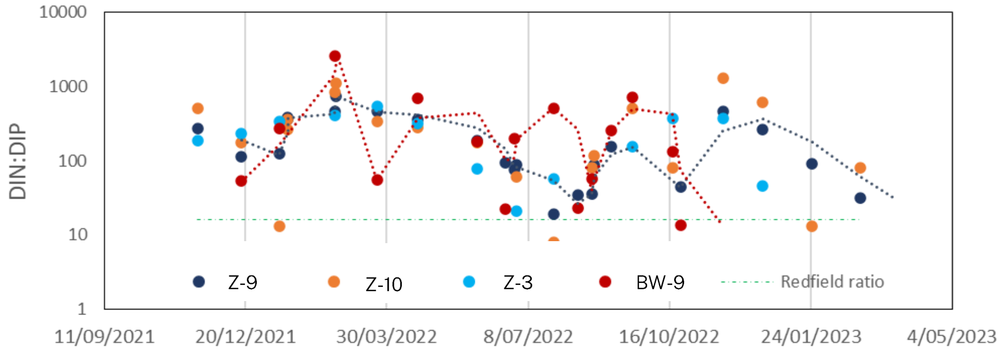


Figure 10. Molar ratio of bio-available nitrogen to phosphorus during the study period. The 'Redfield ratio' (16:1 indicated by blue dash line) is the mean ratio of nitrogen to phosphorus in marine algae. Points plotting above this line indicate the potential for phosphorus limitation of primary productivity.

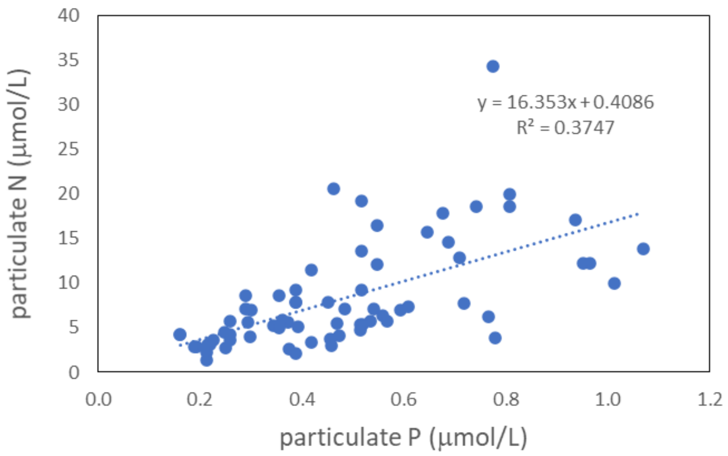


Figure 11. Relationship between particulate nitrogen and phosphorus in Avoca Lagoon. The line of best fit has a slope of 16:1 (Redfield ratio) indicating that particulate nutrients are present as phytoplankton biomass.

3.3 Turbidity

Turbidity was consistently highest at Z-10 compared to the other parts of the lagoon (Figure 12). There are a number of factors that may contribute to this result, as outlined below. While there were no relationships between antecedent rainfall and routine turbidity in any zone during this study, it is notable that TSS and nutrient concentrations were highest in the two sub-catchments draining to Z-10. This, combined with restricted exchange between this zone and the main lagoon at the Avoca Drive bridge, as well as potential backing up of water during events caused by the much higher inflows from Saltwater Creek and other sub-catchments, may cause greater deposition and retention of fine TSS material in the Z-10 basin (see Section 3.6 Sediment quality).

Z-10 turbidity was negatively correlated with water depth and positively correlated with wind speed, suggesting that high turbidity during routine sampling was driven by resuspension of finer bed sediments (Figure 13). Shallow water depth allows greater transferal of wind wave energy to the sediments resulting in higher bed stress and therefore resuspension. Across the wider lagoon, turbidity was positively correlated to chlorophyll indicating that phytoplankton biomass contributed significantly to total suspended solids and light attenuation.

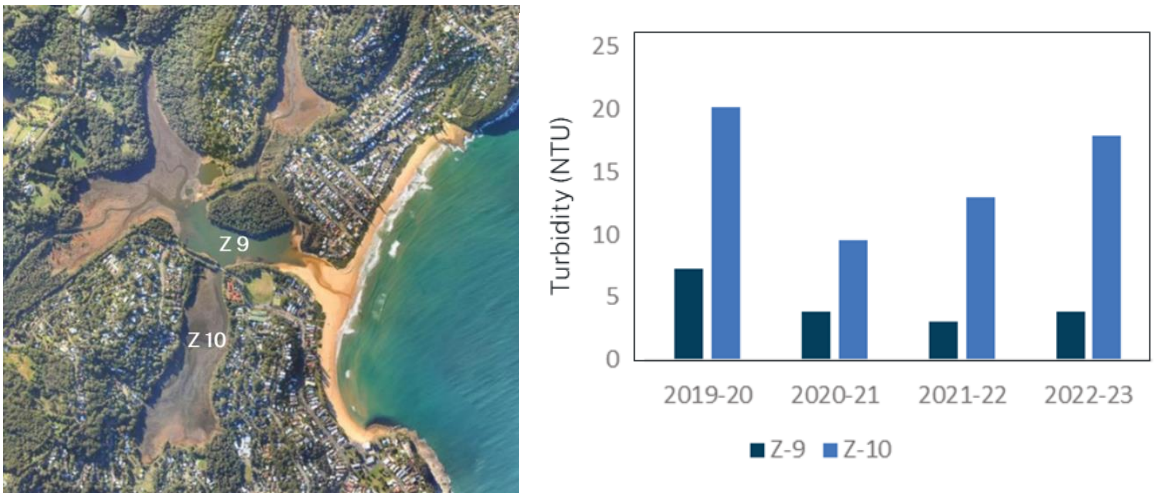


Figure 12. Comparison of MER turbidity results for Z-9 and Z-10

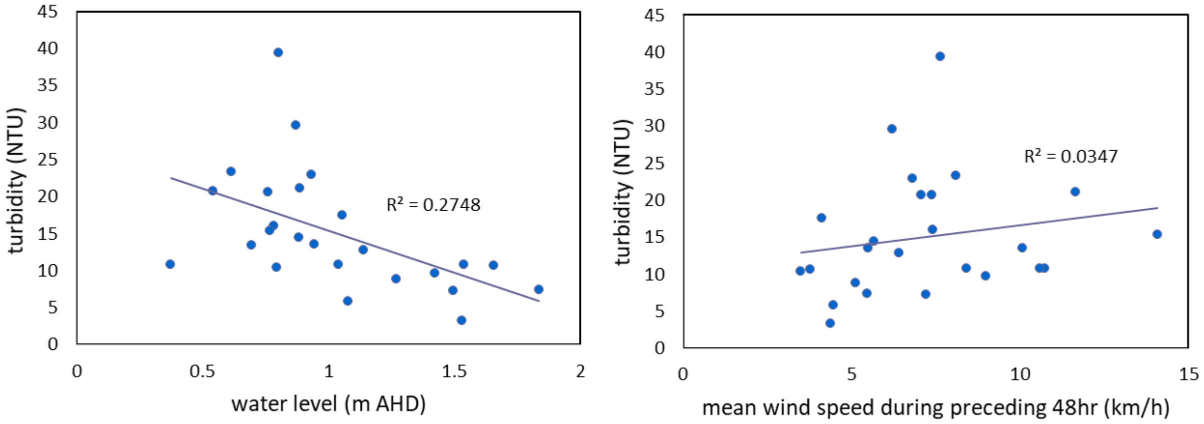


Figure 13. Turbidity in Z-10 during routine sampling versus water level and wind speed

3.4 Stratification and hypoxia

The *in-situ* water quality buoy showed that Avoca Lagoon is prone to extended periods of stratification and hypoxia in the central dredge hole (**Error! Reference source not found.**). Stratification usually develops due to the ingress of ocean water while the entrance is open, which sinks into the dredge hole. Once the entrance berm closes, stratification can last for months, resulting in severe hypoxia/anoxia in bottom waters (e.g., early 2022). Stratification is disrupted during entrance breakout events, or in some cases when surface waters cool sufficiently overnight in winter to overcome density differences.

The isolation of a large body of water in the dredge hole due to stratification has several health implications for Avoca Lagoon. Severe hypoxia/anoxia is lethal to aquatic biota, meaning that the habitat value of this part of the lagoon is severely reduced for extended periods of the year. Anoxia also results in shifts to sediment biogeochemistry including enhanced recycling and release of bio-available ammonium and phosphate, reduced coupled denitrification, and enhanced sulfide release. The highest rates of ammonium release from sediments were observed in the dredge hole compared to other zones in the lagoon (see section below), resulting in high ammonium concentrations in bottom waters (Table 10, Figure 15). This resulted in a constant internal source of bio-available nitrogen which most likely stimulates phytoplankton productivity and contributes to the high chlorophyll concentrations in the lagoon.

A closer inspection of stratification dynamics during different times of the year reveals the influence of different entrance conditions and seasons on the development of stratification of the water column. During the summer months, we observed denser water sinking into the basin due to higher salinity (and therefore density) of the bottom water (31 vs 26 psu at surface) following the previous opening event and subsequent closure in mid-December 2021 (Figure 16). Following 77mm of rain between 2nd and 5th February 2022, water height increased and DO levels in the bottom waters plummeted and remained that way throughout a period of entrance closed state with high water levels. The water column remained in this state until 135mm of rain fell between the 23rd and 25th February 2022, when the lagoon filled to the trigger level before being opened to the ocean. The mixing of the water column only occurred when the lagoon had drained and the incoming tides brought saline, dense ocean water into the basin of the lagoon (Figure 16).

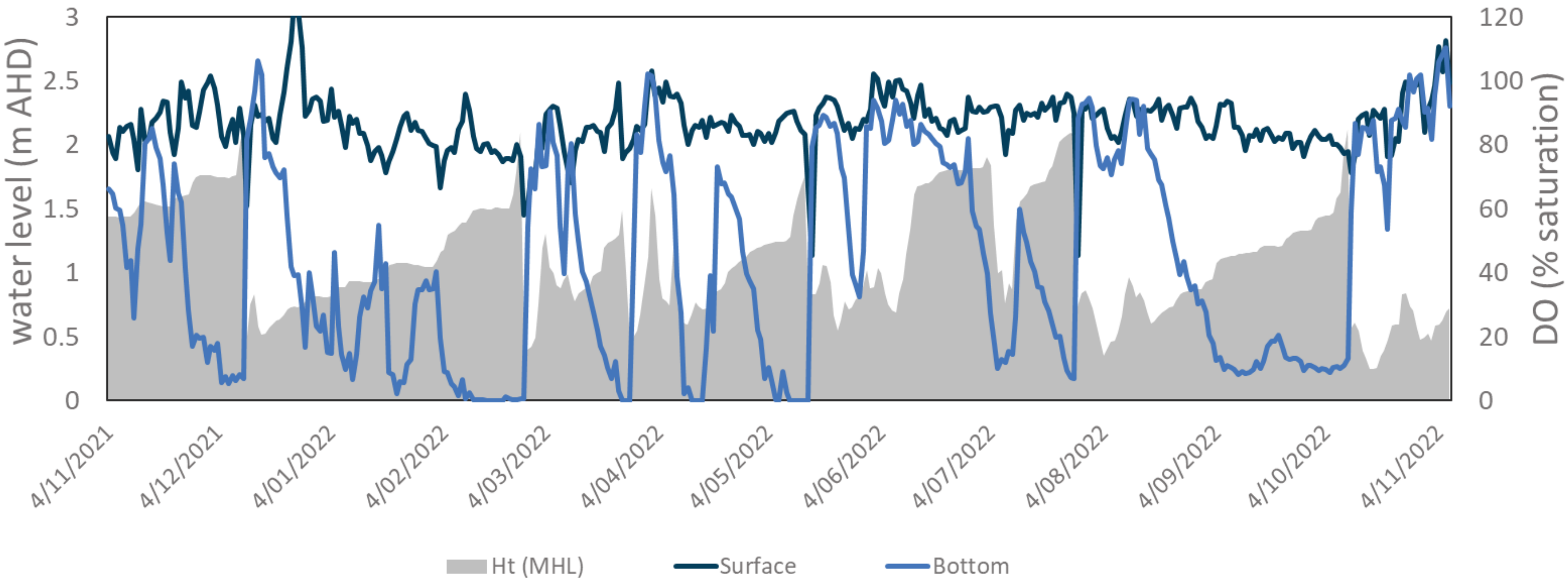


Figure 14 Dissolved oxygen saturation (right y-axis) in surface (dark blue line) and bottom (blue line) waters in the central basin of Avoca Lagoon and water height (left y-axis, shaded area) during the study period

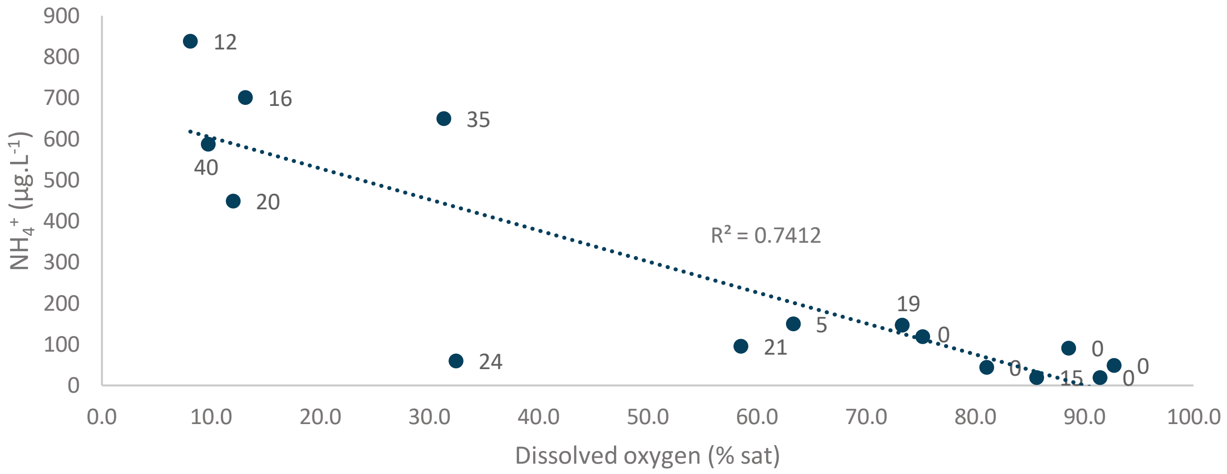


Figure 15. Concentrations of dissolved oxygen and ammonium in the bottom waters of Z-9. Labels represent approximate days since the lagoon was tidal (i.e., period of closure)

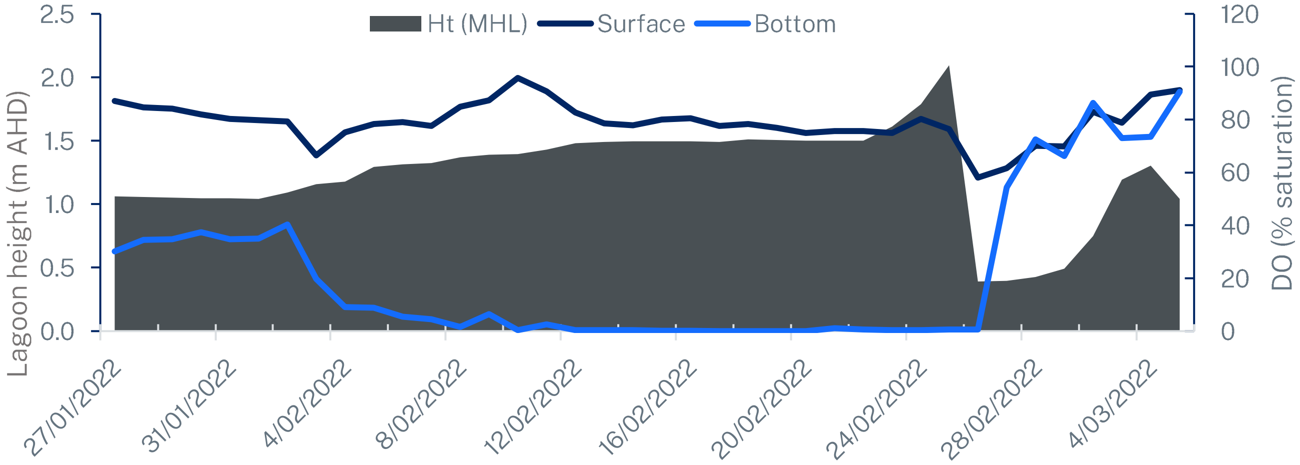


Figure 16. Dissolved oxygen saturation (right y-axis) in surface (dark blue line) and bottom (blue line) waters of the deep basin of Avoca Lagoon (Z-9) relative to lagoon water height (left y-axis, shaded area) during summer 2022

After an entrance breakout on 15th May 2022, Avoca Lagoon remained in a partially-open state for an extended period. During this phase, the lagoon water height fluctuated between 0.6m and 1m AHD (Figure 17). There were several large swell events in early June 2022 which overtopped the berm of Avoca Lagoon and meant there was a succession of minor filling/emptying states between 15th May and 8th June 2022. Interestingly there was relatively little rainfall in this period (65mm, highest daily total 15mm), suggesting there were relatively minor fluvial inputs to the lagoon during this period.

