Transport for NSW

Beaches Link and Gore Hill Freeway Connection

Appendix Q

Marine water quality

Transport for NSW

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Technical working paper: Marine water quality

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Prepared for

Transport for NSW

Prepared by

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Executive summary

The Beaches Link and Gore Hill Freeway Connection project (the project) forms a core component of the broader Western Harbour Tunnel and Beaches Link program of works. The program of works would unlock substantial travel time savings and journey time reliability for public transport, freight, services and commuters travelling between the Northern Beaches region and strategic centres across Sydney.

Transport for NSW is seeking approval under Division 5.2, Part 5 of the *Environmental Planning and Assessment Act 1979* (EP&A Act) to construct and operate the project, which would comprise the following main components

- Twin tolled motorway tunnels connecting the Warringah Freeway at Cammeray and the Gore Hill Freeway at Artarmon to the Burnt Bridge Creek Deviation at Balgowlah and Wakehurst Parkway at Killarney Heights, and an upgrade of Wakehurst Parkway (the Beaches Link)
- An upgrade of the Wakehurst Parkway to two lanes in each direction between the tunnel portals at Killarney Heights and the intersection with Warringah Road at Frenchs Forest linking to the recently completed Northern Beaches Hospital road upgrade project
- A new access road between the Burnt Bridge Creek Deviation and Sydney Road at Balgowlah, improving future local network performance and providing direct connectivity to Beaches Link from key catchments along Sydney Road east and west
- Connection and integration works along the existing Gore Hill Freeway and surrounding roads at Artarmon (the Gore Hill Freeway Connection).

A major part of the works would be a crossing of Middle Harbour between Northbridge and Seaforth that would involve placing immersed tube tunnels in a dredged trench and on piles driven into the sea floor. The height of the structure would be about 9.2 metres above the bed of the harbour at the deepest point. The water depth above the immersed tube tunnels would vary between 16 metres and 22 metres, depending on the distance from the shore. Surface areas, including in Middle Harbour, would be required to support tunnelling activities and to construct the tunnel connections, tunnel portals and operational ancillary facilities.

This report has been prepared to support the environmental impact statement for the project and to address the environmental assessment requirements of the Secretary of the Department of Planning, Industry and Environment on marine water quality.

A review of existing and historical water quality information and field data collection were used to understand the water quality characteristics of Middle Harbour. The total suspended solids concentration is a key water quality characteristic that typically reflects the effects of project activities and particularly dredging works. In Middle Harbour, the natural level of total suspended solids is generally less than one milligram per litre during extended dry periods and peaks to about eight to 20 milligrams per litre, depending upon the rainfall intensity producing catchment runoff. Following isolated rainfall events, the total suspended solids generally decreases to the pre-event values within a few days to a week. During the wetter months, typically January to March, regular rainfall events lead to elevated background total suspended solids concentrations of about three to five milligrams per litre.

Appendix T (Technical working paper: Marine ecology) considered that marine biota are well adapted to the total suspended solids variability in Middle Harbour. Adopting the approach of McArthur et al. (2002), it was assumed that marine biota would likely become stressed when exposed to periods of reduced light that would occur when the total suspended solids exceeded the long term, 95th percentile concentration (the marine ecology tolerance limit). This premise formed the basis for assessing the potential effects of dredging on marine water quality and ecology.

The proposed 37 week program of dredging activities and projections of the dredge plume dispersion are described in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling). A range of marine water quality mitigation options were incorporated into the design of the dredging and construction program (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)). Predictions of the footprint of dredge related suspended sediment plumes were compared to the existing water's total suspended solids concentrations to assess the potential effects of the project dredging activities.

The marine ecology tolerance limit and the frequency of occurrence of the predicted excess suspended sediment concentrations were used to derive boundaries for a Zone of Moderate Impact and a Zone of Influence. The Zone of Influence was predicted to be confined to a distance of less than 500 metres from the dredging operation and would be focused in the deeper waters.

The dredging and construction activities would be likely to cause temporary spikes in the suspended sediment concentrations in the identified zones of moderate impact and influence but the rapid dispersion with Middle Harbour waters would not likely result in any significant water quality effects outside of these zones. Monitoring during the dredging activities will provide data to assess the efficacy of the mitigation measures and verify predicted effects from dredging.

Contaminants within the dredge area have the potential to be mobilised during dredging and construction activities. A backhoe dredge with a closed environmental bucket is proposed for removal of the top one metre layer of contaminated sediment. As a result, it would be unlikely for water quality to be substantially impacted by contaminants mobilised from dredging and construction activities.

Land based construction activities occurring immediately adjacent to marine water bodies may result in transport of sediment via air or runoff to receiving waterways. There is also potential for spills or leaks of fuels and/or oils from maintenance or re-fuelling of construction plant or equipment or vehicle incidents that could be eventually discharged to waterways. The potential for these to occur should be managed using best practice runoff and spill control systems.

The presence of the sill in Middle Harbour created by the immersed tube tunnels is likely to result in a relatively small increase in residence time of the near-bed waters (depths from -22 to -32 metres Australian height datum (AHD)) immediately upstream of the sill. The existing dynamic tidal and salt wedge/fjord-like mixing behaviour within this area suggests it is generally well flushed with periods of relatively low mixing and depletion of dissolved oxygen near the bed of the harbour. These periods are likely to last for only a few days and the subsequent vertical mixing by the tidal currents is likely to rapidly dilute any potential effects of this deep water on the mid-depth and surface waters. The sill created by the immersed tube tunnels will likely increase the rate of mud siltation upstream of the crossing by about three to four millimetres per decade. This rate is within the range of sedimentation rates within Middle Harbour and forms a negligible contribution to overall sedimentation.

The potential impacts of the anticipated changes in dissolved oxygen concentrations in deep water and sedimentation to the marine ecology of Middle Harbour are discussed further in Appendix T (Technical working paper: Marine ecology).

Glossary

Acronym	Definition
AHD	Australian height datum
ANZECC Guidelines	Guidelines for Fresh and Marine Water Quality
BoM	Bureau of Meteorology
Cardno	Cardno (NSW/ACT) Pty Ltd
Chlorophyll-*a*	A specific form of chlorophyll. Measured in water quality as a proxy for phytoplankton abundance
cm	Centimetre
CMA	Catchment Management Authority
Conductivity	A measurement of salinity
CTD	Conductivity, temperature, dissolved oxygen probe
Deltares	Water quality model software developer
DGSE	Daily global solar exposure
Dissolved oxygen (DO)	Measurement of oxygen content in water
DPI Fisheries	(former) NSW Department of Primary Industries (Fisheries), now Department of Planning, Industry and Environment (Regions, Industry, Agriculture and Resources)
DSWR	Downwards short wave solar radiation
e-folding time	the time required for a concentration to fall exponentially to a factor of 1/e (67 per cent)
EPBC Act	Australian Government *Environment Protection and Biodiversity Conservation Act 1999*
Fluoro metric chlorophyll-*a*	See 'Chlorophyll-*a*'
HAT	Highest astronomical tide
Hydro	SHERM high resolution hydrodynamics grid
Hydrodynamics	Water flows
K	Light extinction coefficient
km	Kilometres
L/s	Litres per second
m	Metres
mg/L	Milligrams per litre
mm	Millimetres
MNES	Matters of National Environmental Significance
NSW	New South Wales
NTU	Nephelometric turbidity unit
OCP	Organochlorine pesticides
PAH	Polycyclic aromatic hydrocarbon
PAR	Photosynthetically active radiation
Photic zone	Upper part of the water column where plants are able to carry out photosynthesis
PSU	Practical salinity unit
R^2	Coefficient of determination between total suspended solids and turbidity
SEPP	State Environmental Planning Policy
SHERM	Sydney Harbour Ecological Response Model
SSC	Suspended sediment concentrations

Acronym	Definition
Sydney Harbour	Refers to the broader catchment, of which Middle Harbour is a sub catchment
TBT	Tributyltin
TRH	Total recoverable hydrocarbons
TS	Temperature and salinity
TSS	Total suspended solids
Turbidity	Transparency of water, measured in NTU
WAQ	SHERM medium resolution water quality grid
WQBox	SHERM coarse resolution water quality grid
ZoHI	Zone of high impact
ZoI	Zone of influence
ZoMI	Zone of moderate impact

1 Introduction

This section provides an overview of the Beaches Link and Gore Hill Freeway Connection (the project), including its key features and location. It also outlines the Secretary's environmental assessment requirements addressed in this technical working paper.

1.1 Overview

The Greater Sydney Commission's *Greater Sydney Region Plan – A Metropolis of Three Cities* (Greater Sydney Commission, 2018) proposes a vision of three cities where most residents have convenient and easy access to jobs, education and health facilities and services. In addition to this plan, and to accommodate for Sydney's future growth the NSW Government is implementing the *Future Transport Strategy 2056* (Transport for NSW, 2018), that sets the 40 year vision, directions and outcomes framework for customer mobility in NSW. The Western Harbour Tunnel and Beaches Link program of works is proposed to provide additional road network capacity across Sydney Harbour and Middle Harbour and to improve transport connectivity with Sydney's Northern Beaches. The Western Harbour Tunnel and Beaches Link program of works include:

> The Western Harbour Tunnel and Warringah Freeway Upgrade project which comprises a new tolled motorway tunnel connection across Sydney Harbour, and an upgrade of the Warringah Freeway to integrate the new motorway infrastructure with the existing road network and to connect to the Beaches Link and Gore Hill Freeway Connection project

> The Beaches Link and Gore Hill Freeway Connection project which comprises a new tolled motorway tunnel connection across Middle Harbour from the Warringah Freeway and the Gore Hill Freeway to Balgowlah and Killarney Heights and including the surface upgrade of the Wakehurst Parkway from Seaforth to Frenchs Forest and upgrade and integration works to connect to the Gore Hill Freeway at Artarmon.

A combined delivery of the Western Harbour Tunnel and Beaches Link program of works would unlock a range of benefits for freight, public transport and private vehicle users. It would support faster travel times for journeys between the Northern Beaches and areas south, west and north-west of Sydney Harbour. Delivering the program of works would also improve the resilience of the motorway network, given that each project provides an alternative to heavily congested existing harbour crossings.

1.2 The project

Transport for NSW is seeking approval under Part 5, Division 5.2 of the Environmental Planning and Assessment Act 1979 to construct and operate the Beaches Link and Gore Hill Freeway Connection project, which would comprise two components:

> Twin tolled motorway tunnels connecting the Warringah Freeway at Cammeray and the Gore Hill Freeway at Artarmon to the Burnt Bridge Creek Deviation at Balgowlah and the Wakehurst Parkway at Killarney Heights, and an upgrade of the Wakehurst Parkway (the Beaches Link)

> Connection and integration works along the existing Gore Hill Freeway and surrounding roads at Artarmon (the Gore Hill Freeway Connection).

A detailed description of the project is provided in Chapter 5 (Project description) and Chapter 6 (Construction work) of the environmental impact statement.

The Gore Hill Freeway Connection component of the project is not relevant to this report and is therefore not discussed further.

1.3 Project location

The project would be located within the North Sydney, Willoughby, Mosman and Northern Beaches local government areas, connecting Cammeray in the south with Killarney Heights, Frenchs Forest and Balgowlah in the north.

Commencing at the Warringah Freeway at Cammeray, the mainline tunnels would pass under Naremburn and Northbridge, then cross Middle Harbour between Northbridge and Seaforth. The mainline tunnels would then split under Seaforth into two ramp tunnels and continue north to the Wakehurst Parkway at Killarney

Heights and north-east to Balgowlah, linking directly to the Burnt Bridge Creek Deviation to the south of the existing Kitchener Street bridge.

Surface works would also be carried out at the Gore Hill Freeway in Artarmon, Burnt Bridge Creek Deviation at Balgowlah and along the Wakehurst Parkway between Seaforth and Frenchs Forest to connect the project to the existing arterial and local road networks.

1.4 Key features

Key features of the Beaches Link component of the project are shown in Figure 1-1. The key components which are relevant to this report include:

- Twin mainline tunnels about 5.6 kilometres long and each accommodating three lanes of traffic in each direction, together with entry and exit ramp tunnels to connections at the surface. The crossing of Middle Harbour between Northbridge and Seaforth would involve three lane, twin immersed tube tunnels
- Twin two lane ramp tunnels:
  - Eastbound and westbound connections between the mainline tunnel under Seaforth and the surface at the Burnt Bridge Creek Deviation, Balgowlah (about 1.2 kilometres in length)
  - Northbound and southbound connections between the mainline tunnel under Seaforth and the surface at the Wakehurst Parkway, Killarney Heights (about 2.8 kilometres in length)
  - Eastbound and westbound connections between the mainline tunnel under Northbridge and the surface at the Gore Hill Freeway and Reserve Road, Artarmon (about 2.1 kilometres in length).
- Operational facilities, including a motorway control centre at the Gore Hill Freeway in Artarmon and tunnel support facilities at the Gore Hill Freeway in Artarmon and the Wakehurst Parkway in Frenchs Forest
- Other operational infrastructure including groundwater and tunnel drainage management and treatment systems, surface drainage, signage, tolling infrastructure, fire and life safety systems, roadside furniture, lighting, emergency evacuation and emergency smoke extraction infrastructure, Closed Circuit Television (CCTV) and other traffic management systems.

Subject to planning approval, construction of the project is planned to commence in early 2023, with completion of the main construction works planned for around the end of 2027. Construction works for the new and improved public open space and recreation facilities are planned to commence in 2023 and would be progressively staged to be fully completed in late 2028.

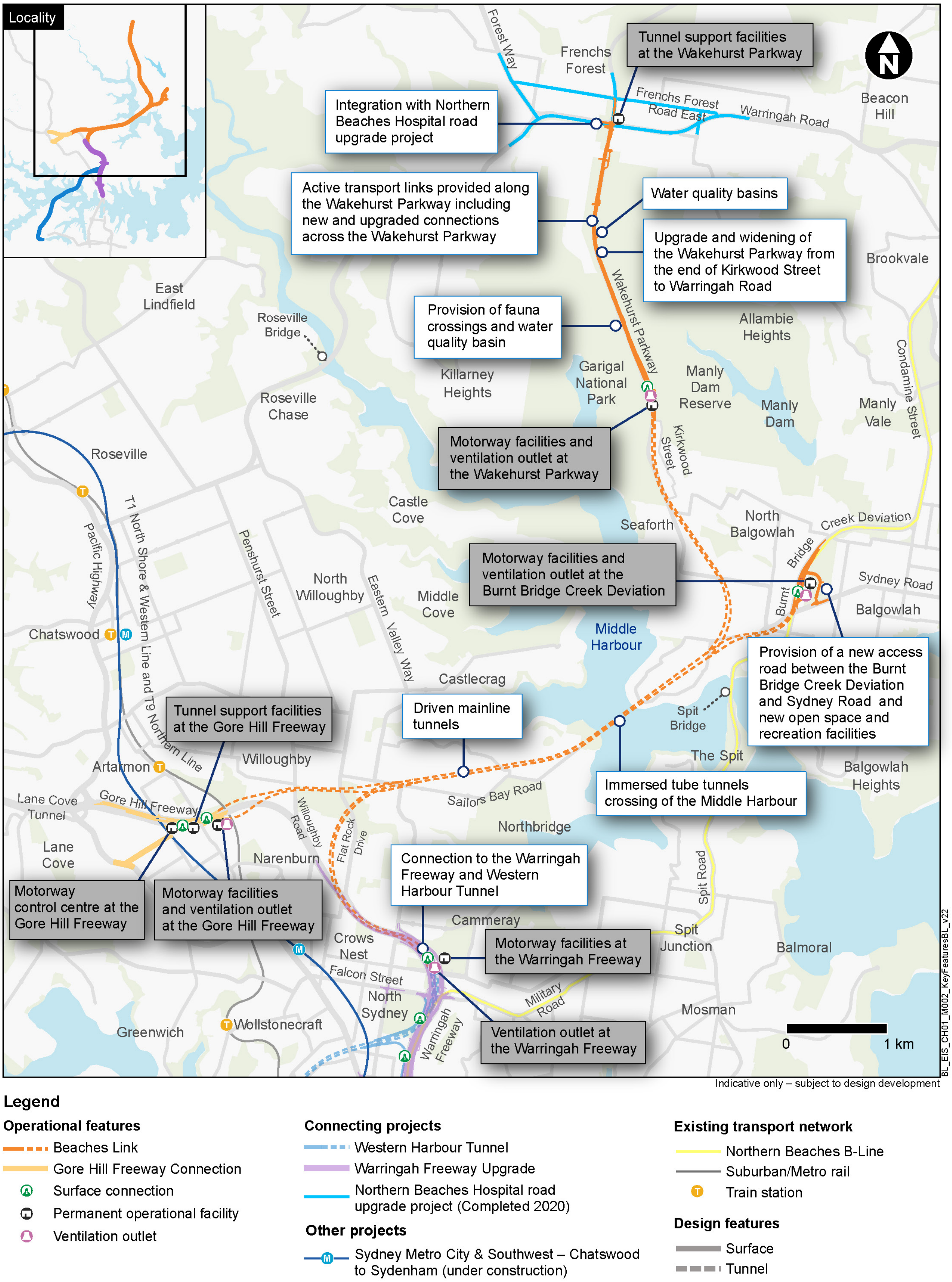


Figure 1-1 Key features of the Beaches Link component of the project

1.1.1 Immersed tube elements

The key feature of the Beaches Link component of the project relevant to this report is the crossing of Middle Harbour between Northbridge and Seaforth, which would be constructed as immersed tube tunnels.

The immersed tube tunnels would connect to the driven mainline tunnels in Middle Harbour offshore from Clive Park, Northbridge, and Seaforth Bluff, Seaforth.

The immersed tube tunnels would be installed as a series of pre-cast units. Due to the profile of the harbour bed, the units would sit both partially within in a trench closer to the shore and above the bed of the harbour towards the centre of the harbour crossing. The middle sections would be placed with the tops of the tunnel units being about 9.2 metres above the existing level of the bed of the harbour.

Given the very soft sediments at the bed of Middle Harbour, supporting piles would be required at discrete locations along the immersed tube crossing. A granular locking fill would be placed around the end sections (closer to the shore) of the immersed tube tunnels for stability and protection.

The water depth above the immersed tube tunnels would vary between 16 metres and 22 metres, depending on the distance from the shore.

The immersion of the tube tunnel elements would be performed by two immersion pontoons. Temporary anchors would be placed into the bed of the harbour prior to the immersion process to securely position the immersion pontoons and the tunnel elements.

Indicative cross sections of the immersed tube tunnel crossing of Middle Harbour are shown in Figure 1-2 (end sections) and Figure 1-3 (middle sections). An indicative long section of the immersed tube tunnels is shown in Figure 1-4.