Stratification began to occur from the 22nd May until 29th May 2022, when large waves overtopped the berm and disrupted the water lying at the bottom of the basin. Surface and bottom DO levels remained similar through the rest of the period until about the end of June (Figure 17), even when the water level in the lagoon increased by about 1m as the berm developed. This suggests that there was not the pronounced stratification that we saw in the summer months when the lagoon was closed. This may be attributed to the turning over of the water column as the cooler surface waters (13°C) sunk down and mixed with warmer (17°C) bottom waters during this period, in the absence of a pronounced difference in surface and bottom water salinity (26 vs 33 psu, respectively).

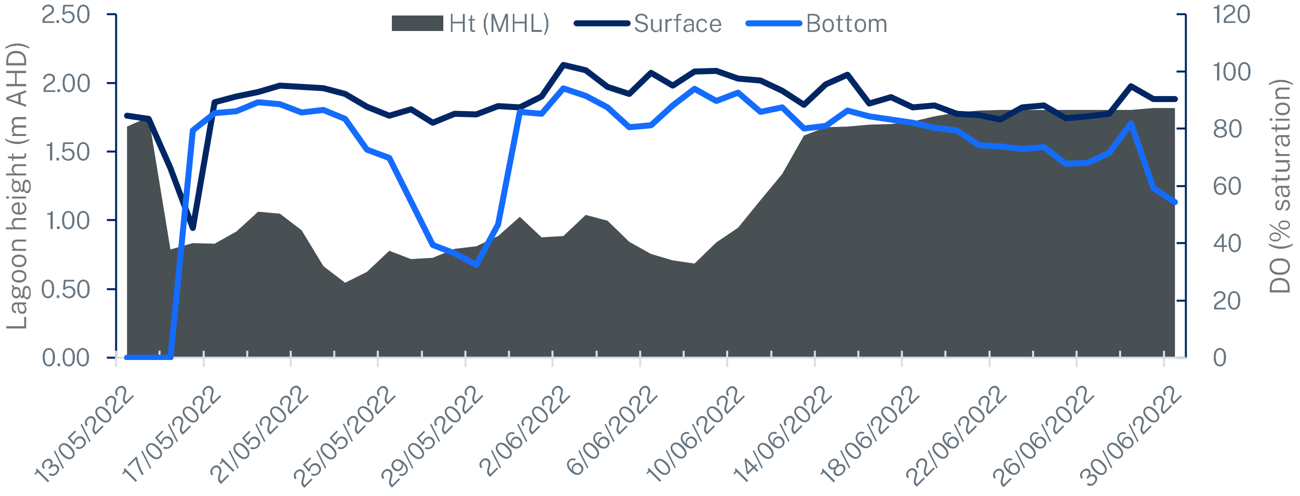


Figure 17. Dissolved oxygen saturation (right y-axis) in surface (dark blue line) and bottom (blue line) waters of the deep basin of Avoca Lagoon (Z-9) relative to lagoon water height (left y-axis, shaded area) **at the start of winter 2022**

Over 100mm of rain fell over four days which led to another entrance opening on 9th October 2022 when the lagoon reached the trigger level. The lagoon remained open for nearly a month after this opening event and remained in a state of low water height into 2023 when runoff from rainfall gradually brought the water level up. Following the entrance opening, the DO levels in the surface and bottom water at Z-9 remained variable but did not indicate any large differences between surface and bottom water (Figure 18), probably due to the constant mixing of estuary waters with the incoming tides.

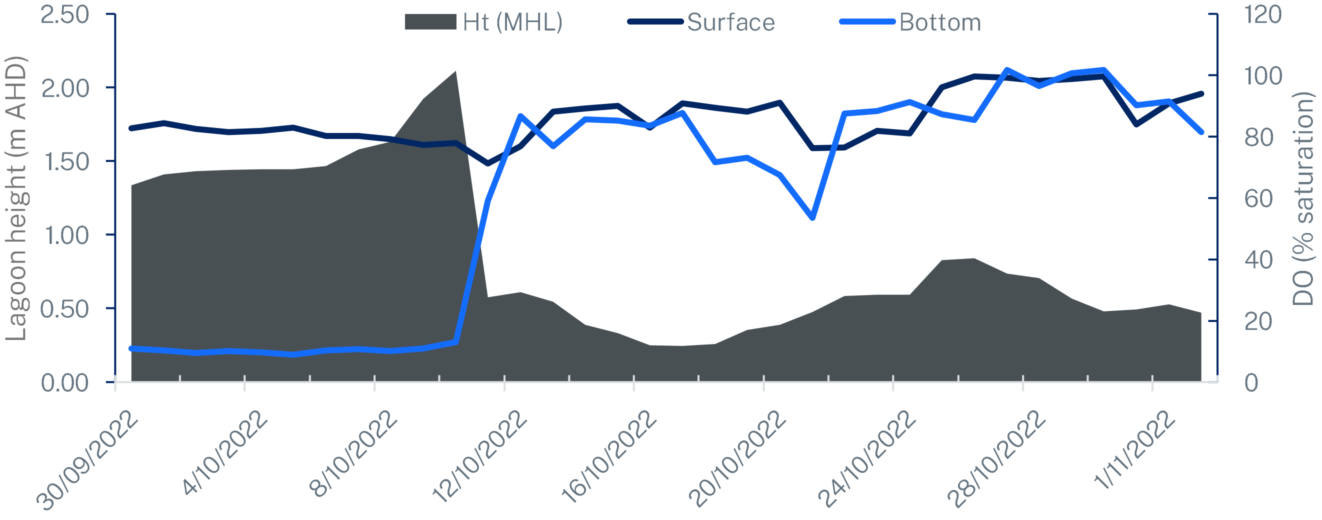


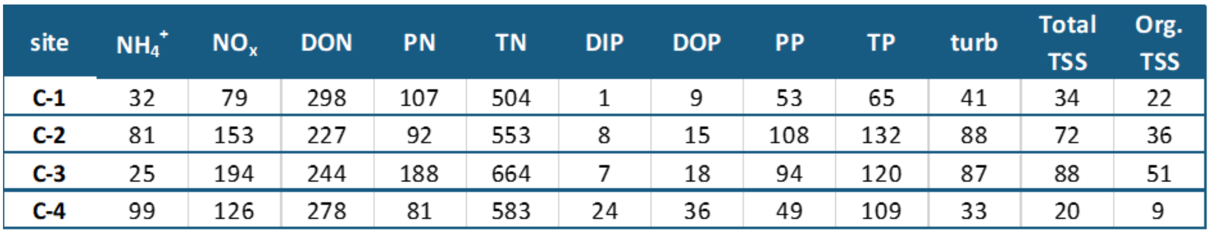
Figure 18. Dissolved oxygen saturation (right y-axis) in surface (dark blue line) and bottom (blue line) waters of the deep basin of Avoca Lagoon (Z-9) relative to lagoon water height (left y-axis, shaded area) **during spring 2022**

3.5 Catchment inputs

Overall, event mean nutrient concentrations in the monitored sub-catchments were at the lower end of the range for similar urbanised and semi-urbanised catchments (Table 11). Nitrogen inputs were dominated by dissolved forms (dissolved organic nitrogen [DON] and dissolved inorganic nitrogen [DIN = NH4+ = NOx]). In contrast, phosphorus inputs were dominated by particulate forms which were closely correlated with TSS concentrations.

The event mean concentrations are placed into context with internal processes in the nutrient budget presented below. Of significance are the relatively high concentrations of bio-available nitrogen, TSS and particulate phosphorus entering the southern arm of the lagoon (C-2 and C-3). The deposition of particulates in this southern arm may be an important factor contributing to high turbidity in this part of the lagoon (see Turbidity section 3.3 for further discussion).

Table 11. Event mean concentrations for nutrients (mg/L) and TSS (mg/L) in catchment inflows (C-1, C-2, C-3, C-4) derived from all event sampling data during the study period



site	NH_4^+	NO_x	DON	PN	TN	DIP	DOP	PP	TP	turb	Total TSS	Org. TSS
C-1	32	79	298	107	504	1	9	53	65	41	34	22
C-2	81	153	227	92	553	8	15	108	132	88	72	36
C-3	25	194	244	188	664	7	18	94	120	87	88	51
C-4	99	126	278	81	583	24	36	49	109	33	20	9

Note: NH_4^+ = ammonium; NO_x = nitrate+nitrite; DON = dissolved organic nitrogen; PN = particulate nitrogen; TN = total nitrogen; DIP = dissolved inorganic phosphorus; DOP = dissolved organic phosphorus; PP = particulate phosphorus; TP = total phosphorus; turb = turbidity; Total TSS = inorganic+organic TSS; org. TSS = organic TSS.

During the first sampling occasion in February 2022, enterococci counts exceeded detection limits at creek sites C1-C4 and were well above guidelines at the creek site C5 - a small drainage in the north east section of the catchment not shown in the map (Figure 1). Very high enterococci concentrations were measured in the southern basin at Z-10 (Table 12). These samples were taken during a runoff event triggered by a daily rainfall total of 35mm at Avoca Lagoon following 47mm in the two weeks before the sampling day. On the other sampling trip, samples were collected on the back of a smaller runoff event following 14mm of rainfall on the previous evening. On this occasion, enterococci concentrations were found to be highest in the northern creeks – C-4 and C-5 – flowing into the northern basin of Avoca Lagoon (Z-6), where bacteria loads accumulated to nearly 1800 mpn/100L (Table 12).

Table 12. Enterococci concentration (mpn/100mL) on two sampling occasions during the study

Site	22/02/2022	24/08/2022
C-1	>24,196	415
C-2	>24,196	81
C-3	>24,196	181
C-4	>24,196	1533
C-5	10831	1480
Z-6	522	1759
Z-8	8	36
Z-10	5610	53

3.6 Sediment quality

The distribution of fine sediments in Avoca Lagoon follows patterns expected for ICOLLs, with coarser sediments in the fluvial deltas reflecting higher scour energy associated with catchment inflows, grading to a zone of finer sandy sediments adjacent to the deltas, and silts/muds in the central basin zones of each arm of the lagoon (Figure 19).

The marine delta is dominated by inputs of marine sands. Total organic matter tended to be highest in the fine sand zone adjacent to the fluvial deltas, and also in the dredge hole. The accumulation of fine sediments and organic matter in the dredge hole highlights a significant ecosystem function shift in the lagoon, with implications for nutrient cycling and overlying water quality as outlined in subsequent sections.

Temporal variation in sediment carbon and nitrogen contents were also measured at the benthic flux sites which are shown in the Appendix.

3.7 Benthic processes

Benthic core incubation experiments were carried out during summer, winter and spring to characterise benthic processes occurring throughout the year and across different states of water quality largely influenced by entrance status (Table 13).

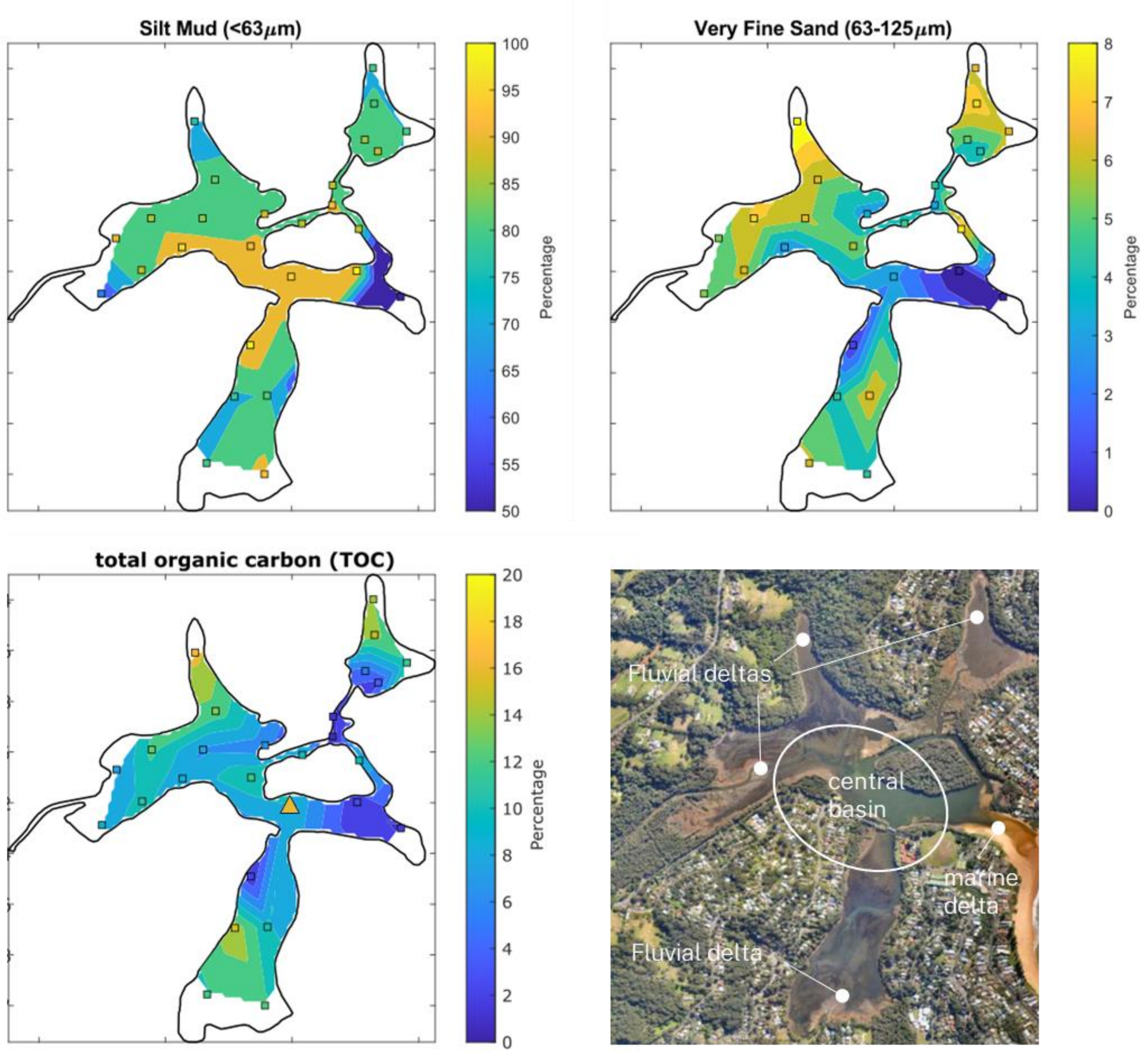


Figure 19. Distribution of silt, very fine sand and total organic carbon (loss on ignition) in Avoca Lagoon. The yellow triangle in the TOC plot represents the high carbon contents recorded in the dredge hole during benthic process surveys. Geomorphic zones are identified in the aerial photo (source Nearmap).

Table 13. Mean ambient water column conditions and entrance status at the time of benthic incubations

	Summer		Winter		Spring	
Entrance Status	Closed		Closed		Open - tidal	
	Shallow	Basin	Shallow	Basin	Shallow	Basin
Salinity (psu)	13.4	24.2	25.5	33.9	0.6 / 29.2*	35.5
Temperature (°C)	25.7	27.1	14.2	16.8	20.5	18.3
DO (%sat)	79	4	97.4	81.9	92.2	92.7
DO (mg/L)	6	0.3	8.5	6.5	8.2	7.1
pH	7.38	7.25	7.5	7.93	7.8	8.09
Light intensity (µE)	300	<10	200	33	na	na

*Stratified water column- low salinity at shallow sites but incubation water collected in near-surface water (29.2psu)

The rates of benthic oxygen respiration (a proxy for organic matter breakdown) in Avoca Lagoon were in the moderate range expected for NSW ICOLLs and estuaries (Figure 20). Notably, the respiration rates for the basin site were low, which is most likely an underestimation of total respiration due to the exclusion of anaerobic respiration. Anaerobic respiration can occur when dissolved oxygen concentrations in overlying water are low and the sediments contain a high content of fines and organic matter. In contrast, the rates of benthic primary production were at the high end of the expected range for NSW ICOLLs, and most likely reflect the stimulation of productivity by high availability of bio-available nutrients in the lagoon.