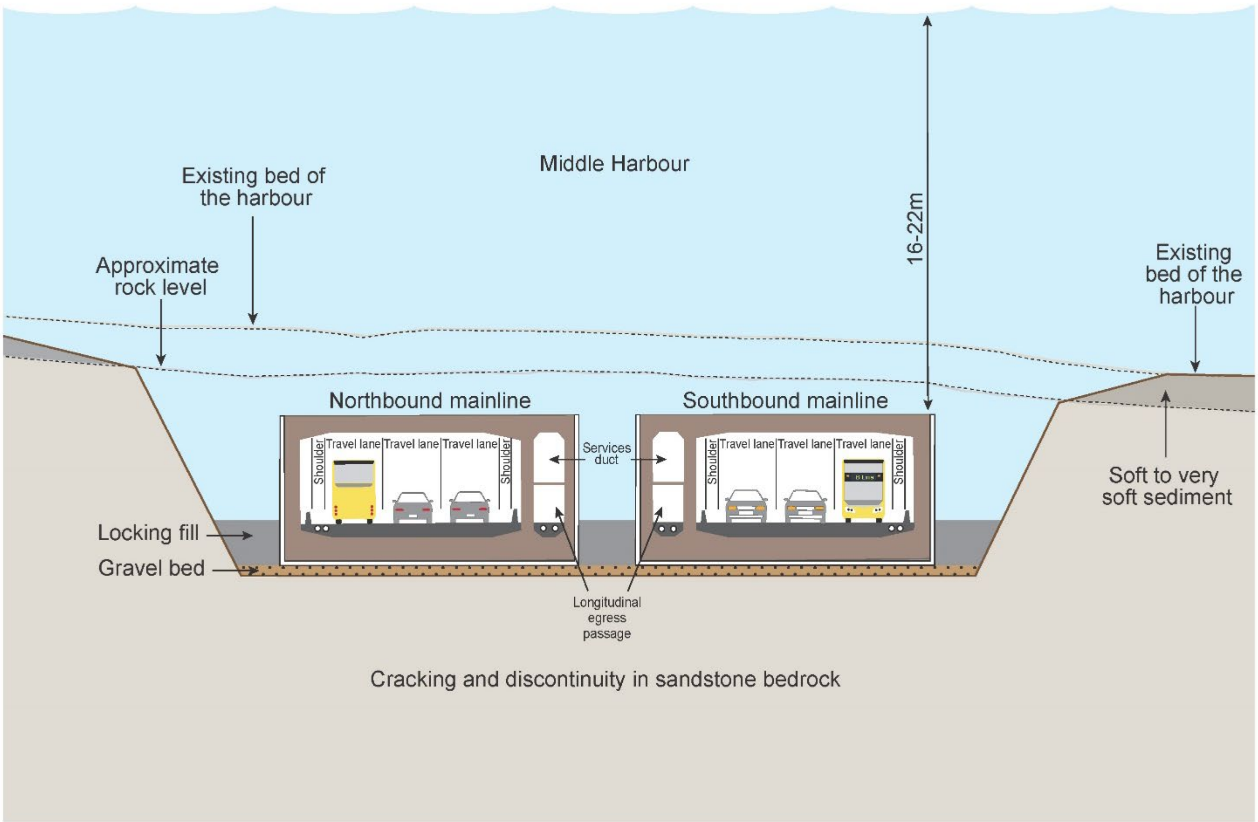


Figure 1-2 Indicative cross section of the end sections of immersed tube tunnels at Middle Harbour

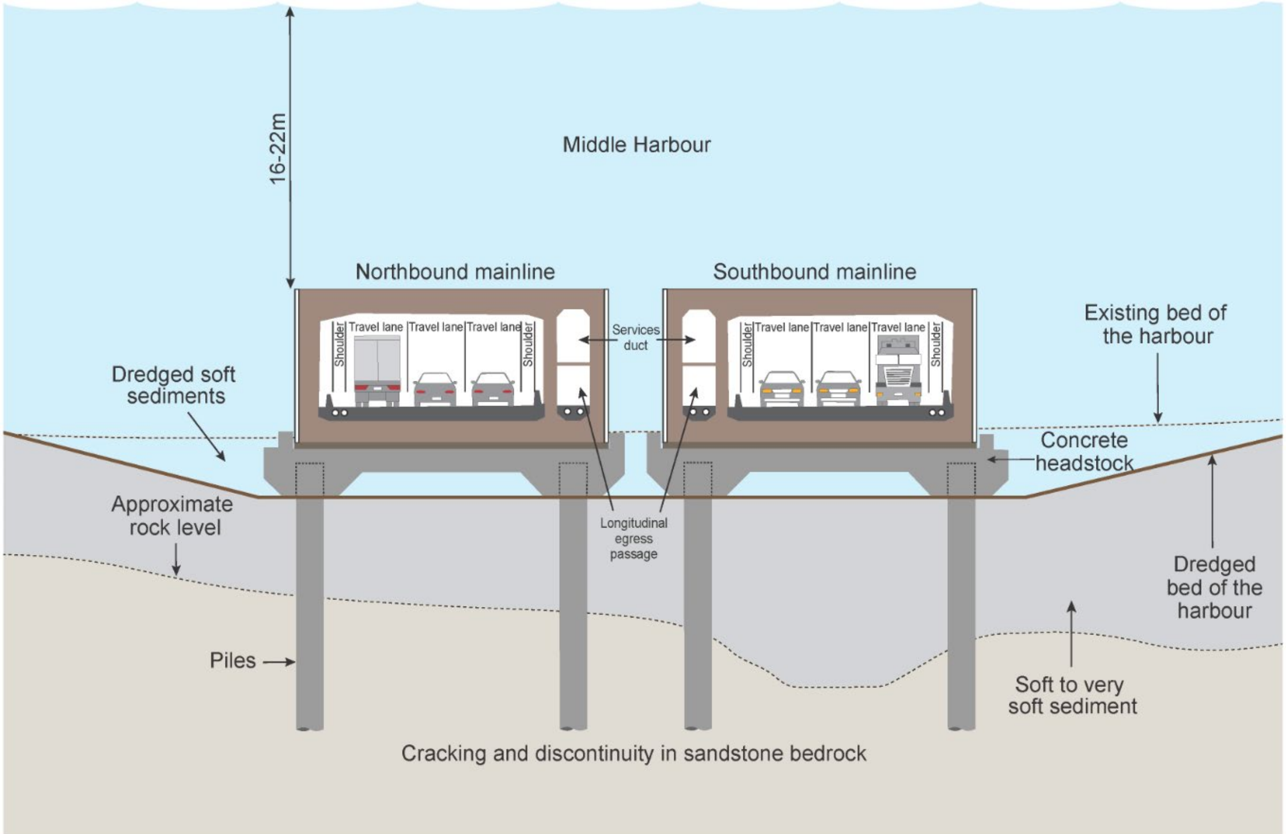


Figure 1-3 Indicative cross section of the middle section of immersed tube tunnels at Middle Harbour

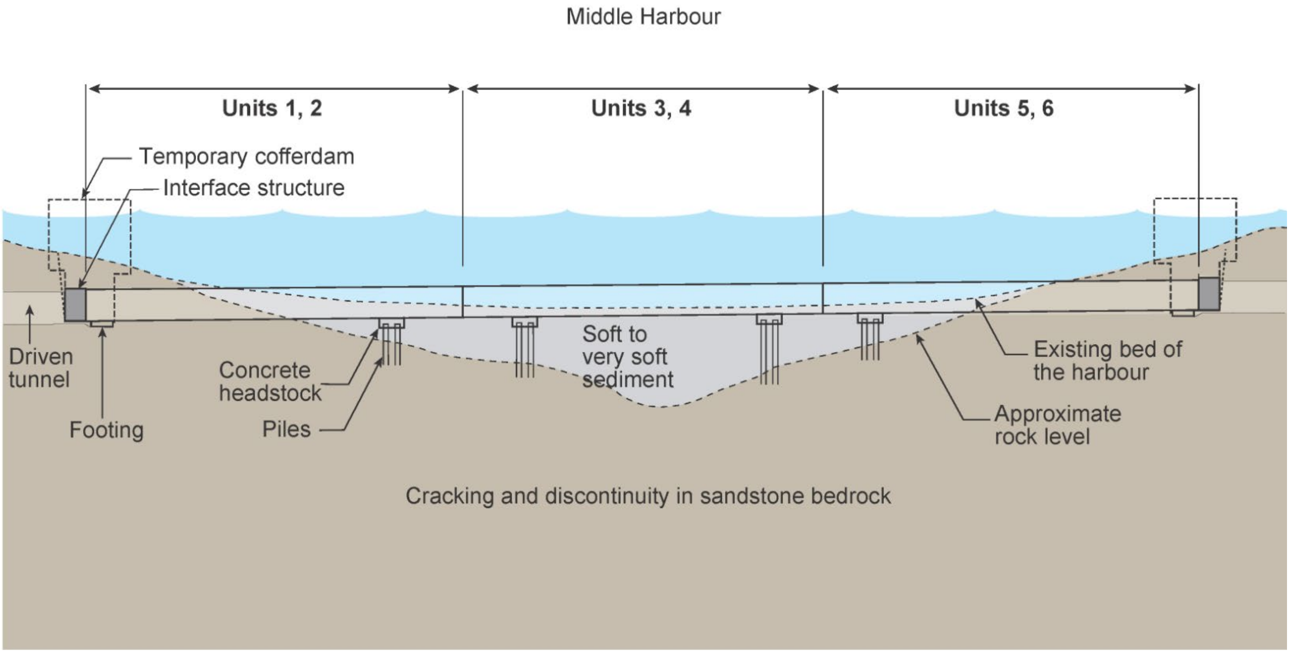


Figure 1-4 Indicative long section of the immersed tube tunnels at Middle Harbour

1.5 Key construction activities

The area required to construct the project is referred to as the construction footprint. The majority of the construction footprint would be located underground within the mainline and ramp tunnels. However, surface areas would also be required to support tunnelling activities and to construct the tunnel connections, tunnel portals, surface road upgrades and operational facilities.

Key construction activities would include:

- Early works and site establishment, with typical activities being property acquisition and condition surveys, utilities installation, protection, adjustments and relocations, installation of site fencing, environmental controls (including noise attenuation and erosion and sediment control), traffic management controls, vegetation clearing, earthworks, demolition of structures, building construction support sites including acoustic sheds and associated access decline acoustic enclosures (where required), construction of minor access roads and the provision of property access, temporary relocation of pedestrian and cycle paths and bus stops, temporary relocation of swing moorings and/or provision of alternative facilities (mooring or marina berth) within Middle Harbour
- Construction of the Beaches Link, with typical activities being excavation of tunnel construction access declines, construction of driven tunnels, cut and cover and trough structures, construction of surface upgrade works, construction of cofferdams, dredging and immersed tube tunnel piled support activities in preparation for the installation of immersed tube tunnels, casting and installation of immersed tube tunnels and civil finishing and tunnel fitout
- Construction of operational facilities comprising:
  - A motorway control centre at the Gore Hill Freeway in Artarmon
  - Tunnel support facilities at the Gore Hill Freeway in Artarmon and at the Wakehurst Parkway in Frenchs Forest
  - Motorway facilities and ventilation outlets at the Warringah Freeway in Cammeray (fitout only of the Beaches Link ventilation outlet at the Warringah Freeway (being constructed by the Western Harbour Tunnel and Warringah Freeway Upgrade project), the Gore Hill Freeway in Artarmon, the Burnt Bridge Creek Deviation in Balgowlah and the Wakehurst Parkway in Killarney Heights
  - A wastewater treatment plant at the Gore Hill Freeway in Artarmon
  - Installation of motorway tolling infrastructure
- Upgrade and integration works at Balgowlah and along the Wakehurst Parkway with typical activities being earthworks, bridgeworks, construction of retaining walls, stormwater drainage, pavement works and linemarking and the installation of roadside furniture, lighting, signage and noise barriers
- Testing of plant and equipment and commissioning of the project, backfill of access declines, removal of construction support sites, landscaping and rehabilitation of disturbed areas and removal of environmental and traffic controls.

Temporary construction support sites would be required as part of the project (refer to Figure 1-5) and would include tunnelling and tunnel support sites, civil surface sites, cofferdams, mooring sites, wharf and berthing facilities, laydown areas, parking and workforce amenities.

Only three construction support sites are relevant to this report. These are:

- Middle Harbour south cofferdam (BL7)
- Middle Harbour north cofferdam (BL8)
- Spit West Reserve (BL9).

A detailed description of construction works for the project is provided in Chapter 6 (Construction work) of the environmental impact statement.

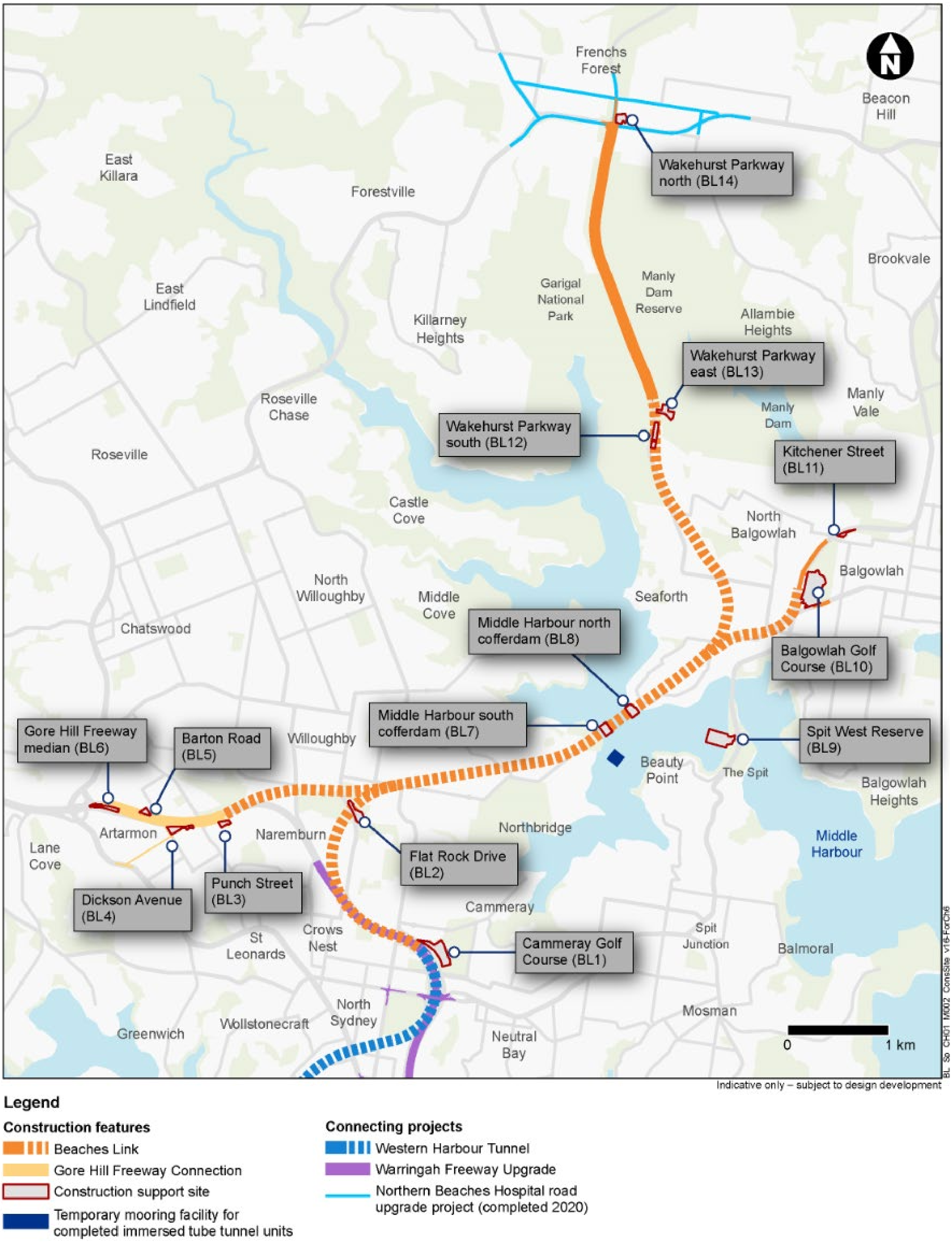


Figure 1-5 Overview of the construction support sites

1.6 Purpose of this report

This report has been prepared to support the environmental impact statement for the project and to address the environmental assessment requirements of the Secretary of the NSW Department of Planning, Industry and Environment.

The purpose of this report is to assess the potential impacts of the project during construction and operation on the water quality of Middle Harbour.

1.7 Secretary's environmental assessment requirements

The Secretary's environmental assessment requirements relating to marine water quality, and where these requirements are addressed in this report, are outlined in Table 1-1.

Table 1-1 Secretary's environmental assessment requirements – Marine water quality

Secretary's environmental assessment requirements	Where addressed
Water Quality (Key Issue no.10)	
10.1 (b) State the ambient NSW Water Quality Objectives (NSW WQO) (as endorsed by the NSW Government [see www.environment.nsw.gov.au/ieo/index.htm]) and environmental values for the receiving waters (including groundwater where appropriate) relevant to the project, including the indicators and associated trigger values or criteria for the identified environmental values in accordance with the ANZECC (2000) Guidelines for Fresh and Marine Water Quality and/or local objectives, criteria or targets endorsed by the NSW Government; 10.1 (c) Identify and estimate the quality and quantity of all pollutants that may be introduced into the water cycle by source and discharge point and describe the nature and degree of impact that any discharge(s) may have on the receiving environment, including consideration of all pollutants that pose a risk of non-trivial harm to human health and the environment; 10.1 (f) Demonstrate how construction and operation of the project (including mitigating effects of proposed stormwater and wastewater management) will, to the extent that the project can influence, ensure that: ▪ where the NSW WQOs for receiving waters are currently being met they will continue to be protected; and ▪ where the NSW WQOs are not currently being met, activities will work toward their achievement over time. 10.1 (g) justify, if required, why the WQOs cannot be maintained or achieved over time; 10.1 (k) Identify how the development meets the objectives of the *Coastal Management Act 2016* and management objectives of relevant Coastal Management Areas defined under the *Coastal Management Act 2016*. 10.1 (l) Demonstrate consistency with any relevant certified Coastal Management program (or Coastal Zone Management Plan).	This report assesses impacts to all marine water quality values related to the project in accordance with the NSW WQO, *ANZECC Water Quality Guidelines* (ANZECC/ARMCANZ, 2000) and *NSW Water Quality and River Flow Objectives* (DEC, 2006) and provides supporting information for the marine ecology impact assessment. The impacts of the construction and operation of the project on marine water quality are outlined in Section 5.1and Section 5.2. For surface water quality impacts refer to Section 5 and 6 of Appendix O (Technical working paper: Surface water quality and hydrology). Existing groundwater quality is described in Section 5.5 of Appendix N (Technical working paper: Groundwater). Mitigation measures are outlined in Section 6. The impacts of the sill created by the crossing on marine water quality are outlined in Sections 2.6, 3.5, 3.6, 4.2 and 5.2 and Annexures B and C. The Greater Sydney Harbour coastal management program objectives, which are consistent with the CM Act, are assessed for their relevance and consistency in Section 1.9.2.
Biodiversity (Key Issue no.6)	
6. 10 Identify and assess the impact of tidal flushing on the crossing of Middle Harbour. This assessment should also include details of any potential sediment accumulation and the impact this may have on marine populations that dwell on the harbour floor.	For marine ecology impacts refer to Appendix T (Technical working paper: Marine ecology).