Ammonium fluxes were mostly directed out of the sediment, representing a source of bioavailable nitrogen to the water column (Figure 20). The exception was at site 5 (in Z-11) which recorded uptakes of ammonium during the study, consistent with marine delta sands in other ICOLLs and estuaries. In contrast, nitrate was taken up by sediments most likely reflecting direct denitrification. There were significant uptakes of dissolved organic nitrogen by sediments, which may reflect the consumption of dissolved organic material by sediment microbes. In contrast to nitrogen, phosphorus fluxes were close to zero reflecting tight retention of phosphorus by sediments.

Bio-available ammonium is a primary product of organic matter breakdown in sediments and is therefore related to the sediment organic matter content (Figure 21). As outlined above, however, this ammonium is also subject to assimilation by benthic microalgae, and hence the ‘net daily flux’ represents the balance between production during organic matter breakdown and assimilation. The productivity / respiration ratio (p/r) provides a proxy of the balance between these two processes and is closely related to the net flux of ammonium (Figure 21). The strong relationship between p/r and bio-available nitrogen fluxes has a number of significant implications in the context of Avoca Lagoon:

- The dredge basin site is currently a large source of bio-available nitrogen due to a combination of the accumulation of organic matter and the light limitation of sediments. The dredge basin was previously a shallow benthic habitat (Figure 2) that would have received good light and had high p/r. Dredging has therefore converted a large area of the lagoon from a nutrient sink to a nutrient source.
- The elevation of lagoon turbidity due to a combination of resuspension and high phytoplankton biomass (chlorophyll) has reduced light penetration to sediments and therefore most likely increased the release of bio-available ammonium.
- Fluxes of bio-available phosphorus (dissolved inorganic P = DIP) were almost all directed into the sediment across the lagoon, with uptakes increasing with benthic p/r indicating assimilation by benthic microalgae. In contrast, there were releases of DIP from sediments in the dredge hole which increased under anoxia. This, combined with periodically high DIP concentrations recorded in bottom water of the dredge hole suggest an internal source of bio-available phosphorus in the lagoon which may be important for stimulating phytoplankton production (and hence increasing chlorophyll concentrations).

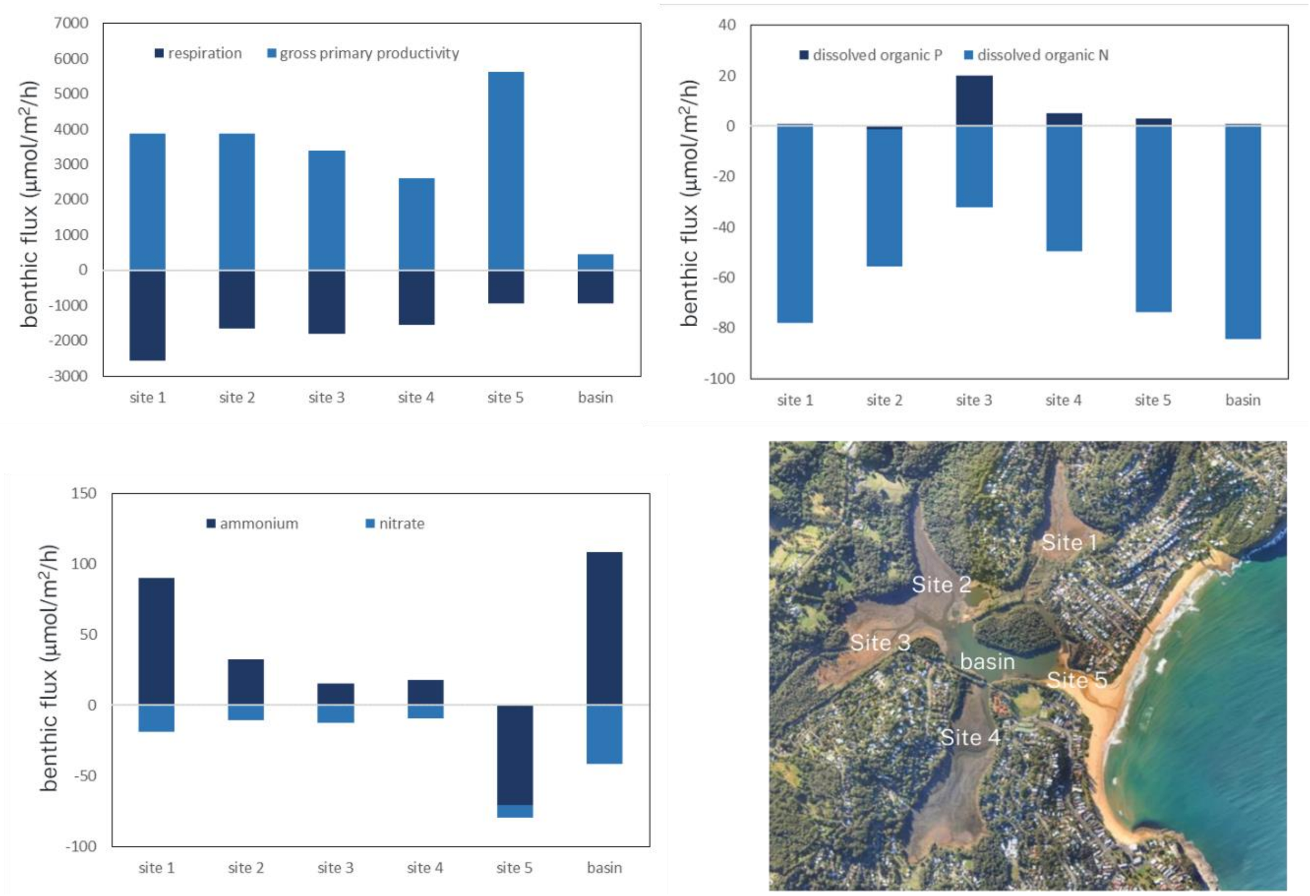


Figure 20. Mean benthic fluxes of oxygen, dissolved inorganic nitrogen (ammonium and nitrate), and dissolved organic nitrogen and phosphorus during the study period (Note: data are means for all replicates and sample times at each site. Benthic flux data from sites 1-5 and basin sites from summer, winter and spring experiments are shown in the Appendix)

Note: Site 1 is in Z-6, site 2 is in Z-7, site 3 is in Z-8, site 4 is in Z-10, site 5 is in Z-11 and the basin is in Z-9 (see below)

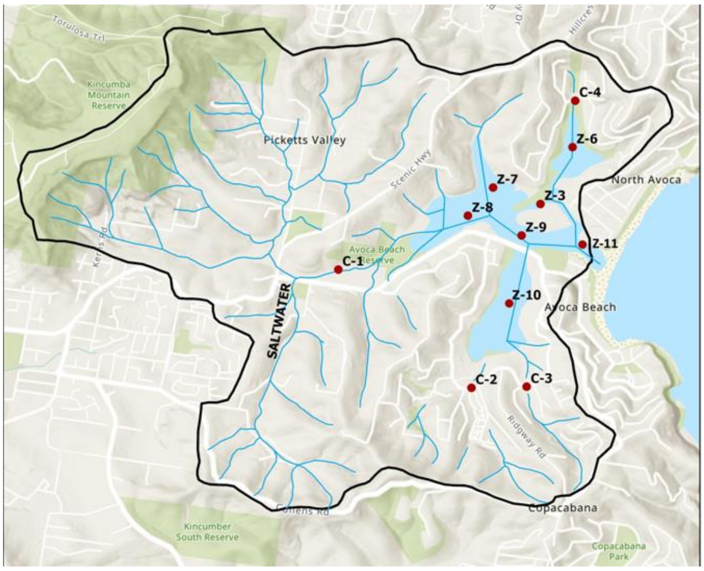


Figure 1 – Monitoring zones in Avoca Lagoon (from page 11)

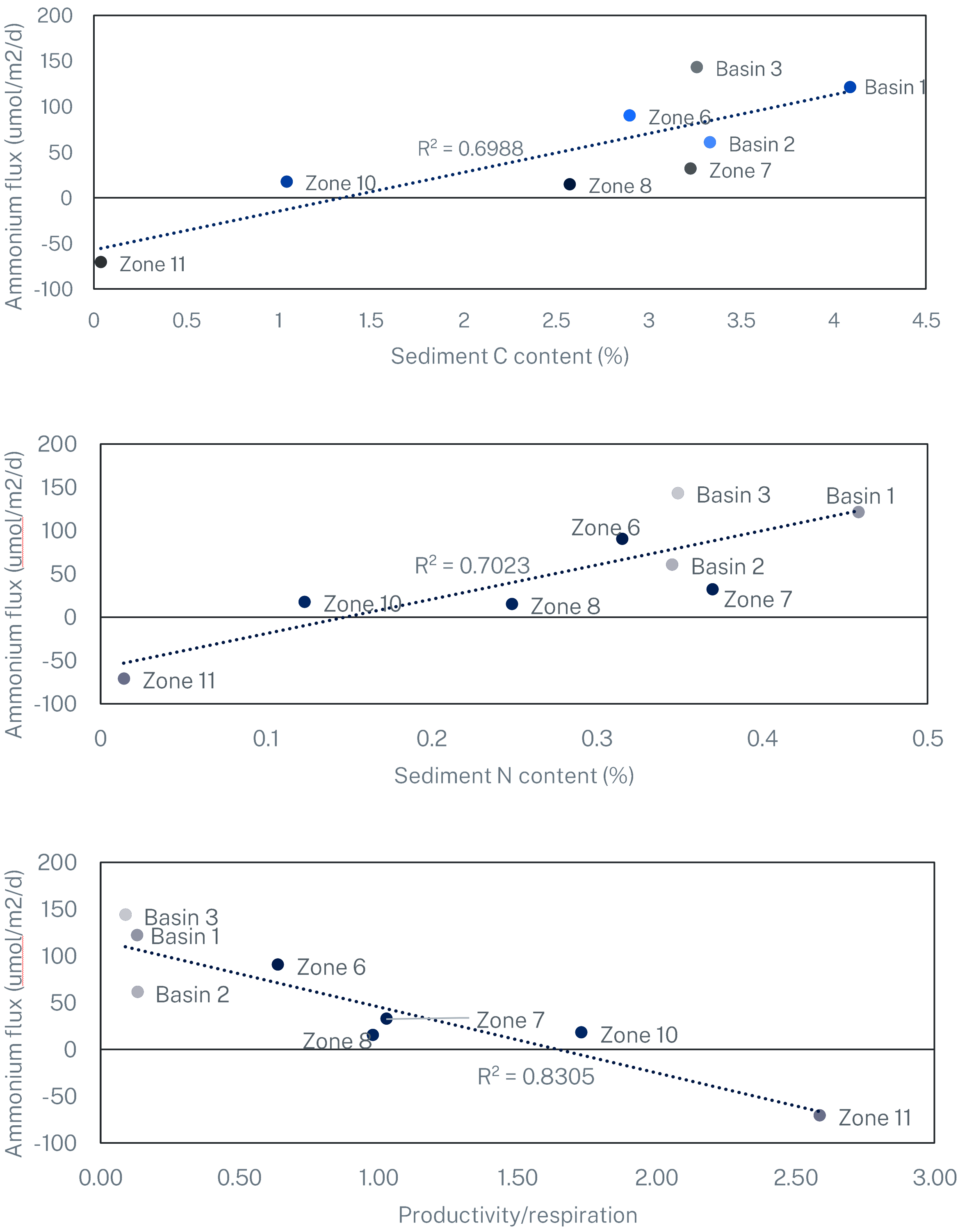


Figure 21. Net daily fluxes of bio-available ammonium versus sediment C content (organic matter, top plot), sediment N content (middle plot) and productivity / respiration ratio (bottom plot) which is an estimate of the balance between the rates of organic matter production and breakdown (p/r). Note: data are means of all replicates and sample times

Note: Site 1 is in zone 6, site 2 is in zone 7, site 3 is in zone 8, site 4 is in zone 10, site 5 is in one 11 and Basin 1, Basin 2 and Basin 3 are in zone 9 (Figure 1)

3.8 Entrance opening event

Groundwater seepage

Radon activity in surface waters in the central basin of the lagoon prior to the entrance opening indicated a background groundwater influence in the lagoon of between 1-10% (i.e., radon mass balance indicates that shallow groundwater accounted for 1-10% of the water in the lagoon; Figure 22). There was marked increase in radon activity as the lagoon water level dropped below 1m AHD following the entrance opening. Radon activity continued to rise, peaking at a maximum of 36% shallow groundwater in lagoon water by the end of monitoring (Figure 22). These results indicate that groundwater seepage from fringing wetlands is a significant influence on lagoon water quality following entrance opening events.

Groundwater quality was determined from grab samples taken from three shallow bores located within 50m of lagoon edge on the day prior to the entrance opening. Concentrations of all nutrient forms were significantly higher than concentrations in the lagoon (Table 14, Table 10). Ammonium dominated total dissolved nitrogen, while dissolved organic phosphorus dominated total dissolved phosphorus (Table 14). There were high concentrations of particulate nitrogen and phosphorus at all sites (Table 14).

Table 14 Water quality in groundwater bores (nutrient concentration units are µg/L)

	DON	NH_4^+	NOx	PN	TN	DOP	DIP	PP	TP
GW-1	29.5	278	0.5	66	374	45	0.5	111	156
GW-3	1233	1224	11	1930	4398	39	0.5	451	490
GW-4	22	516	17	122	677	70	0.5	102	172

Note: NH_4^+ = ammonium; NO_x = nitrate+nitrite; DON = dissolved organic nitrogen; PN = particulate nitrogen; TN = total nitrogen; DIP = dissolved inorganic phosphorus; DOP = dissolved organic phosphorus; PP = particulate phosphorus; TP = total phosphorus

The timeseries of pH from the smartbuoy showed a slight depression in surface water pH as the lagoon drained, followed by a marked increase as tidal influence caused the input of oceanic water to the lagoon (Figure 23). There was no evidence of acid runoff from acid sulfate soils during the drainage of the lagoon.

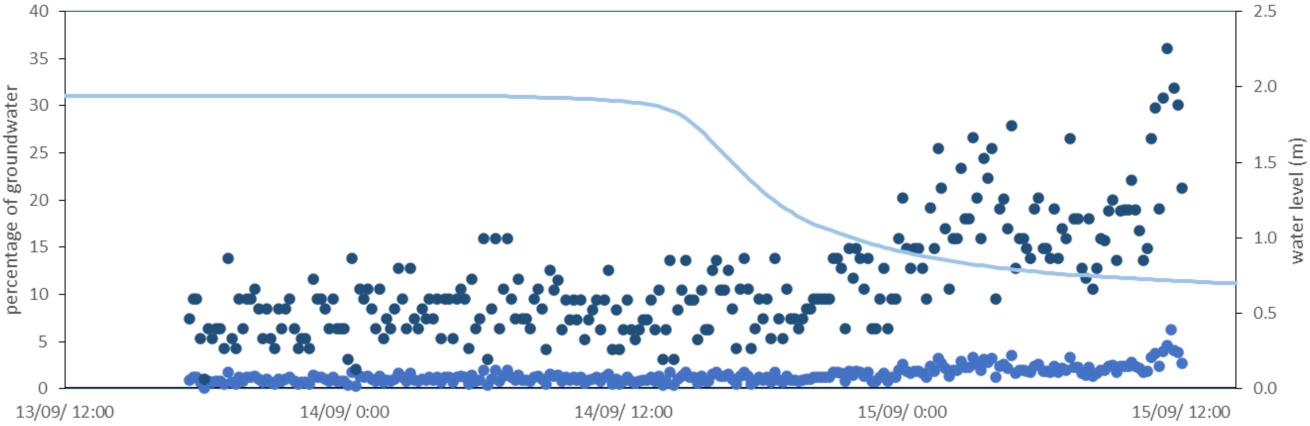


Figure 22. The estimated minimum (light blue dots) and maximum (dark blue) percentage of groundwater (left y-axis) in the lagoon water column prior to and during the lagoon drainage as indicated by water level (m, right y-axis)

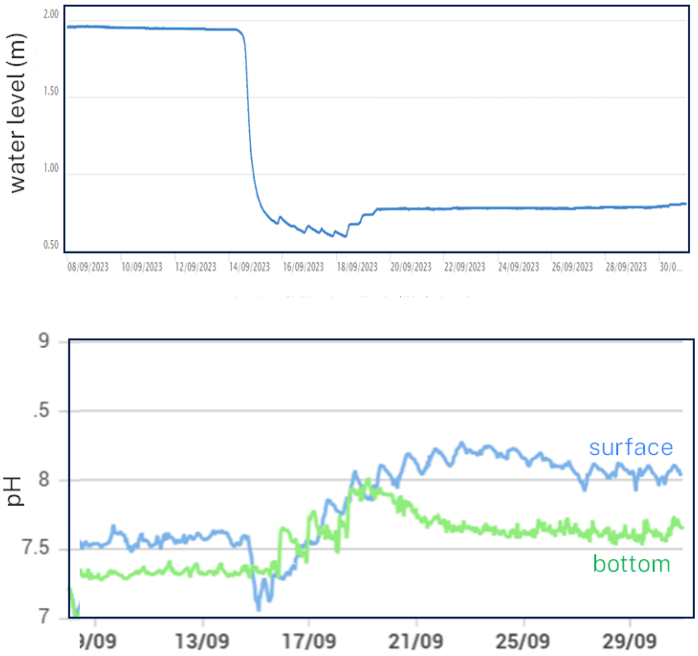


Figure 23. Surface (blue) and bottom (green) water pH in Avoca Lagoon prior to, during and following the entrance opening event on 14th September. Note dates on x-axes are aligned.