1.8 Avoid and minimise

Under the *Biodiversity Guidelines: Protecting and managing biodiversity on RTA projects* (Roads and Traffic Authority (RTA), 2011) the management of biodiversity should aim to:

1. Avoid and minimise impacts first
2. Mitigate impacts where avoidance is not possible
3. Offset where residual impacts cannot be avoided.

The *Policy and Guidelines for Fish Habitat Conservation and Management* (NSW Department of Primary Industries (DPI), 2013) requires that proponents should, as a first priority, aim to avoid impacts upon key fish habitat as a general principle. Where avoidance is impossible or impractical, proponents should then aim to minimise impacts. Any remaining impacts should then be offset with compensatory works. NSW Department of Planning, Industry and Environment (Regions, Industry, Agriculture and Resources) assesses activity and development proposals in relation to general policies and with consideration for the 'sensitivity' of the affected fish habitat (DPI, 2013).

The Secretary's environmental assessment requirements issued for the project specifically identified the following as a key issue and desired performance outcome:

"Key issue no. 6 Biodiversity - The project design considers all feasible measures to avoid and minimise impacts on terrestrial and aquatic biodiversity."

The project has been designed to avoid and minimise potential impacts to marine water quality and marine ecology. The construction footprint has been reduced as far as practicable to avoid areas of marine vegetation and habitat. Standard environmental management measures should be implemented at construction sites to minimise potential impacts on marine water quality and its flow on impacts on marine ecology. These management measures should include:

> Treatment of tunnel wastewater via a treatment plant prior to discharge from construction sites to avoid adverse impacts to water quality in the harbour

> Installation of 10 to 12 metre deep-draft silt curtains around the dredge works during dredging

> Use of a backhoe dredge with a closed environmental bucket operated through a silt curtain to dredge the top layer of marine sediment

> Installation of additional shallow silt curtains along the adjacent foreshore areas for added protection of sensitive nearshore areas

> Construction staging

> Management of contaminated sediments and acid sulfate soils.

Further detailed information in relation to the description of the project along with the parameters of associated construction activities (and how they are to be managed) are presented in Chapter 5 (Project description) and Chapter 6 (Construction work) of the environmental impact statement and would be refined during design development to reduce further the area of impact on marine vegetation and habitat.

The secondary impacts of marine water quality to marine ecology as a result of the project are discussed in Appendix T (Technical working paper: Marine ecology).

1.9 Legislative context

Legislation and planning policies relevant to the protection of marine water quality in this report are provided below. These statutory instruments provide conditions, matters for consideration, guidance notes and requirements to seek authorisation (licences and approvals) to carry out various actions and activities. The list of NSW and Australian Government legislation and guidelines with relevance to this assessment are:

> NSW *Environmental Planning and Assessment Act 1979* (EP&A Act)

> NSW *Coastal Management Act 2016* (CM Act)

> Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)

> *Australian and New Zealand guidelines for fresh and marine water quality* (Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), 2000)

> *NSW Water Quality and River Flow Objectives (*https://www.environment.nsw.gov.au/ieo/*)*

- *National Health and Medical Research Council: Guidelines for Managing Risks in Recreational Water* (NHMRC, 2008)
- *Sydney Harbour Water Quality Improvement Plan* (Greater Sydney Local Land Services, 2015).

1.9.1 Environmental Planning and Assessment Act 1979

All projects assessed as State significant infrastructure under Part 5, Division 5.2 of the EP&A Act require an environmental impact statement to address the Secretary's environmental assessment requirements (see Section 1.7).

According to the Secretary's environmental assessment requirements, the environmental impact statement must assess marine water quality impacts.

1.9.2 Coastal Management Act 2016

The previous *Coastal Protection Act 1979* was implemented through a series of coastal zone management plans. However, coastal zone management plans have been superseded by the development of coastal management programs in four areas across NSW as part of the coastal management legislation reform gazetted in the CM Act. The four areas are defined in the new CM Act as part of the *State Environmental Planning Policy (Coastal Management) 2018* (Coastal Management SEPP). Management objectives are listed in the CM Act for each of the four areas. The Coastal Management SEPP integrates and improves coastal-related SEPPs and ensures that future coastal development is appropriate and sensitive to the coastal environment, and that public access to beaches and foreshore areas is maintained. The Coastal Management SEPP is the single land use planning policy for coastal development, bringing together and modernising provisions from SEPP 14 – Coastal Wetlands, SEPP 26 – Littoral Rainforest and SEPP 71 – Coastal Protection.

The study area traverses through the North Sydney, Mosman, Willoughby City and Northern Beaches council areas. A Clontarf/Bantry Bay Estuary Management Plan (Manly Council, 2008) was endorsed in 2008 which addressed the portion of Middle Harbour estuary and foreshore on the boundary of the former Manly Council local government area (now Northern Beaches Council). However, NSW Local Land Services completed the Greater Sydney Harbour Estuary Coastal Management Program Scoping Study (BMT WBM Aither, 2018) in 2018 to facilitate the development of the coastal management program for Greater Sydney Harbour. This program would soon supersede the Clontarf/Bantry Bay Estuary Management Plan (Manly Council, 2008) and provide more coverage over the study area. A vision and objectives were presented in this report that are consistent with the CM Act for inclusion in the development of the Greater Sydney Harbour Coastal Management Program. The vision and objectives of the program, relevance to marine water quality and references to applicable parts of this and related parts of the environmental impact statement are outlined in Table 1-2.

Table 1-2 Greater Sydney Harbour coastal management objectives

Coastal management objectives	Relevance to marine water quality	Consideration
To protect and enhance natural processes and environmental values of the Greater Sydney Harbour coastal zone.	✓	Section 4 (this report) and Appendix T (Technical working paper: Marine ecology) with respect to the protection of environmental values of the estuary.
To support the social and cultural values of the Greater Sydney Harbour and maintain public access, amenity, use and safety.	✓	Section 4 (this report) with respect to the maintenance of the estuary as a public amenity and for public use and safety.
To acknowledge Aboriginal peoples' spiritual, social, customary and economic connection with and use of the Greater Sydney Harbour coastal zone.	-	Not applicable.
To recognise the Greater Sydney Harbour coastal environment is a vital economic zone, the maritime gateway to Australia's largest city.	-	Not applicable.
To facilitate ecologically sustainable development in the Greater Sydney Harbour coastal zone and promote strategic, coordinated and sustainable land use planning decision-making.	-	Not applicable.

Coastal management objectives	Relevance to marine water quality	Consideration
To mitigate current and future risks from coastal hazards, taking into account the effects of climate change, including impacts from extreme storm events.	-	Not applicable.
To recognise that the local and regional scale coastal processes and shoreline dynamics effect on Sydney Harbour's beaches and estuary foreshores.	-	Not applicable.
To promote integrated and co-ordinated coastal planning, management and reporting that benefits from, and guides implementation of, the Greater Sydney Region Plan and coastal zone District Plans.	-	Not applicable.
To facilitate co-ordination of the policies and activities of government and public authorities relating to the Greater Sydney Harbour coastal zone and to facilitate the proper integration of their management activities across all tiers of government.	-	Not applicable.
To support public participation in coastal management and planning in Greater Sydney Harbour and greater public awareness, education and understanding of coastal processes and management actions.	-	Not applicable.
To support the objects of the *Marine Estate Management Act 2014*.	-	Not applicable.

1.9.3 Environment Protection and Biodiversity Conservation Act 1999

The EPBC Act protects nationally and internationally important flora, fauna, ecological communities and heritage places, which are defined in the EPBC Act as Matters of National Environmental Significance (MNES). MNES relevant to marine biodiversity are:

> Wetlands of international importance
> Nationally listed threatened species and ecological communities
> Migratory species
> Commonwealth marine areas.

The significance of impacts on MNES is determined in accordance with the *Significant Impact Guidelines 1.1 – Matters of National Environmental Significance* (Department of the Environment, 2013).

Where an action is likely to have a significant impact on a MNES, the action is referred to the Australian Minister for the Environment. The referral process involves a decision on whether or not the action is a 'controlled action'. When an action is declared a controlled action, approval from the Australian Minister for the Environment is required.

1.9.4 Australian and New Zealand guidelines for Fresh and Marine Water Quality

The Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ, 2000) provide guidelines for water quality. The guidelines have been updated to incorporate new science and knowledge developed over the past 18 years (ANZG, 2018). Together they form part of the National Water Quality Management Strategy and list a range of environmental values assigned to water bodies classified according to their climate zone, proximity to population centres and uses as well as other common identifiers. These objectives and guidelines provide benchmarks for assessment of the existing water quality and are dependent on the environmental values assigned to the waterway.

The ANZG (2018) and ANZECC/ARMCANZ (2000) water quality guidelines recommend development of a scientifically rigorous understanding of local water quality variability to form the basis for the assessment of potential impacts of proposed developments. Where local data on the broad suite of water quality parameters is not available, the ANZECC/ARMCANZ (2000) guidelines provide generic water quality criteria (scientifically based benchmark values) for a wide range of parameters. The ANZECC/ARMCANZ (2000) guidelines state that 'the Guidelines are not intended to be used as mandatory standards because there is significant uncertainty associated with the derivation and application of water quality guidelines'. However, the guidelines provide a useful basis for assessing risks to aquatic ecosystem health.

The ANZG (2018) and ANZECC/ARMCANZ (2000) guidelines provide default trigger values for physical and chemical stressors, and toxicants for rivers, estuaries and lakes in different regions across Australia. Both guidelines continue to be applied for this assessment as the default trigger values for aquatic ecosystems for the relevant geographic region 'Southeast Coast' have not yet been completely updated. These default trigger values are proposed to be applied in the absence of a suitable reference site for water quality trigger values.

ANZECC/ARMCANZ (2000) indicates that the guidelines have not been designed for direct application to discharge criteria. Nonetheless, adopting the relevant triggers values as discharge criteria would be protective of the desired environmental values of the receiving waters.

When designing construction wastewater treatment plants, it is proposed to adopt the ANZECC/ARMCANZ (2000) default trigger values for physical and chemical stressors for estuarine and lowland river ecosystems and the ANZG (2018) 90 per cent species protection levels for toxicants. For toxicants known to bioaccumulate, the ANZG (2018) 95 per cent species protection level would be adopted. As construction wastewater treatment plants would discharge into moderately to highly disturbed waterways with significant tidal exchange that would promote dilution and mixing, adopting the ANZG (2018) 90 per cent species protection levels would be unlikely to result in ecological impacts to downstream water quality.

The operational wastewater treatment plant at Gore Hill Freeway would be designed to meet the guideline values for the relevant physical and chemical stressors set out in ANZECC/ARMCANZ (2000), the ANZG (2018) 95 per cent species protection levels for toxicants, and the ANZG (2018) 99 per cent species protection levels for toxicants known to bioaccumulate.

1.9.5 NSW Water Quality and River Flow Objectives

The NSW Water Quality and River Flow Objectives (DEC, 2006) are consistent with the agreed national framework of the ANZECC Water Quality Guidelines (ANZECC/ARMCANZ, 2000) and its recent update, ANZG (2018). The NSW objectives are 'primarily aimed at maintaining and improving water quality, for the purposes of supporting aquatic ecosystems, recreation and where applicable, water supply, and the production of aquatic foods suitable for consumption and aquaculture activities' (DEC, 2006).

The Water Quality Objectives and nominated environmental values relevant to the project include:

> Protection of aquatic ecosystems – Ecological condition of waterways and their riparian zone (Lower and Upper Estuary)

> Protection of visual amenity - Aesthetic qualities of waters (Lower and Upper Estuary)

> Protection of primary contact recreation – Water quality for activities, such as swimming (Lower and Upper Estuary)

> Protection of secondary contact recreation - Water quality suitable for activities, such as boating and wading (Lower and Upper Estuary).

The protection of aquatic foods (cooked) has also been identified for the Lower Estuary as a long term objective of the community. However, from 2006, Sydney Harbour has been closed to commercial fishing as a precautionary measure due to elevated levels of dioxins in some fish and seafood. Recreational fishing is still allowed but recreational fishers are recommended to follow dietary advice from the Ministry of Health on the consumption of seafood.

The relevant NSW river flow objectives (DEC, 2006) and their application to the project are presented in Table 1-3.

Table 1-3 River flow objectives

River flow objective	Applicable waterway	Consideration
Maintain wetland and floodplain inundation	Upper and Lower Estuary	Refer to Appendix R (Technical working paper: Flooding)
Manage groundwater for ecosystems	Upper Estuary	Refer to Appendix N (Technical working paper: Groundwater)
Minimise effects of weirs and other structures	Upper and Lower Estuary	Not applicable. No weirs or fish barriers are proposed as part of the project.
Maintain or rehabilitate estuarine processes and habitats	Upper and Lower Estuary	Refer to Appendix T (Technical working paper: Marine ecology)

1.9.6 Guidelines for Managing Risks in Recreational Water

The *Guidelines for Managing Risks in Recreational Water* (NHMRC, 2008) aim to protect the health of humans from threats posed by the recreational use of coastal, estuarine and fresh waters. The guidelines have been considered as part of the assessment of the project to understand the current recreational water quality and threat to public health of waterways that have the potential to be impacted by runoff during the construction and operation of the project.

1.9.7 Sydney Harbour Water Quality Improvement Plan

The *Sydney Harbour Water Quality Improvement Plan* (Greater Sydney Local Land Services, 2015) was developed by Greater Sydney Local Land Services, NSW Office of Environment and Heritage (now the Department of Planning, Industry and Environment (Environment, Energy and Science)) and local government in collaboration with a range of stakeholders. This plan provides a coordinated management framework for the local councils, state government agencies and federal government agencies that have a stake in improving the future health of Sydney Harbour and its catchments. This plan applies to the majority of the study area which ultimately drains to Sydney Harbour.

While the plan itself does not include pollutant reduction targets for individual developments, catchment load and estuary condition targets have been developed for sub-catchments and local government areas using feasible scenario options for both the management of stormwater and improvements in sewer outflow performance. These targets are based on the following scenarios including assumptions of feasible change/actions:

- Water Sensitive Urban Design incorporated into 70 per cent of infill developments
- Water Sensitive Urban Design retrofitted into 10 per cent of existing urban areas
- Improving sewer overflow performance to limit overflows to no more than 40 events in 10 years.

The targets are designed to provide direction to change rather than being prescriptive of the exact management actions that should be carried out to achieve these goals. It is acknowledged that different scenarios to that assumed above could also achieve the targets. Targets are currently available for some of the Sydney Harbour sub-catchments. No project discharges would occur in estuarine water and project discharges to freshwater bodies would aim to comply with the ANZECC/ARMCANZ (2000) guidelines.

1.10 Previous investigations for the project

A preliminary environmental investigation identified the key issues to marine water quality potentially associated with the project (Cardno, 2016a). The preliminary environmental investigation was used to develop the State significant infrastructure application for the project.

This report builds on and incorporates the relevant details from these previous investigations where appropriate.

1.11 Other project investigations

The marine ecology assessment has been informed by predictions of changes to marine water quality, sedimentation, hydrodynamics, underwater noise and mobilisation of contaminants during construction. These predictions were detailed in various specialist reports, including:

> Appendix T (Technical working paper: Marine ecology)

> Summaries from the *Western Harbour Tunnel and Beaches Link Geotechnical Investigation: Contamination Factual Report – Marine Investigations* (Douglas Partners and Golder Associates, 2017)

> Appendix M (Technical working paper: Contamination)

> Appendix O (Technical working paper: Surface water quality and hydrology)

> Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling).

1.12 Definitions

The following definitions are used in this report:

> This report: this marine water quality technical working paper

> The project: refers to that described in sections 1.1 to 1.5

> Project area: refers to the aboveground area to be directly impacted by the project

> Operation footprint/Immersed tube tunnel footprint: refers to the final immersed tube tunnel footprint in Middle Harbour

> Study area: refers to the estuarine areas from the highest astronomical tide (HAT) encompassing the project area and areas nearby from Yeoland Point to Grotto Point (Figure 1-6).

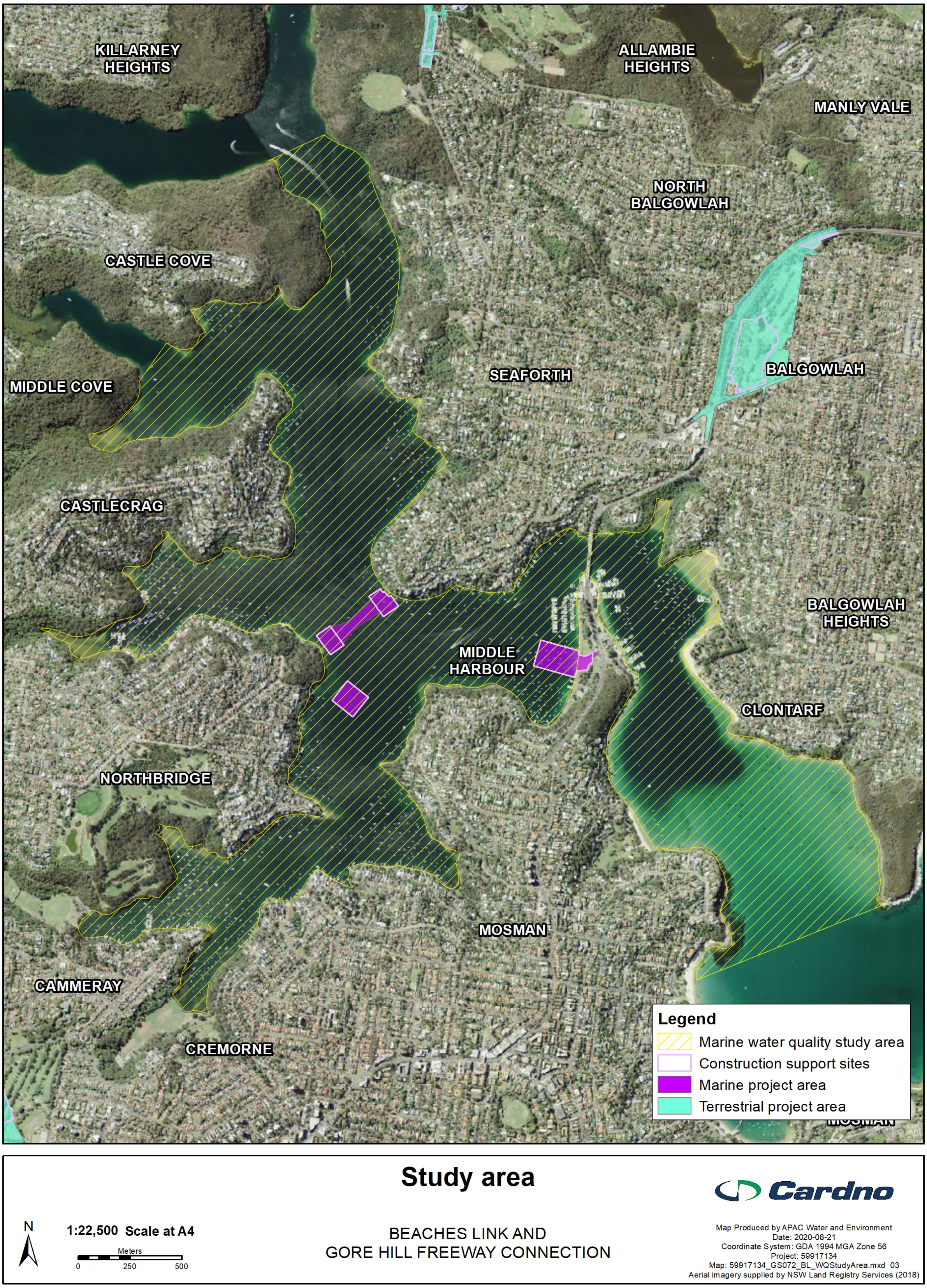


Figure 1-6 Marine water quality study area and study locality

2 Methods

2.1 General approach

The potential effects of the project on marine water quality were assessed including from dredging, tunnel construction activities and the operational effects of the tunnel.