Lagoon water quality

Water quality in the lagoon prior to and during the entrance opening event is presented in **Error! Reference source not found.** – Figure 26. There was a clear increase in ammonium (**Error! Reference source not found.**B), dissolved organic nitrogen (**Error! Reference source not found.**A) and dissolved organic phosphorus concentrations (Figure 25A) as water level dropped below 1m AHD. Suspended solid concentrations increased soon after lagoon water level started dropping, reflecting resuspension of sediments due to outflowing currents (Figure 26A-C). TSS was comprised of approximately 75% inorganic solids and 25% organic solids (Figure 26B-C). Particulate nutrient concentrations only increased during the last stages of lagoon drainage (Figure 25B-C).

This is consistent with a progressive increase in groundwater influence during the last stages of lagoon drainage as highlighted by radon tracer results (see previous section, Figure 22).

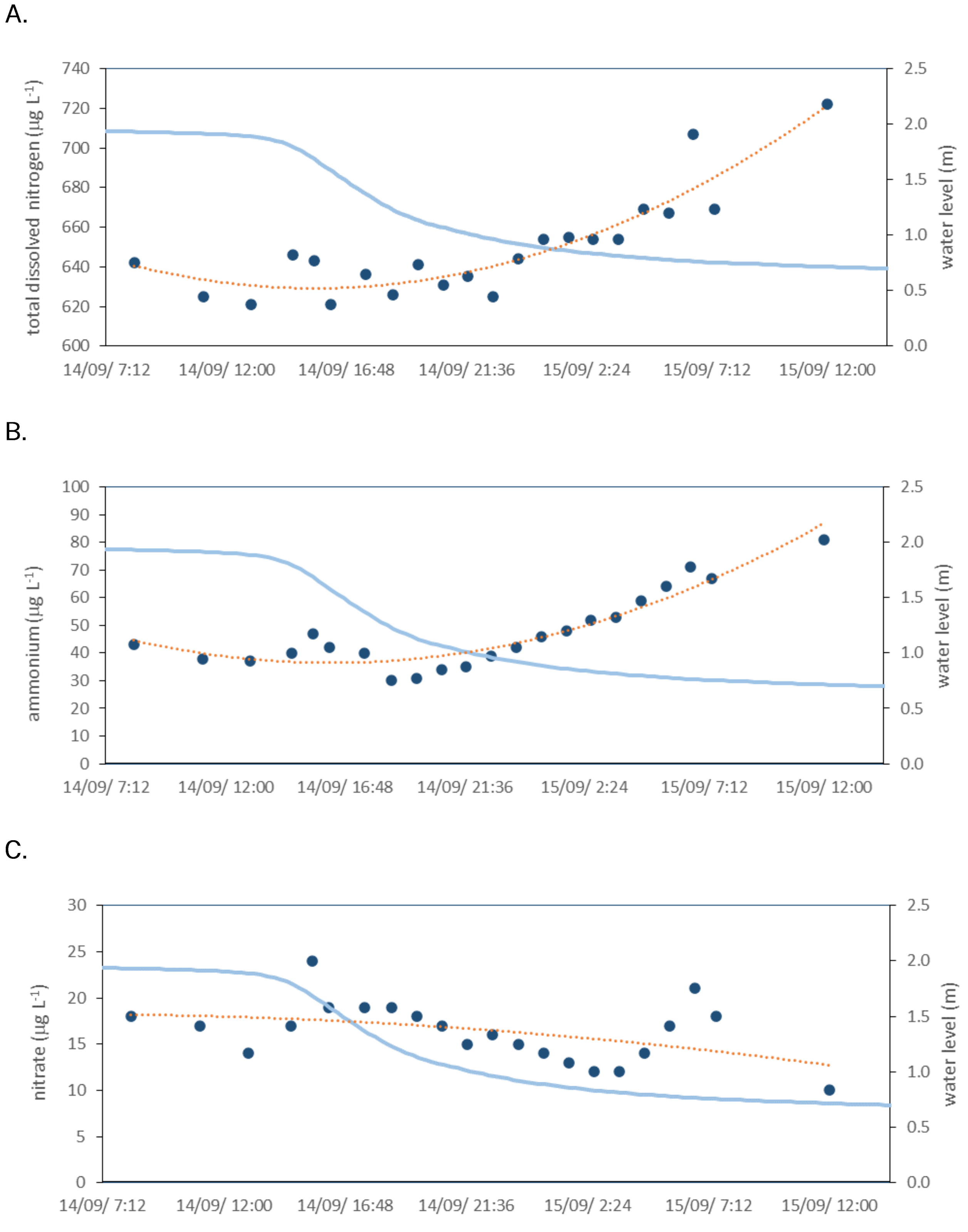


Figure 24. Nutrient concentrations (left y-axis) in the lagoon prior to and during the lagoon opening with water level indicated by right y-axis. **A.** total dissolved nitrogen (µg.L^{-1}), **B.** ammonium (µg.L^{-1}) and **C.** nitrate (µg.L^{-1})

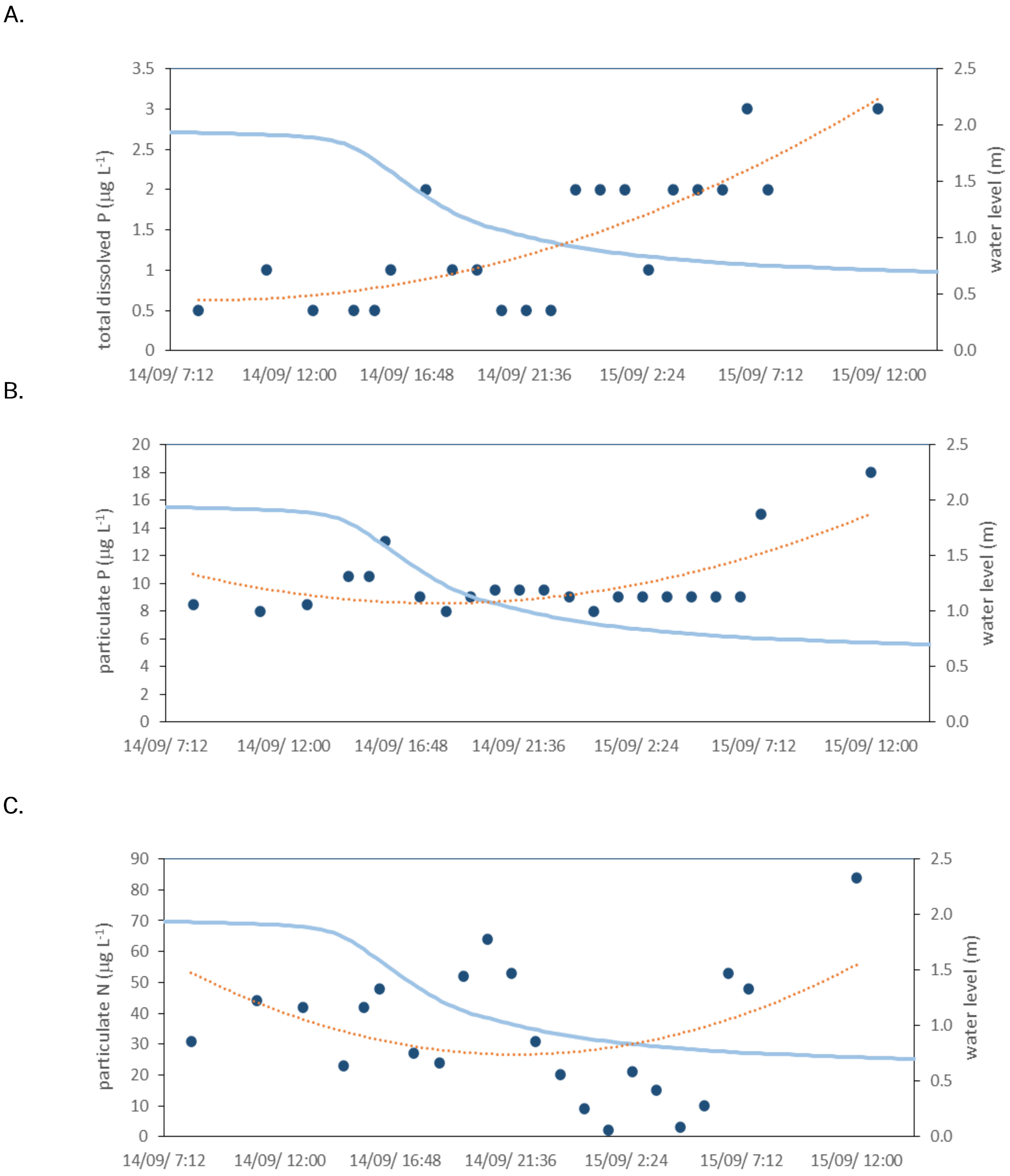


Figure 25. Nutrient concentrations (left y-axis) in the lagoon prior to and during the lagoon opening with water level indicated by right y-axis. **A.** total dissolved phosphorous (µg.L^{-1}), **B**. particulate phosphorous (µg.L^{-1}) and **C.** particulate nitrogen (µg.L^{-1})

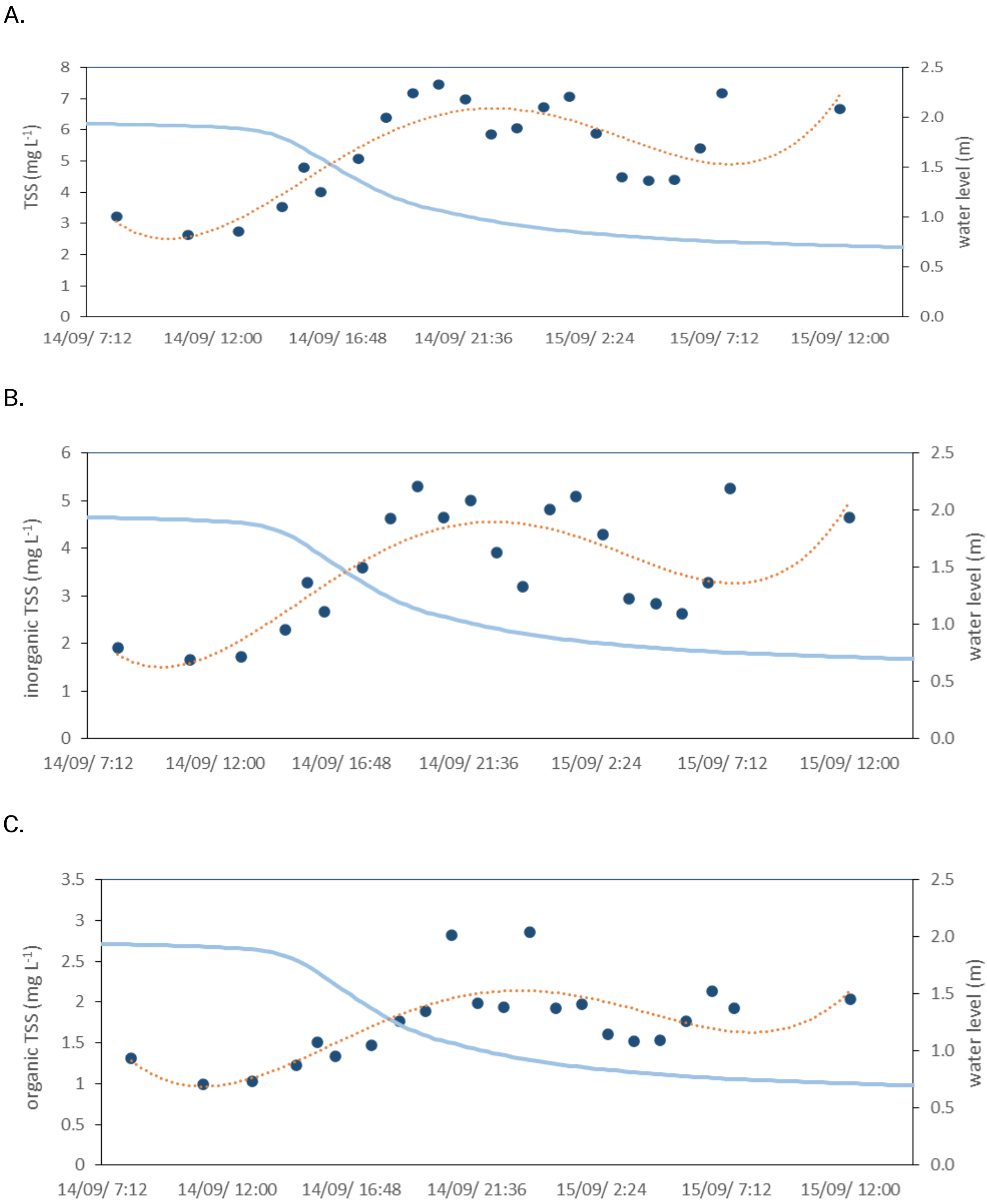


Figure 26. Suspended solids (left y-axis) in the lagoon prior to and during the lagoon opening with water level indicated by right y-axis. **A.** total suspended solids (mg.L^{-1}), **B.** inorganic suspended solids (mg.L^{-1}) and **C.** organic suspended solids (mg.L^{-1})

Nutrient and sediment export

Nutrient and suspended sediment concentrations were integrated with discharge calculations (see next section; Table 16, Table 17, Table 18) to estimate the total mass exported to the ocean during the entrance opening event (Table 15). Dissolved organic nitrogen accounted for 86% of total nitrogen exports. In contrast, particulate phosphorus accounted for 90% of total phosphorus exports. The molar ratio of nitrogen to phosphorus exported was 128. Suspended sediment exports comprised 31% particulate organic matter and 69% inorganic sediment.

Table 15. Total mass of nutrients and suspended sediments exported to the ocean from Avoca Lagoon during the September 2023 entrance opening event.

	DON	**NH4**	**NOx**	**PN**	**TN**	**TDP**	**PP**	**TP**	**TSS organic**	**TSS inorganic**
Mass (kg)	-474.8	-34.5	-15.0	-28.8	-553.1	-1.0	-8.6	-9.6	-1152	-2552

Hydrodynamics

The hydrodynamic measurements started at 5:30am on 14th September 2023 and continued until 4:30pm, followed by measurements the next morning. The flow measurements were taken using an M9 doppler current profiler near the smartbuoy (near Z-9, Figure 1).

Pre-opening

Before the mechanical opening of the entrance, the flows in the main basin were measured to establish the initial or baseline flow magnitudes and directions. Four separate time-series measurements profiling for initial conditions are shown in Figure 27.

The pre-opening state of the hydrodynamics had slow speeds in the eastward and northward directions with magnitudes remaining under 0.01 m/s for most of the water column (Figure 27). At a depth of about 2m, there was a band of high turbulence which may indicate the presence of stratification, i.e., a pycnocline. The measured water depth in the main basin was 3.2m.

During opening

Water level in the lagoon only dropped by ~0.05m during the initial hours (7 AM - 1 PM) of the entrance being opened (Figure 24, Figure 28). By the end of the day the discharge had accelerated to near peak discharge, and the water level had dropped by ~0.41m. The effect of the entrance opening can be seen at 8:00 AM as a disturbance along the pycnocline but was mostly prevalent at 11:30 AM. After 11:30 AM, there was a strong flow in the eastward direction. Initially, the eastward (towards entrance) flow was confined to a sub-surface layer just above the pycnocline (Figure 28). At the surface, the flow was upstream (southwest-ward) likely driven by the NNE morning winds experienced at the site. By the end of the day the entire surface layer was moving eastward towards the entrance of the lagoon, with a surface layer depth of approximately 2.25m (Figure 28). The bottom layer in the main basin remained stationary which indicates that the opening of the lagoon only removes the surface layer. A small fraction of bottom water, however, may be entrained into the surface layer due to the turbulence at the pycnocline.