Natural variability of key water quality parameters was identified through a review of existing information supplemented by two months of field data collection. Existing information included a range of historical water quality data collection programs and the Sydney Harbour Ecological Response Model (SHERM) (Cardno, 2015, 2016b). Field data were collected at a number of sites in Middle Harbour spanning the area that might be affected by the dredging and construction activities.

Predictions of the suspended sediment plumes and sediment deposition likely to be generated by the dredging and construction activities have been simulated by Royal Haskoning DHV group and are reported in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling).

The existing and collected data were analysed to provide a site specific statistical summary of key water quality parameters, including the key tolerance limits of the marine biota. Results of predictive modelling of the likely dredging-related suspended sediment plumes were combined with the natural system variability and ecosystem tolerance limits to provide an interpretation of potential impacts on water quality.

The potential for localised increases in turbidity associated with construction activities (ie piling, construction of temporary wharf facilities and vessel movements) was also considered.

Simulations of flushing times of the waters around the Middle Harbour crossing location for both the existing system and final tunnel configuration were used to inform the assessment of the longer term effects of the project.

Estimates of these and other water quality effects (ie contaminants in sediment mobilised during dredging) were used to inform Appendix T (Technical working paper: Marine ecology).

2.2 Review of existing and historical water quality information

2.2.1 Historical water quality assessments

There is a range of existing and historical water quality information available for Middle Harbour and Sydney Harbour more broadly (refer to Table 2-1). Typically, water quality investigations have focused on specific areas where there are known water quality issues, for example dispersion of contaminants from historical industrial sites in Homebush Bay, or to assess impacts of proposed activities by State agencies and private developers. The information reported in these studies was used to develop an understanding of the natural variability in turbidity and total suspended solids within Middle Harbour.

Table 2-1 Summary of publications containing water quality information on Sydney Harbour

Article	Focus Area
Birch and O'Hea (2007)	Homebush Bay
Cardno (2008)	Parramatta River estuary
Hatje et al. (2001, 2003)	Homebush Bay and Parramatta River estuary
Laxton (1997)	Sydney Harbour
Robinson GRC Consulting (1999)	Upper Parramatta River estuary
Harrison (2013)	Parramatta River and Middle Harbour
Taylor and Birch (1999)	Parramatta River estuary
Lend Lease (2017)	Darling Harbour

The historical data used to inform the natural variability of turbidity and total suspended solids within Middle Harbour was the water quality sampling in Sydney and Middle Harbour carried out for the Catchment Management Authority (CMA) (now WaterNSW) from January to June 2013 (Harrison, 2013). A range of in situ water quality measurements (including turbidity) were taken at 25 locations within Middle Harbour and the Parramatta River (refer to Figure 2-1). A YSI model 6600 V2 sonde fitted with a YSI model 6136 turbidity sensor was used for in situ data collection. Where sufficient preserved water samples were available a subset of samples were analysed for total suspended solids (photometric method). This data allowed for the relationship between total suspended solids (total suspended solids in milligrams per litre) and turbidity (in NTU, nephelometric turbidity units) to be determined – see Section 3.2.1.

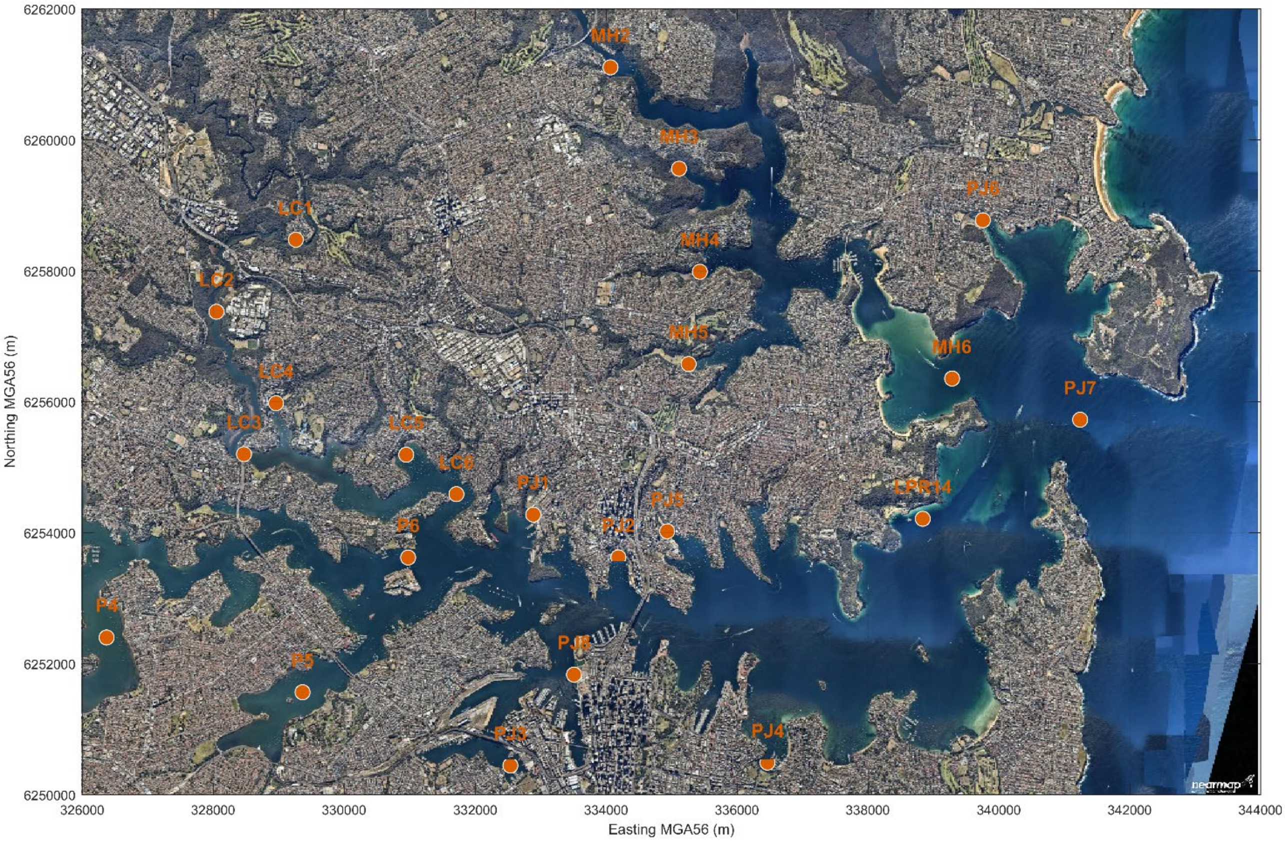


Figure 2-1 Sydney Harbour and Middle Harbour monitoring sites adopted by the Upper Parramatta Trust CMA (Harrison, 2013)

2.2.2 Sydney Harbour Ecological Response Model (SHERM)

The former Upper Parramatta Trust Catchment Management Authority (now part of Greater Sydney Local Land Services) supported a range of historical studies including water data collection, modelling of catchment rainfall runoff and constituent loads and development of the Sydney Harbour Ecological Response Model, or 'SHERM' (Cardno, 2015, 2016b). SHERM includes the learnings from a long history of modelling in Sydney Harbour and was developed by Cardno over a three year program using the Deltares suite of hydrodynamics and water quality models (for descriptions see Deltares website https://www.deltares.nl/en/software-solutions). SHERM simulates numerous physical, nutrient, algal and biological processes in response to tidal forcing, river inflows, wind, waves and atmospheric heat fluxes.

SHERM was not run specifically for this project. Available simulation results were used from a 12 month simulation period (April 2012 to March 2013), comprising of an initial three-month calibration period and a subsequent nine month investigative period. This 12 month simulation period includes typical annual, summer and winter catchment inflows (Stewart, 2013) and as such can be considered representative of the range of seasonal influences on water quality characteristics of the actual waters of Middle Harbour. The seasonal influences and catchment inputs characterised in SHERM are appropriate for the current catchment conditions.

To simulate the broad range of water quality variables and space-time scales, SHERM comprises a suite of three models with differing grid resolution within the broader Sydney Harbour:

> Hydro – high resolution hydrodynamics grid (about 100,000 cells from 10 metres to 150 metres cell sizes and eight vertical layers) to simulate the water levels, currents, salinity and temperature response to tides, wind, 173 sub-catchment inflows and surface heating

> WAQ – a medium resolution water quality grid (20,000 cells at about 100 metre scale) for simulating dispersion and response of a broad number of water quality variables to catchment loads and internal processes

> WQBox – a coarse water quality box model grid (33 laterally averaged boxes ranging from about one to four kilometres in length and eight vertical layers, refer to Figure 2-2) to simulate long term water quality behaviour in response to drought/wet cycles.