Day after opening

A time-series measurement was taken in the main basin the day after the entrance opening (Figure 29). At 9:00 AM on the 15th September, the water level of the lagoon had dropped to 0.74m at the MHL station (this represented ~92% decrease in the total water level height observed). In the main basin, the water level height had dropped to 2.25m and the pycnocline depth had dropped to 1m (Figure 29). The initial mixed surface layer thickness of 2.25m had decreased to a thickness of 1 m which is consistent with the 1.2m decrease in the water level height recorded at the MHL station. This suggests that the opening of the lagoon entrance had decanted the surface water layer of the lagoon. Surface waters typically have better water quality than deeper waters and the deeper water layers which remained in the lagoon had poorer water quality (Figure 24 - Figure 26).

Transects - southern basin

As the lagoon drained, the cross-sectional transects show a strong north-eastward flow out of the southern basin (Figure 30). As the water drains and the cross-section depths became shallower, the flow was confined mostly to the channel. After the water level had dropped by about 1.2m the next day, the flows had returned to the initial flow magnitudes but some zones of strong outflow from the southern basin were still evident in the lower depths of the channel. The discharge magnitudes from the southern basin are shown in Table 16. At the near peak discharge at the entrance (see Figure 33) the southern basin was discharging at ~11.9 m^3/s.

Table 16. Measured discharge rates (m^3/s) across the southern basin entrance.

Time stamp	Discharge Rate (m^3/s)
11:30 AM 14th Sept	0.9
03:15 PM 14th Sept	11.9
05:14 PM 14th Sept	11.1
08:00 AM 15th Sept	0.3

Transects - eastern basin

The transect across the main basin describes the flow of water from the eastern basin towards the entrance (and possibly some diversion into the southern basin due to its proximity). The cross-section plots show two distinct channels that drain the eastern basin (Figure 31). During the drainage period, the peak discharge rate was close to 20.8 m^3/s (Table 17), roughly double the discharge from the southern basin (Table 16). Due to the larger flows, the channels also showed a significant amount of turbulence, reflected by the noise in the flow magnitudes (Figure 31). This noise weakened but continued the next day, likely caused by the slower but continued entrance exchange.

Table 17. Measured discharge rates (m^3/s) across the eastern basin

Time stamp	Discharge rate (m^3/s)
11:34 AM 14th Sept	3.5
03:10 PM 14th Sept	20.8
05:07 PM 14th Sept	22.1
08:05 AM 15th Sept	1.0

Transects - northern basin

The transect across the channel from the northern basin showed a strong southward flow confined in the deep channel (Figure 32). The near peak discharge out of the channel was about 5 m^3/s. The northern basin can also exchange through a secondary channel connected to the eastern basin. Our discharge measurements across the eastern basin already included this factor. The cross-section for the northern basin had a large floodplain that drains close to empty by the end of the lagoon opening.

Table 18. Measured discharge rates (m^3/s) across the northern basin

Time stamp	Discharge Rate (m^3/s)
12:05PM 14th Sept	1.8
3:35 PM 14th Sept	5.3
7:44 AM 15th Sept	0.2

Discharge

The cross-sectional discharge profiling across the three basins between 3:00-3:30 PM shows the large bulk of water flow was moving from the eastern basin, followed by the southern basin and the northern basin. The discharge through the entrance of the lagoon is shown in Figure 33.

The peak discharge was 29.4 m^3/s, calculated from data recorded at the MHL water level station. At that time, the measured discharge across the southern basin was 11.9 m^3/s, the eastern basin was at 20.8 m^3/s and the northern basin was at 5.3 m^3/s (Table 16, Table 17, Table 18).

The sum of the discharges across the three basins was larger than the expected discharge at the entrance, which suggests that there is a certain amount of recirculation happening between basins i.e., the discharge from the eastern basin may enter the southern basin and then exit. Some data offset is expected as the cross-sectional measurements are not simultaneous.

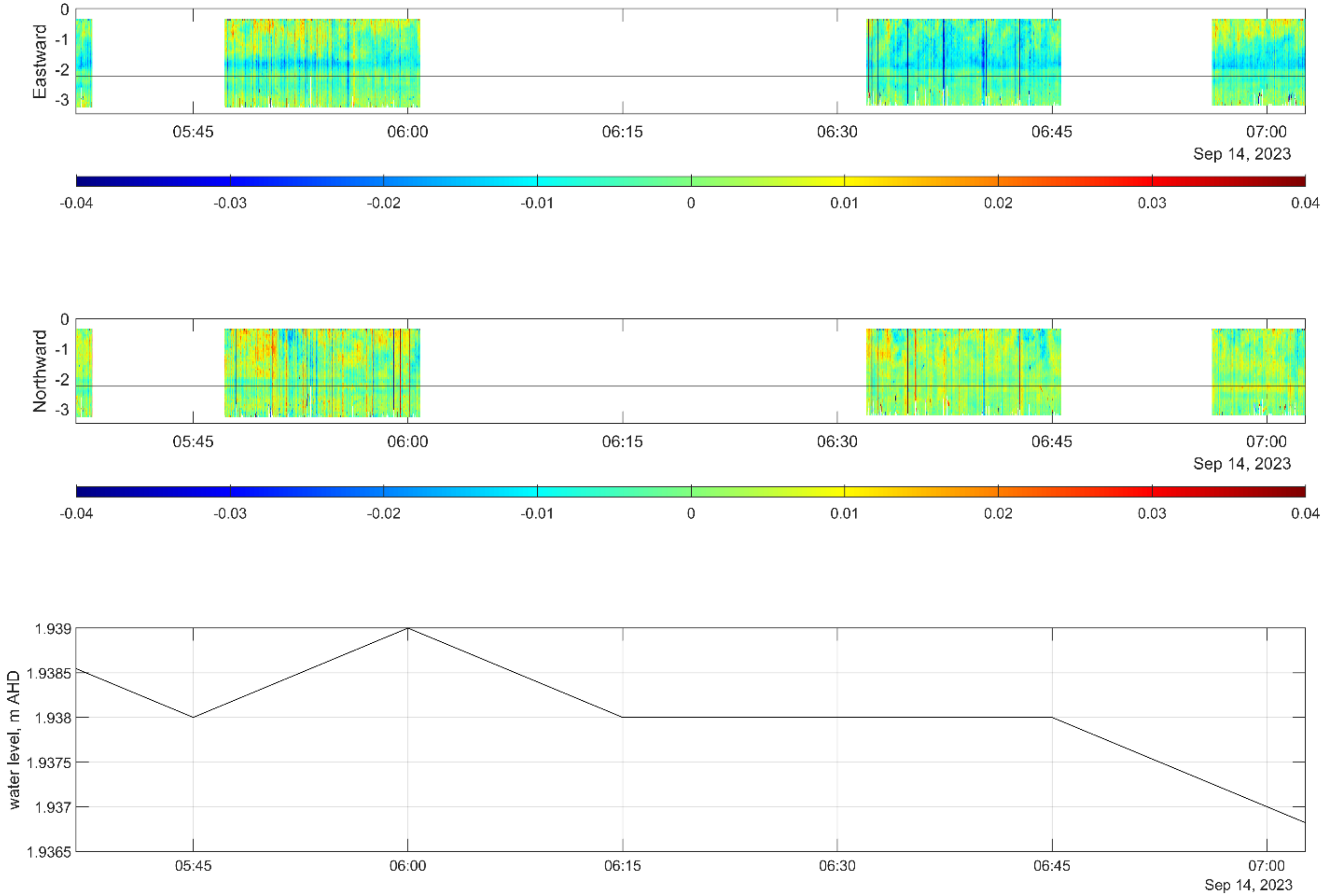


Figure 27. M9 current profiling of flow speeds (m/s) in the water column (water depth, y-axis) before the lagoon opening on 14th September 2023. Time-series of flow speeds in an eastward direction (positive colour scale, top plot), westward direction (negative colour scale, top plot), northward direction (positive colour scale, middle plot) and southward direction (negative colour scale, middle plot). A 2.25m line is plotted as a reference guide. Lower plot shows the water level height at the MHL station in Avoca Lagoon.

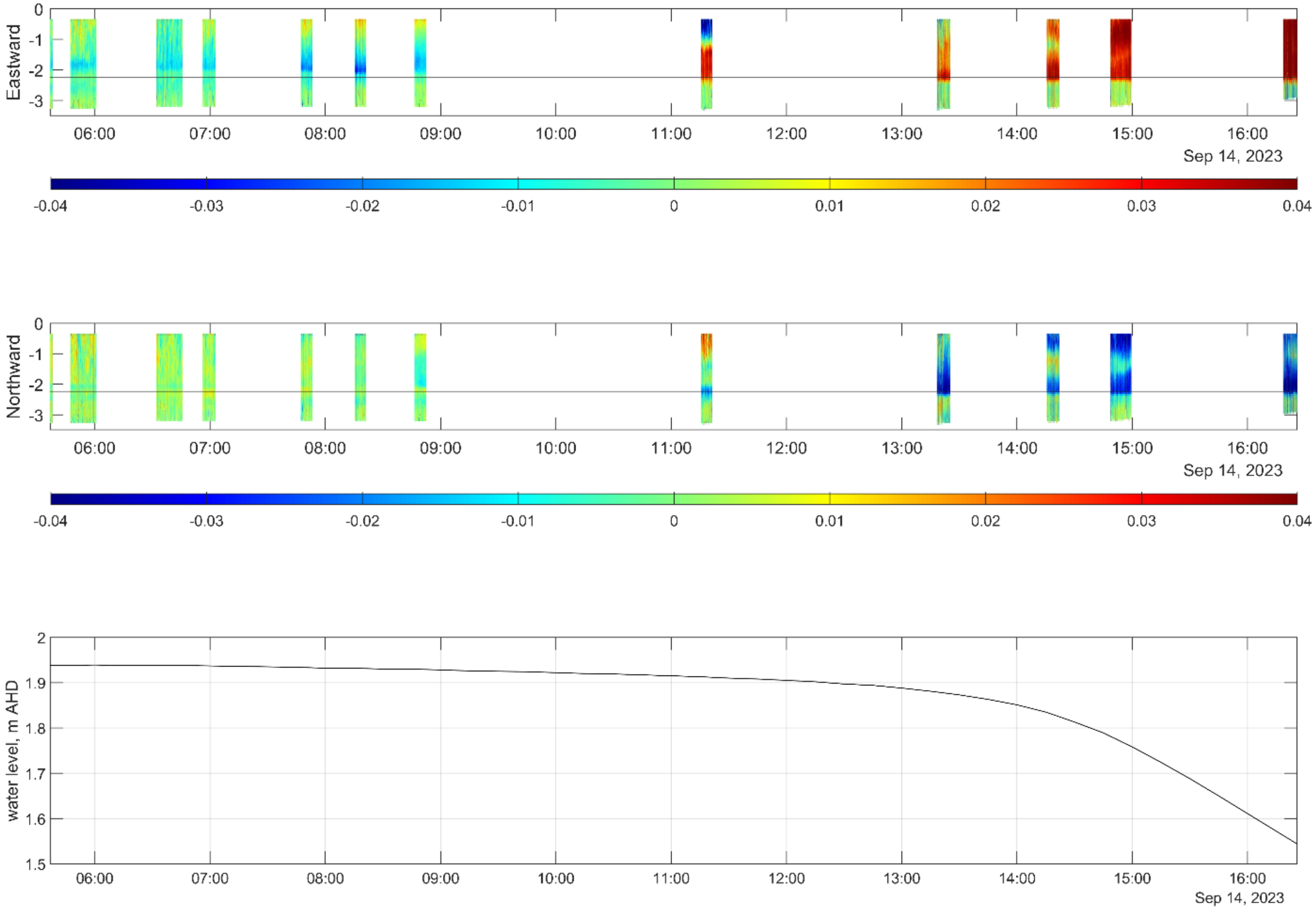


Figure 28. M9 current profiling of flow speeds (m/s) in the water column (water depth, y-axis) during the lagoon opening on 14th September 2023. Time-series of flow speeds in an eastward direction (positive colour scale, top plot), westward direction (negative colour scale, top plot), northward direction (positive colour scale, middle plot) and southward direction (negative colour scale, middle plot). A 2.25m line is plotted as a reference guide. Lower plot shows the water level height at the MHL station in Avoca Lagoon.

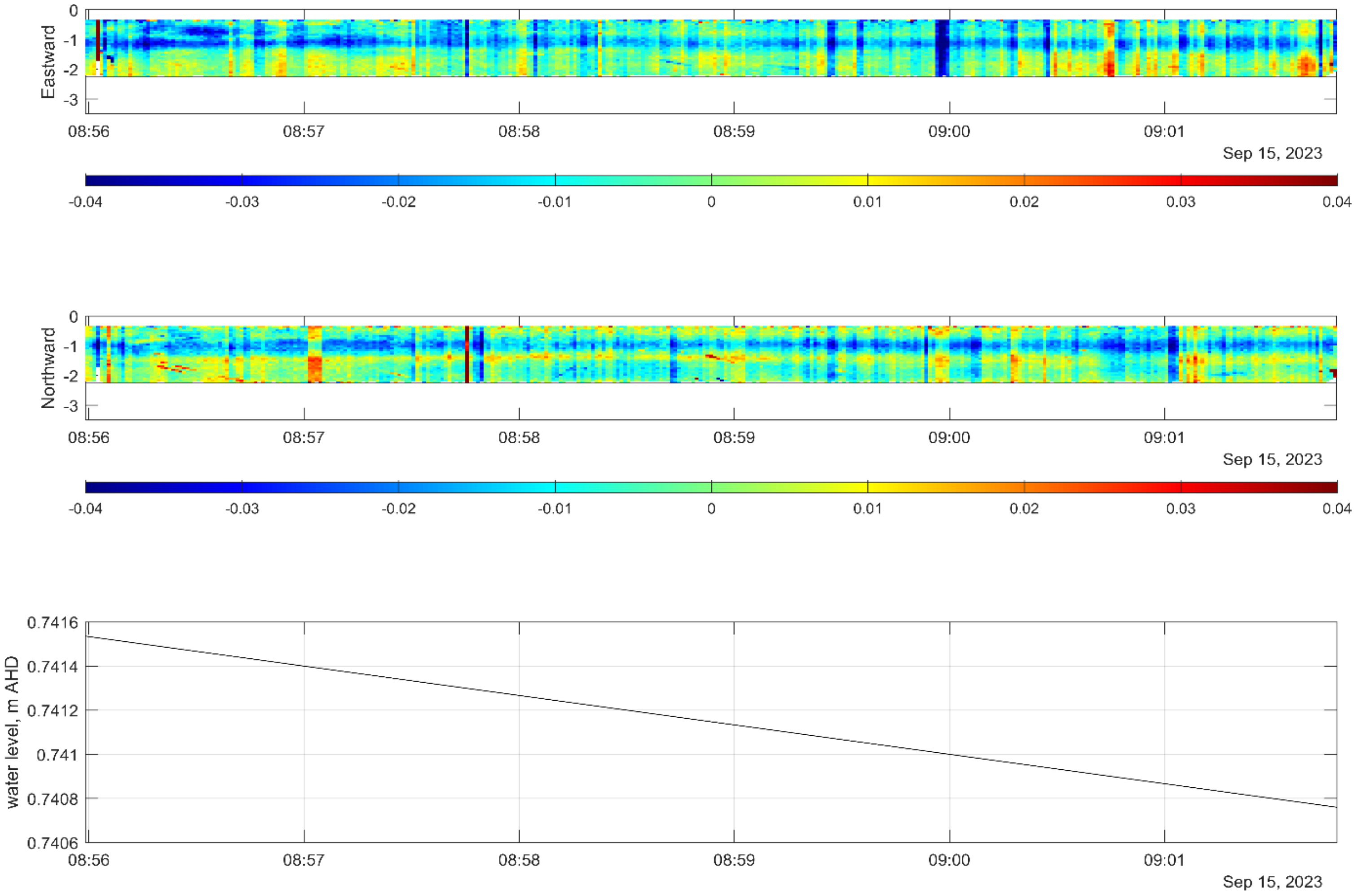


Figure 29. M9 current profiling of flow speeds (m/s) in the water column (water depth, y-axis) the day after lagoon opening on 15th September 2023. Time-series of flow speeds in an eastward direction (positive colour scale, top plot), westward direction (negative colour scale, top plot), northward direction (positive colour scale, middle plot) and southward direction (negative colour scale, middle plot). A 2.25m line is plotted as a reference guide. Lower plot shows the water level height at the MHL station in Avoca Lagoon.

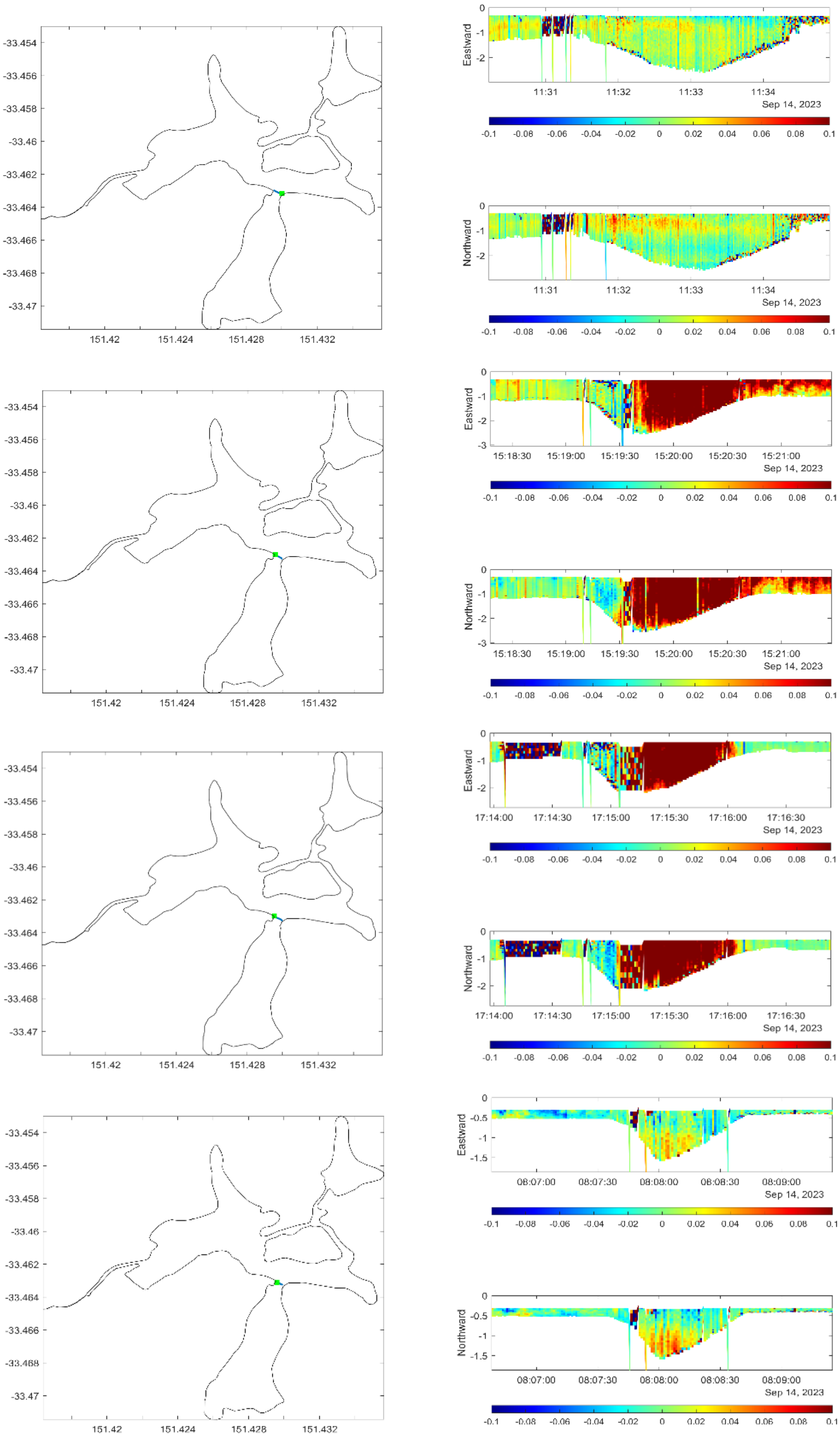


Figure 30 M9 current profiling of flow speeds (m/s, x-axes colour scale) in the water column (water depth, y-axis) at transects done across the entrance of the southern basin at 11:30 AM, 3:15 PM, 5:14 PM on 14th September and at 8:00 AM on 15th September.

Note: the transect line is reversed for the 11:30 AM transect (the cross-section is looking into the southern basin), while the other cross-sections are looking out of the southern basin. The green marker on the map shows the start of the transect i.e., left start point of the contour plot. Also note that the date on final two plots should read Sep 15, 2023.

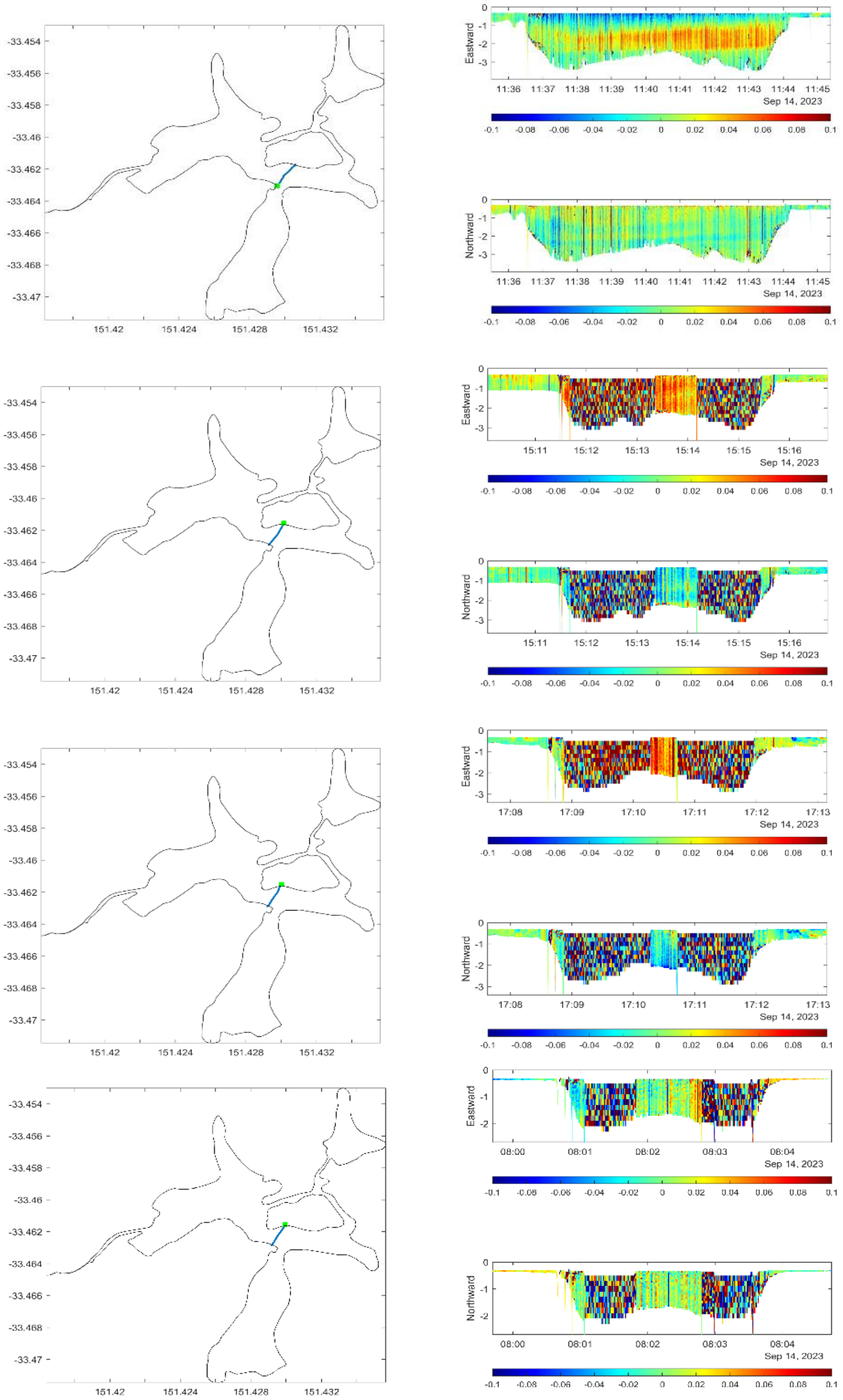


Figure 31. Contour plots of M9 current profiling of flow speeds (m/s, x-axes colour scale) in the water column (water depth, y-axis) at transects done across the eastern basin at 11:34 AM, 3:10 PM, 5:07 PM on 14th September and at 8:05 AM on 15th September.

The green marker on the map shows the start of the transect i.e., left start point of the contour plot. Also note that the date on final two plots should read Sep 15, 2023.

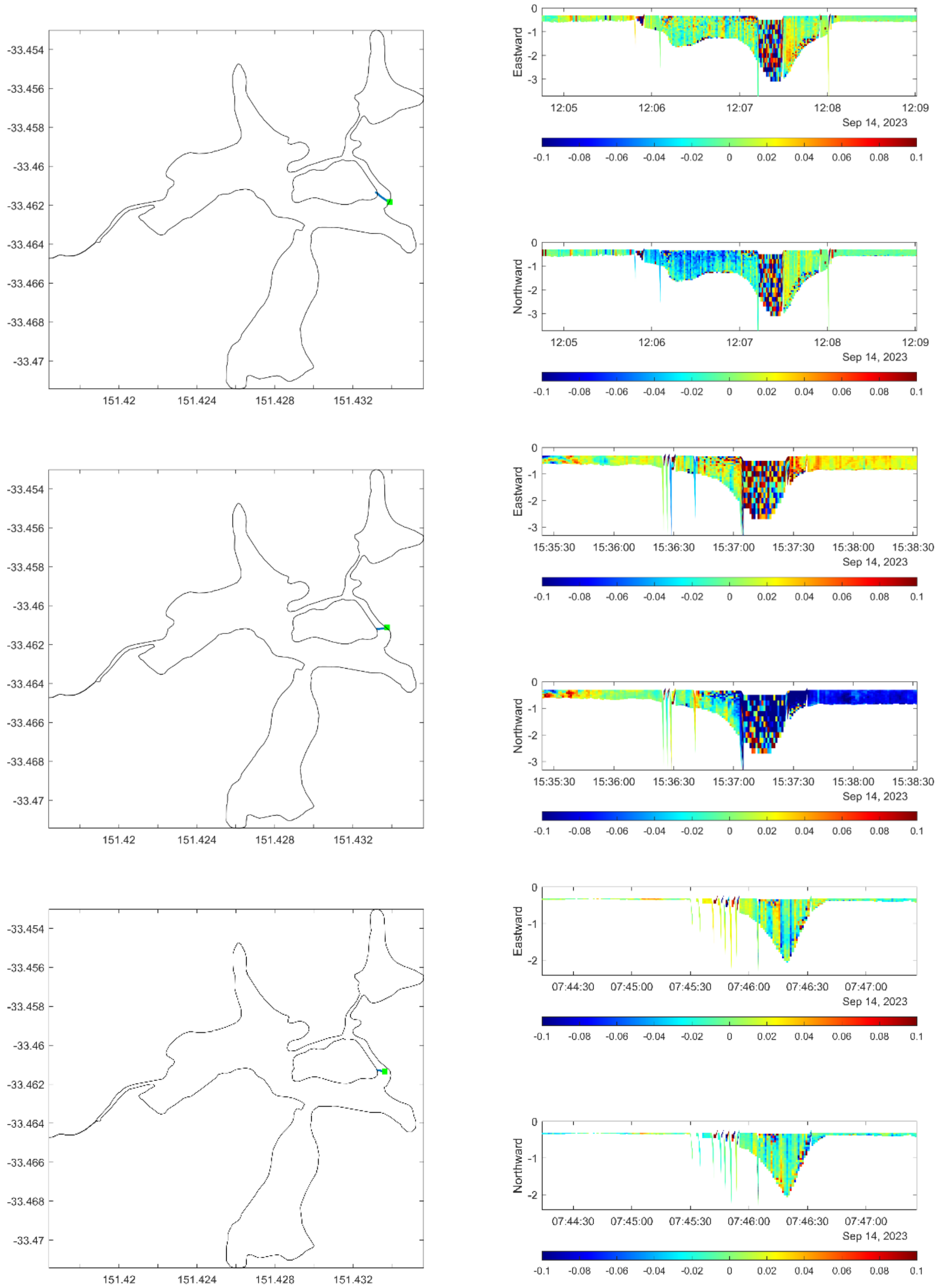


Figure 32. Contour plots of M9 current profiling of flow speeds (m/s, x-axes colour scale) in the water column (water depth, y-axis) at transects taken across the northern basin done at 12:05 PM and 3:35 PM on 14th September and at 7:44 AM on 15th September 2023.

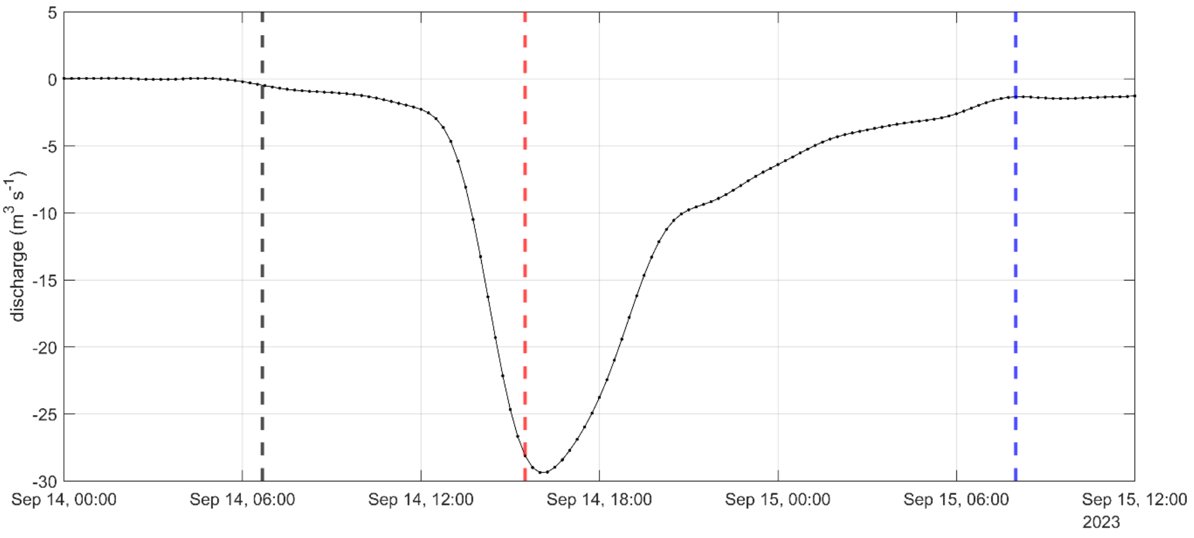


Figure 33. The discharge across the entrance of the lagoon onto the coastal ocean calculated using the MHL water level observations. The black line shows the start of the discharge measurements, the red line shows when the discharges across each basin was done, and the blue line show the final set of discharge measurements done for the experiment.

3.9 Nutrient budget

Estimates of catchment inputs, internal recycling (i.e., benthic fluxes), and export during breakout events were combined to provide indicative budgets for summer and winter that illustrate the relative importance of these terms. Each budget covers the period from entrance closure to the next breakout event.

Limitations

The budgets are a first-order estimation of nutrient sources, sinks and exports in Avoca Lagoon. It was not possible to derive accurate budgets for relevant periods (e.g., entrance closure or annual) due to the lack of contemporaneous data for all processes. However, the budget approach uses robust estimates of the main processes, and these have been scaled appropriately according to well-constrained system metrics and hydrology.

The following limitations of the budget approach are recognised:

- Catchment load estimates are based on limited flow-weighted sampling of freshwater inflows during relatively small summer runoff events. It is likely that these estimates do not account for seasonal variation in nutrient concentrations, nor variations introduced by much larger runoff events
- Catchment flows were not measured directly in the various sub-catchments
- While the study has highlighted the importance of shallow groundwater seepage, this term has not been included in the budget. As such the assessment of this term is qualitative and is likely to introduce error to the estimates of total inputs and therefore budget residuals.
- Internal biogeochemical processes in the water column (e.g., uptake by algae, nitrification) are not considered in the budget. This limits the ability to constrain the likely transformations and sinks of nutrients within the lagoon.

Budget scenarios

The summer budget was developed for a 72-day period of entrance closure from 16th December 2021 to 25th February 2022. The lagoon water level rose 1.51m during this period due to freshwater inflows and dropped 1.28m when the entrance was opened (Figure 34). The winter-spring budget was developed for a 55-day period of entrance closure from 17th August 2021 to 8th October 2022. The lagoon water level rose 1.48m during this period due to freshwater inflows and dropped 1.47m when the entrance was opened (Figure 34).

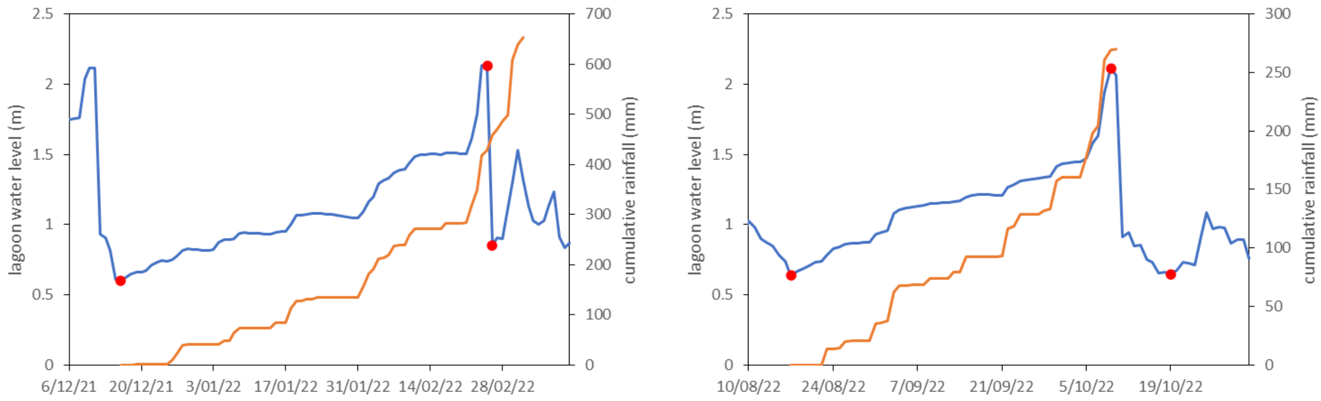


Figure 34. Water level and cumulative rainfall for the two budget periods. The red dots indicate the levels used to calculate the volume changes during the closure period and during lagoon drainage.

Budget results

The nutrient budgets shown in Table 19 indicate that the Avoca Lagoon system tends to retain phosphorus and export nitrogen. This result can be explained by considering the different biogeochemical pathways that control these elements.

Table 19. Nutrient budgets for Avoca Lagoon during summer and winter-spring. The residual term is the difference between catchment input and ocean export loads. A positive residual indicates a net retention of material over the budget period and vice versa. Units are kg.

Summer	DON	NH4	NOx	PN	TN	TDP	PP	TP
Catchment	241	33	137	121	291	12	65	77
Benthic flux	-384	96	-228	n/a	n/a	-131	n/a	n/a
Export	-482	-35	-15	-29	-561	-1	-9	-10
Residual	-241	-2	121	92	-271	11	56	67

Winter-spring	DON	NH4	NOx	PN	TN	TDP	PP	TP
Catchment	235	33	134	118	284	12	63	75
Benthic flux	-1006	321	-88	n/a	n/a	-5	n/a	n/a
Export	-554	-40	-18	-34	-646	-1	-10	-11
Residual	-319	-8	116	84	-362	11	53	64

Note: NH$_4$ = ammonium; NO$_x$ = nitrate+nitrite; DON = dissolved organic nitrogen; PN = particulate nitrogen; TN = total nitrogen; DIP = dissolved inorganic phosphorus; DOP = dissolved organic phosphorus; PP = particulate phosphorus; TP = total phosphorus

Both budgets show a retention of particulate nitrogen and phosphorus, indicating a net deposition of particulate material. A certain proportion of the deposited material is subject to remineralisation and therefore is not buried. Net deposition of particulate material is consistent with the gradual infilling of the lagoon, as described by the model of geomorphic evolution of NSW estuaries during the Holocene epoch (Roy et al. 2001).

The vast bulk of nitrogen export is in the form of dissolved organic nitrogen (DON), despite large internal uptakes of DON by sediments which can account for all catchment inputs. This suggests an internal source of DON not accounted for by the budget. The most likely source is groundwater seepage from fringing wetlands which may occur while shallow groundwater levels are higher than lagoon water levels (see section 3.8).

Internal benthic fluxes of bio-available ammonium (NH_4^+) exceed catchment inputs in both budgets. However, the estimated export of ammonium was less than the sum of catchment and internal sources, suggesting alternative internal fates not included in the budgets. Three possible fates include 1) uptake by algae, 2) retention of ammonium in bottom water trapped in the dredge hole, and 3) nitrification-denitrification. The latter process can account for all of the excess ammonium during the summer budget, but not during the winter-spring budget where a large residual remains.

Avoca Lagoon is a net sink of nitrate. Uptake of nitrate by sediments (most likely due to direct denitrification) accounts for all catchment inputs and is likely augmented by internally produced nitrate via nitrification.

Avoca Lagoon is a sink for dissolved and particulate phosphorus. Nitrogen:phosphorus ratios indicate that primary productivity in the lagoon is limited by phosphorus availability. As such, dissolved phosphorus is readily assimilated by algae resulting in very low dissolved P concentrations in the water column which limits P exports during entrance breakout. Phosphorus is mainly exported from the lagoon in particulate form due to the resuspension of bed sediments during the final stages of lagoon drainage.

The budgets highlight the relative importance of benthic fluxes in the transformation and attenuation of nutrients in Avoca Lagoon. Benthic fluxes have the potential to significantly influence water column nutrient concentrations as illustrated in Figure 35 which shows that benthic fluxes in the dredge hole can cause a 35 μg/L increase in ammonium concentrations per day. This increase is offset by other processes that consume or transform ammonium (e.g., nitrification), however, there appears to be a constant internal source of bioavailable nitrogen in the lagoon.

While not apparent in the budgets, benthic fluxes of bioavailable phosphorus were measured in the dredge hole sediments. These represent a significant source of phosphorus in the highly P-limited lagoon.

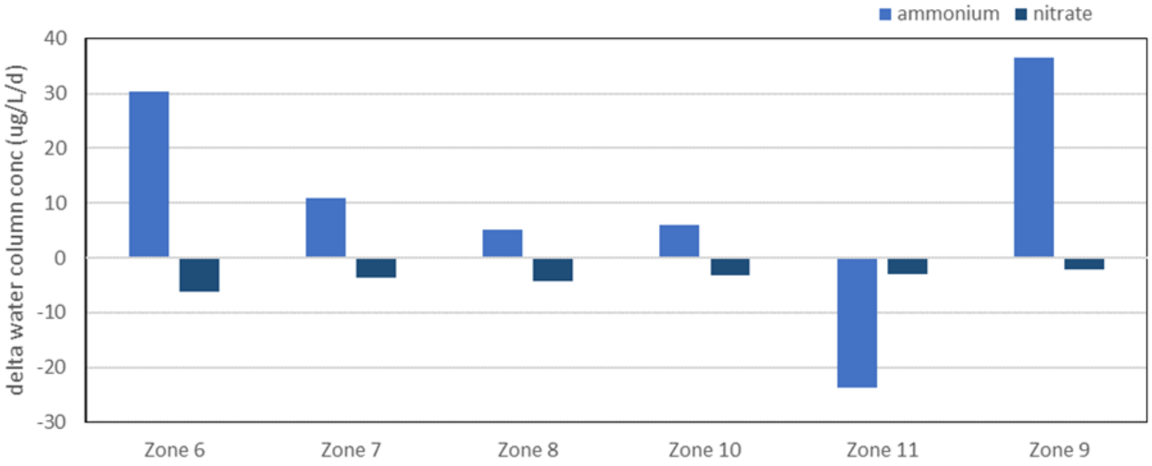


Figure 35. The potential influence of benthic fluxes on water column concentrations of ammonium and nitrate at Avoca Lagoon

4 Summary

This study investigated processes underpinning the poor water quality grades for Avoca Lagoon over the past decade. The study period was characterised by above average rainfall which resulted in the lagoon entrance opening eight times over the year.

The in-situ water quality buoy showed that Avoca Lagoon is prone to extended periods of stratification and hypoxia in the central dredge hole. Stratification usually develops due to the ingress of ocean water while the entrance is open, which sinks into the dredge hole. Once the entrance berm closes, stratification can last for months, resulting in severe hypoxia/anoxia in bottom waters (e.g., early 2022).

The poor water quality grades for chlorophyll indicate that the lagoon is experiencing moderate eutrophication due to elevated nutrient loading. This study has shown that primary productivity is likely to be strongly phosphorus limited and therefore management strategies should be directed at reducing catchment inputs of phosphorus. It is important to note that water quality in the different lagoon basins is subject to localised drivers. The current water quality grading system hides important detail about the health of different zones by conflating data and reporting grades for the whole lagoon

The nutrient budget indicated that the lagoon is a net sink of sediments including particulate nitrogen and phosphorus. This is consistent with the gradual infilling of the lagoon over Holocene epoch. Internal loads of ammonium from sediment fluxes results in a constant supply of bio-available nitrogen. This means that algae in the lagoon is poised to respond to any inputs of phosphorus.

The deep basin artificially created by the dredge hole results in the trapping and accumulation of fine sediments and organic matter. This has caused chronic stratification in the lagoon basin, characterised by hypoxia/anoxia and high ammonium concentrations in bottom waters. The enhanced recycling of nitrogen and phosphorus in dredge hole sediments represents a significant internal source of bio-available nutrients that contributes to lagoon eutrophication.

The assimilation of bio-available nutrients by benthic microalgae in well-lit sediments represents a significant sink and serves to ameliorate eutrophication. This process represents a valuable ecosystem service in NSW ICOLLs.

Groundwater seepage from fringing wetlands was shown to significantly influence the lagoon as it drains below 1m AHD following entrance opening. Groundwater has high concentrations of ammonium and dissolved organic N and P which cause a significant increase in lagoon concentrations following entrance opening.

Data from the smartbuoy showed no evidence of acidification due to acid runoff from acid sulfate soils during the study period. This is despite multiple entrance opening events and high rainfall which would be expected to promote conditions conducive to the seepage of groundwater from fringing wetlands.

The poor water quality grades for turbidity are driven by significantly higher turbidity in the southern basin of the lagoon. This results from a combination of high suspended solid concentrations in catchment runoff, the trapping of this material in the southern basin, and the subsequent resuspension by wind waves when lagoon water levels are low.

While not a focus of this study, enterococci counts in samples collected on two occasions during the study period indicated high counts in creeks draining to the northern basin of the lagoon. These preliminary results highlight a need to better understand pathogen sources and risks in Avoca Lagoon.

The current study was undertaken during an above average rainfall year and as such the results of the various experiments and sampling undertaken should be viewed as representative of those climatic conditions. It is likely that extended periods of drought during a succession of El Nino years will cause shifts in ecosystem processes.

5 Recommendations

Coupled with historic impacts, including dredging, catchment inputs appear to be a major driver for poor water quality within the lagoon; therefore, developing strategies to reduce catchment inputs, in particular phosphorus, is needed to improve the long-term health of the lagoon. In light of the long-term impacts caused by the deep basin, it is also recommended that investigations into the feasibility of filling the dredge hole are undertaken.

To improve understanding of the sources of catchment pollutants and to develop future lagoon models, it is recommended that further flow-weighted monitoring of creeks draining to Avoca Lagoon is undertaken, constraining catchment pollutant loads across all seasons and flow conditions. This work will also allow for the calibration of turbidity as a proxy for catchment pollutant concentrations (see point below).

It is recommended that waterway health be monitored and tracked by maintaining the current routine monitoring program. These continuous datasets provide an invaluable resource for understanding ecosystem function and health in response to climatic and landuse drivers within the lagoon. The routine monitoring program could be bolstered by:

1. including sediment processes in routine monitoring as a primary indicator of ecosystem health. Benthic processes are an important component of ICOLL ecosystem function and are sensitive indicators of catchment pressures.
2. including faecal pathogen indicators to augment the existing Beachwatch program and further understand pollution sources. Additional targeted sampling for genomic source tracking could identify primary sources of pollution.

Maintaining the deployment of the smartbuoy in Avoca Lagoon will continue to provide high-frequency multi-depth data that is valuable for tracking lagoon water quality dynamics (e.g. stratification) in response to catchment inputs and entrance opening events. The data is also useful for the development of ecosystem response models.

The continued development of an Avoca Lagoon ecosystem response model will also support assessing future management strategies and climate change impacts.

6 References

APHA (2012. *Standard methods for the examination of water and wastewater* (22 ed.). (E. W. Rice, R. B. Baird, A. D. Eaton, & L. S. Clesceri, Eds.) Washington, D.C., USA: American Water Works Association (AWWA) and Water Environment Federation (WEF).

Beachwatch (2023) *Beachwatch - Avoca Lagoon*. Retrieved from https://beachwatch.nsw.gov.au/siteDetails/dba60ca2-9e3e-49f7-8cb7-087e734ad7b9

Bureau of Meteorology (2023) *Climate Data Online*. Retrieved from https://reg.bom.gov.au/climate/data/

Cardno Lawson Treloar (2010) *Gosford Coastal Lagoons Estuary Processes Study.* prepared for Gosofrd City Council.

DPIE (2021) *Form and function of NSW intermittently closed and open lakes and lagoons.* State of NSW and Department of Planning, Industry and Environment.

DPIE (2023) *Estuary Report Cards.* Sydney: Department of Planning Industry and Environment.

Johnson, C. (2020). *Towards safer swimming – Terrigal region: Terrigal Bay, Terrigal Lagoon and Avoca Lagoon stormwater catchment audit.* Parramatta, NSW: NSW Department of Planning, Industry and Environment.

Maher, D.T et al. (2013) Groundwater-derived dissolved inorganic and organic carbon exports from a mangrove tidal creek: The missing mangrove carbon sink? Limnol. Oceanogr. 58, 475–488.

Maher, D.T. et al. (2015) Methane and carbon dioxide dynamics in a subtropical estuary over a diel cycle: Insights from automated in situ radioactive and stable isotope measurements. Mar. Chem. 168, 69-79.

Maher, D.T. et al. (2019) Hydrological Versus Biological Drivers of Nutrient and Carbon Dioxide Dynamics in a Coastal Lagoon. Estuaries and Coasts 42, 1015-1031.

Manly Hydraulics Laboratory (2023) Retrieved from https://mhl.nsw.gov.au/Station-212452

Nearmap (2024) *Nearmap*. Retrieved from https://apps.nearmap.com/maps/

OEH (2016) *Assessing estuary ecosystem health: Sampling, data analysis and reporting protocols.* NSW Office of Environment and Heritage.

Raven, J., & Falkowski, P. G. (1999) Oceanic sinks for atmospheric CO2. *Plant, Cell & Environment*. 22(6), 741-755

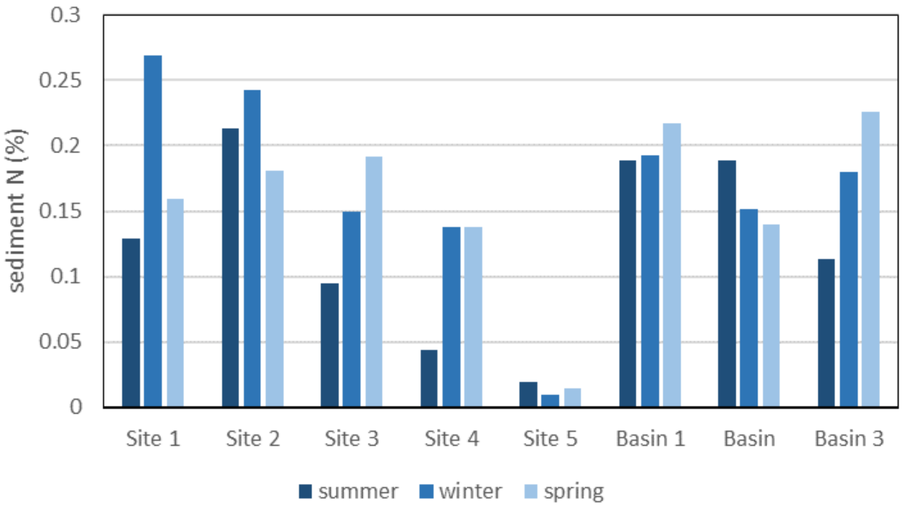
Rizzo, W. M., Lackey, G., & Christian, R. (1992) *Significance of euphotic, subtidal sediments to oxygen and nutrient cycling in a temperate estuary*. Marine ecology progress series. 86, 51-61

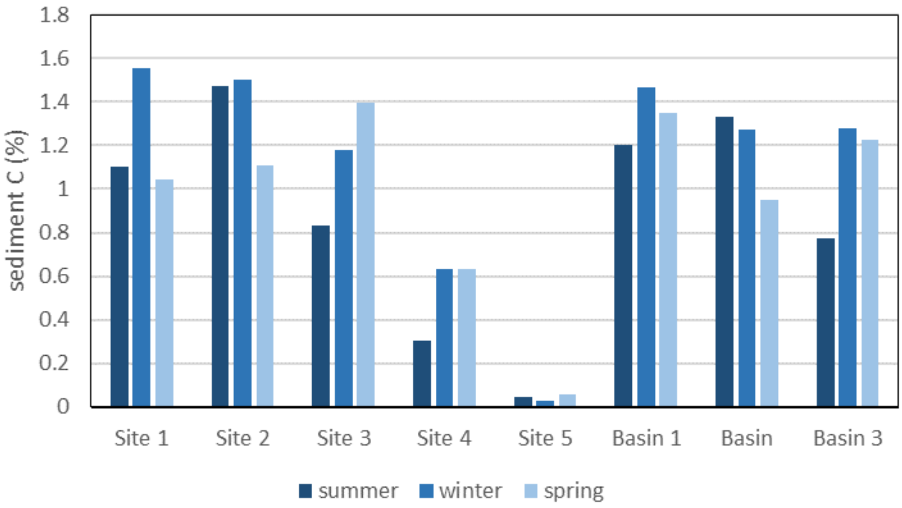
Roy, P.S. et al. (2001) *Structure and function of south-east Australian estuaries*. Estuarine, Coastal and Shelf Science. 53, 351-384

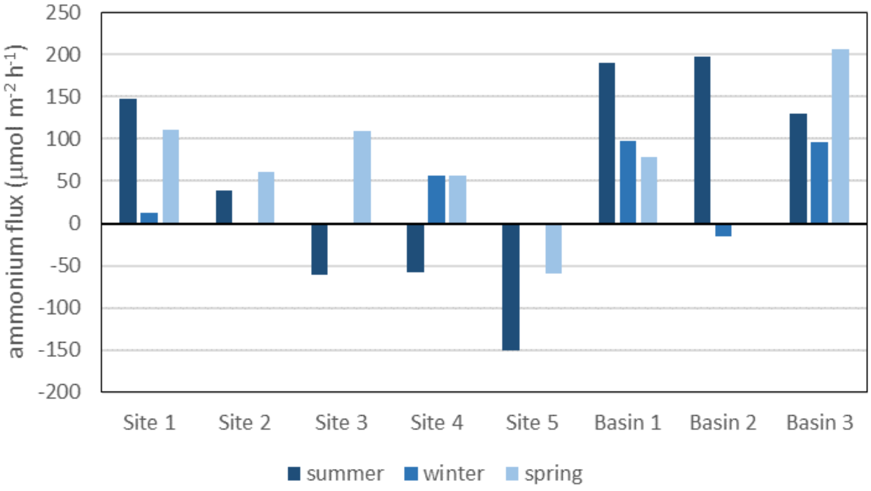
Sundbäck, K., & Jönsson, B. (1988) Microphytobenthic productivity and biomass in sublittoral sediments of a stratified bay, southeastern Kattegat. *Journal of Experimental Marine Biology and Ecology*. 550, 47-55

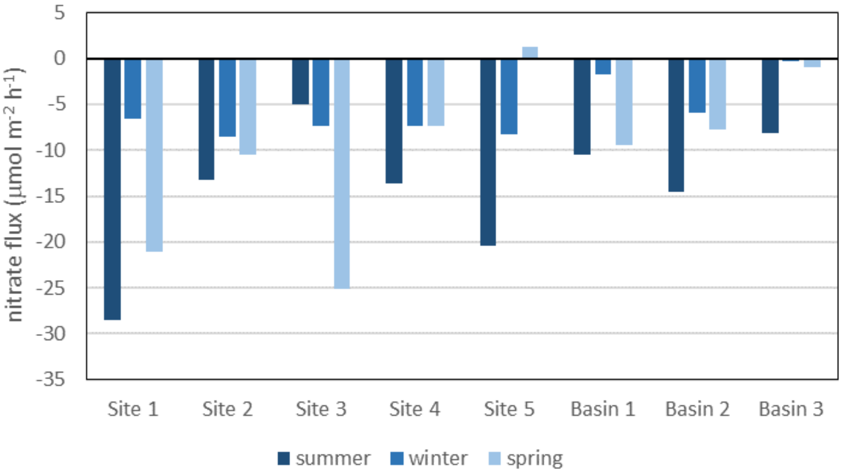
7 Appendix

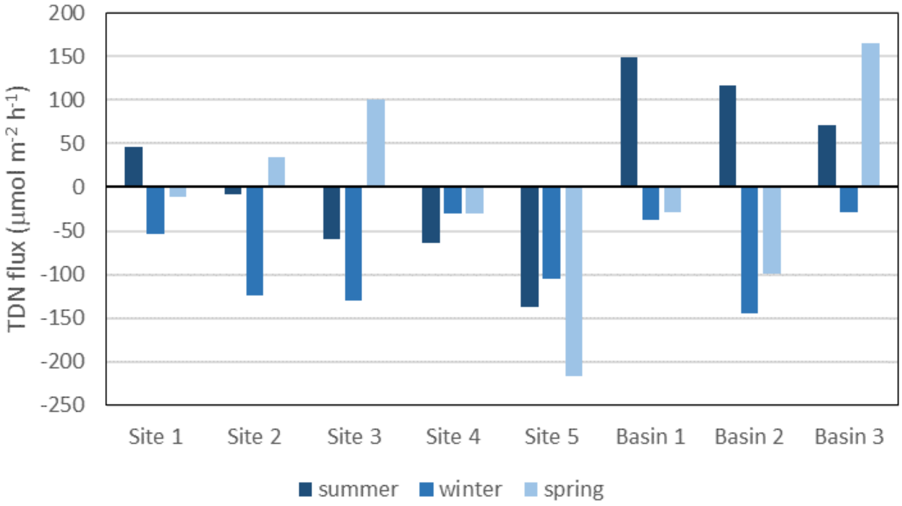
Temporal variation in summer, winter and spring of 2022 in sediment quality (% nitrogen, % carbon), benthic fluxes (ammonium flux, nitrate flux, TDN flux, DIP flux, TDP flux, light oxygen flux) respiration and productivity at sites 1-5 and the basin 1-3 sites are shown below. These data were averaged for presentation and discussion in the main body of the report in sections 3.6 and 3.7.

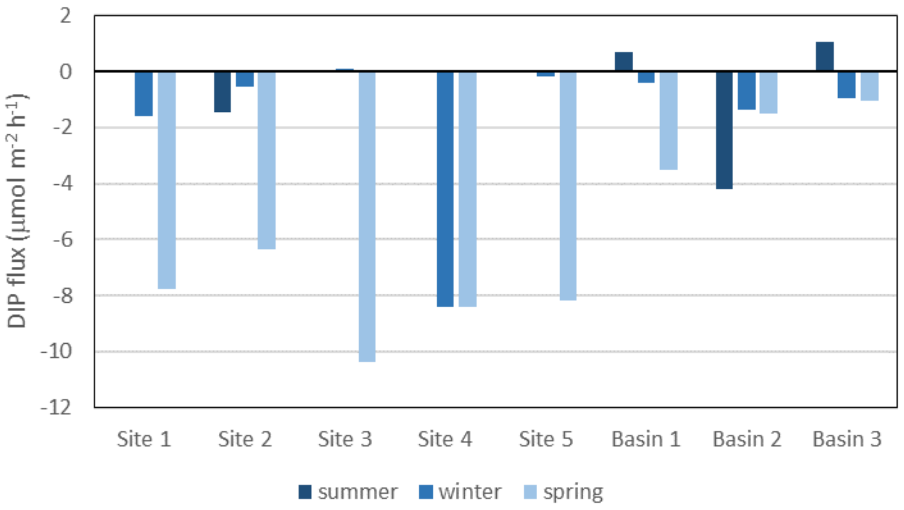


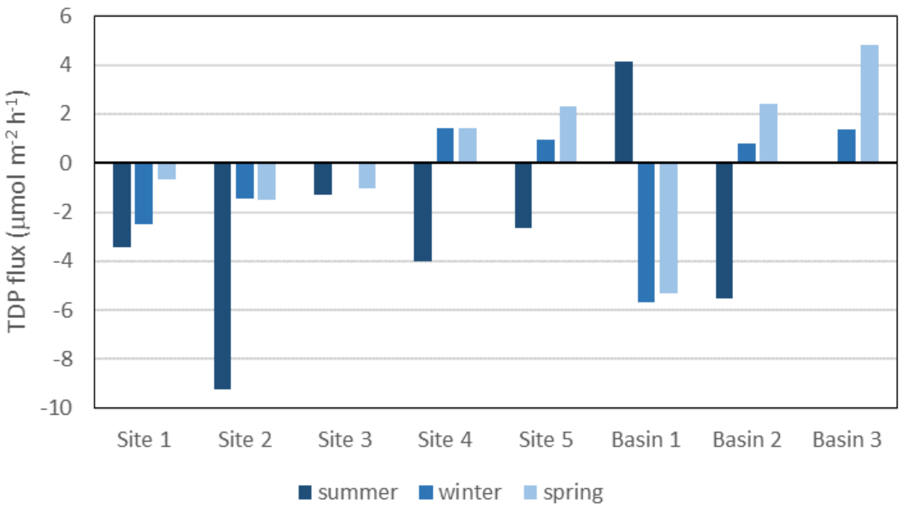


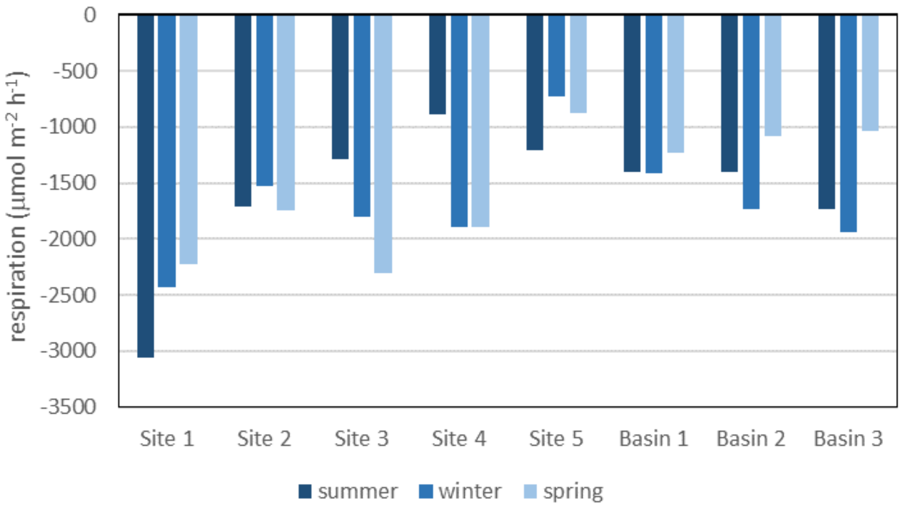

250
200
150
100
50
0
-50
-100
-150
-200
ammonium flux (µmol m-2 h-1)
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring

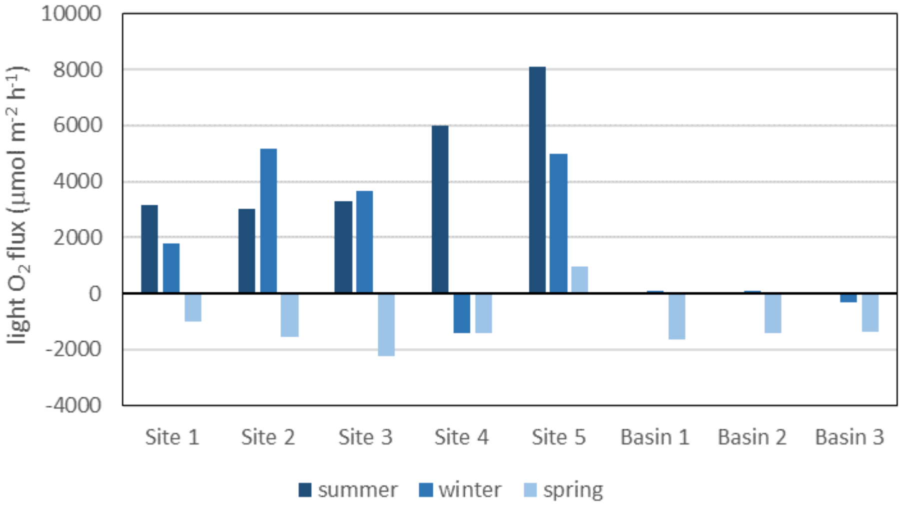

5
0
-5
-10
-15
-20
-25
-30
-35
nitrate flux (µmol m-2 h-1)
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring

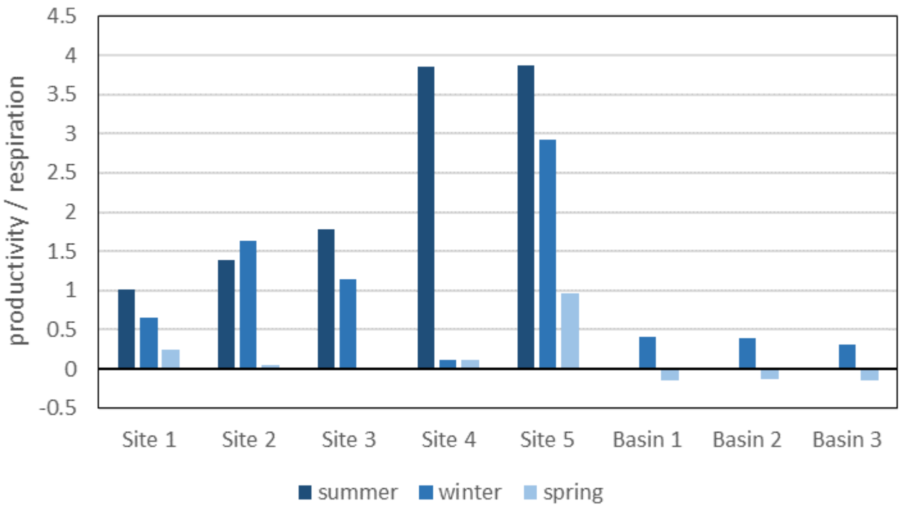

200
150
100
50
0
-50
-100
-150
-200
-250
TDN flux (µmol m-2 h-1)
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring

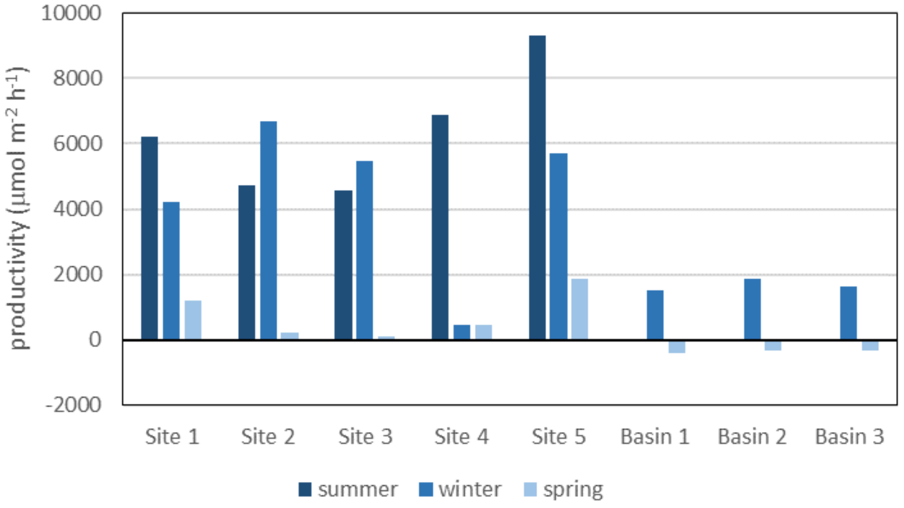

DIP flux (µmol m-2 h-1)
2
0
-2
-4
-6
-8
-10
-12
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring


TDP flux (µmol m-2 h-1)
6
4
2
0
-2
-4
-6
-8
-10
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring


respiration (µmol m-2 h-1)
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring


light O_2 flux (µmol m^{-2} h^{-1})
10000
8000
6000
4000
2000
0
-2000
-4000
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring


productivity / respiration
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring


productivity (µmol m^{-2} h^{-1})
10000
8000
6000
4000
2000
0
-2000
Site 1
Site 2
Site 3
Site 4
Site 5
Basin 1
Basin 2
Basin 3
summer
winter
spring