The hydro model outputs provide the currents and water level variations in Sydney Harbour. These outputs form the inputs to the WAQ and WQBox models to model dispersion. In addition to simulating the transport between box elements, the WAQ and WQBox models simulate the in situ water quality processes that affect concentrations within each element.

Outputs of the model 12 month simulations (April 2012 to March 2013) used in this investigation include the simulated fields of temperature and salinity from the hydro model and temperature, salinity, suspended sediments, underwater light and light extinction from the WQBox model.

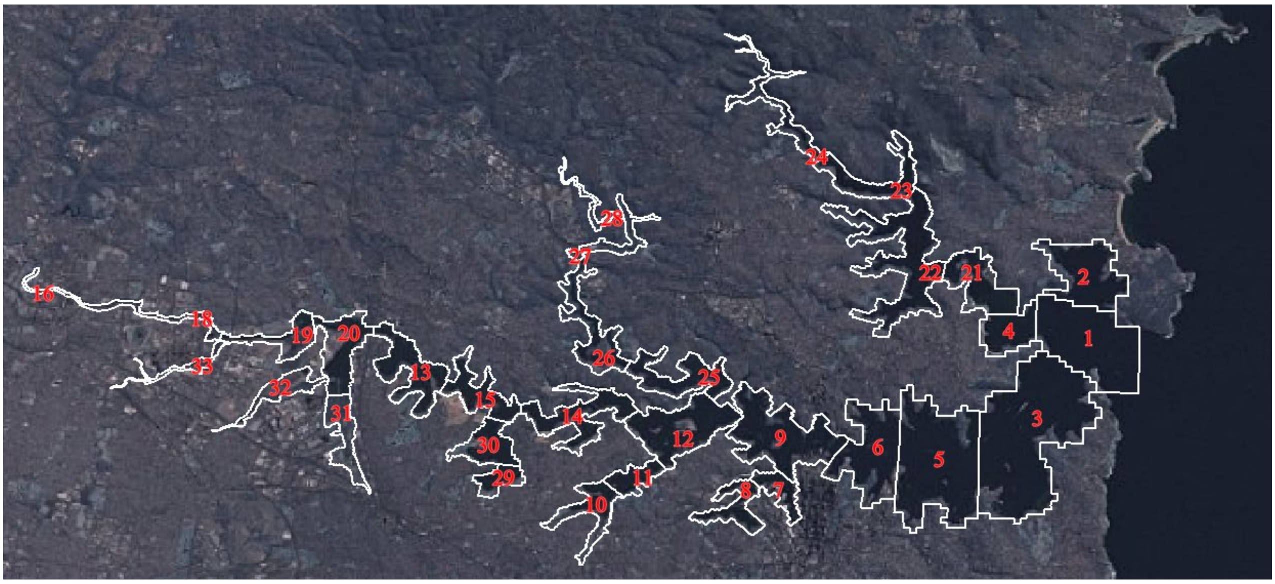


Figure 2-2 Cardno (2015) SHERM 33 Element Box Model set-up

The catchment inflows and water quality inputs to the SHERM estuary models, from the rivers (Parramatta and Lane Cove Rivers), creeks (eg Scotts, Bates, Flat Rock, Sugarloaf, Gordon, Moores and other creeks that enter Middle Harbour), streams and stormwater channels (including sewer overflows) that flow into Sydney Harbour were simulated using the Catchment Source and Simhyd rainfall-runoff and water quality simulation tools (Stewart, 2013). The wider Sydney Harbour catchment was divided in 550 sub-catchments and flows and water quality simulated for each of these and then aggregated into 173 inputs to the SHERM. The Middle Harbour estuary component of the model includes 25 inflows upstream of the harbour crossing that contribute flows, sediment and loads of water borne constitutes derived from the catchment runoff. These inputs affect the estuarine stratification and ‘salt wedge’ behaviour. Vertical stratification in combination with topographic features such as the natural sand sill at the entrance to Middle Harbour can lead to longer flushing times of the deeper waters upstream of the sill in the deepest parts of the estuary.

2.3 Field data collection

The historical data sets and SHERM outputs provide information on the background water quality in Middle Harbour. However, information was also required at a shorter time resolution (ie hourly) to sufficiently assess potential effects of the dredging program. As such, historical data describing natural variability in water quality was supplemented with data collected in the field at sites in the vicinity of the crossing of Middle Harbour, as well as at upstream and downstream locations. Data were collected in two discrete sampling periods:

- Sampling Period 1 - an eight week period from 5 December 2017 to 31 January 2018
- Sampling Period 2 - a five week period from 17 April 2020 to 1 June 2020.

Sampling Period 1 focused on collecting information about the effects of turbidity on underwater light that would assist interpretation of the potential effects of dredging. Data were collected at a high temporal resolution using the following methods (see Table 2-2):

- Two water quality monitoring moored loggers deployed from 5 December 2017 to 31 January 2018 in shallow waters near areas of known benthic primary producers, namely seagrass and rocky reef habitats
- Water sampling and water column vertical profiling carried out on two days (18 and 31 January 2018)
- The collation of meteorological and oceanographic data to provide information on the weather and ocean conditions that are key drivers of the estuary water quality response.

Vertical profiles conducted in Sampling Period 1 indicated that the water quality upstream of The Spit could be subject to periods of naturally low dissolved oxygen concentrations after rainfall (refer to Section 3.3.2.1).

Sampling Period 2 was designed to better understand oxygen variability within the deep water that would assist with understanding potential impacts of the Middle Harbour crossing and included the following methods:

- Two water quality monitoring moored loggers deployed from 27 April 2020 to 1 June 2020 (see Table 2-2)
- Water column profiling carried out on six days in 2020 (17 April, 4 May, 14 May, 23 May, 27 May and 1 June)
- The collation of meteorological and oceanographic data to provide the key information on the weather and ocean conditions that are key drivers of the flushing and water quality response.

2.3.1 Moored loggers

The locations of the moored loggers for Sampling Period 1 are shown in Figure 2-3 and site coordinates are provided in Annexure A. The locations of monitoring sites for Sampling Period 1 were informed by preliminary predictions of the dredge plume footprint in Middle Harbour (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)).

Sampling Period 1 included monitoring at two water quality moored loggers at sites BL1 and BL2 (refer to Figure 2-3), configured on a fixed harbour bed frame which was deployed for the eight-week monitoring period from 5 December 2017 to 31 January 2018. BL2 was located in the footprint of the proposed crossing and BL1 was located further upstream. Instruments included a NexSens Submersible Datalogger (SDL500) with WET Labs ECO NTU (Nephelometric Turbidity Unit) turbidity and PAR (Photosynthetically Active Radiation) light sensors, a Sea-Bird Electronics MicroCAT SBE37SMP conductivity and temperature logger and a WET-Labs EcoFLNTUSB with integrated fluorometric (chlorophyll-*a)* and optical backscatter (turbidity) sensors (refer to Table 2-2).

Sampling Period 2 included deployment of two water quality moored loggers at sites BM1 and BM2 (refer to Figure 2-3). Site coordinates are provided in Annexure B. These were deployed for the five-week monitoring period from 28 April 2020 to 1 June 2020. Instruments included two Sea-Bird Electronics MicroCAT SBE37SMP-ODO instruments with integrated conductivity, temperature, depth and dissolved oxygen sensors and a WET-Labs EcoFLNTUSB with integrated fluorometric (chlorophyll-*a*) and optical backscatter (turbidity) sensors (refer to Table 2-2).

2.3.2 Water sampling and profiling

In addition to the two moored loggers deployed during the two sampling periods, vertical water column profiles were collected at various sites within Middle Harbour with a Sea-Bird Scientific SBE 19plus V2 SeaCAT profiler fitted with turbidity, PAR, conductivity, temperature, depth, fluorometric chlorophyll-*a*, pH and dissolved oxygen sensors. The profiler was lowered through the water column from the surface to the harbour bed at six sites on two days during Sampling Period 1 and 13 sites on six days during Sampling Period 2 (refer to Figure 2-3 and Annexure A and B). Vertical water column profiles were also collected at the two moored logger monitoring sites during the two sampling periods. Sites for Sampling Period 2 were spread further apart to better understand upstream and downstream potential variability in tidal flushing.

During Sampling Period 1 water samples were collected at each of the six water column profile sites at a depth of 1.5 metres below the water surface. Samples were collected on 18 and 31 January 2018. Water samples were transferred to the ALS laboratory for accurate determination of levels of total suspended solids and chlorophyll-*a* (Chl-*a*) concentrations for comparison with sensors on fixed loggers.

Table 2-2 Summary of water quality data from moored loggers during Sampling Period 1 (5 December 2017 – 31 January 2018) and Sampling Period 2 (17 April 2020 – 1 June 2020)

	Sampling period					
	5 December 2017 – 31 January 2018			17 April 2020 – 1 June 2020		
Sensor	**Sample frequency (min)**	**BL1 sensor height above seabed at -6.2 m AHD**	**BL2 sensor height above seabed at -6.4 m AHD**	**Sample frequency (min)**	**BM1 sensor height above seabed at -25.0 m AHD**	**BM2 sensor height above seabed at -30.3 m AHD**
Photosynthetically Available Radiation (PAR)	15	0.51	0.51			
	15	1.98	1.98			
Turbidity	15	0.51	0.51	15	18.6	24
	10	0.51	0.51			
Chlorophyll-*a* (Chl-*a*)	10	0.51	0.51	15	18.6	24
Salinity	15	0.67	0.67	15	1	1
				15	18.6	24
Pressure	15	0.67	0.67	15	1	1
				15	18.6	24
Temperature	15	0.67	0.67	15	1	1
				15	18.6	24
Dissolved Oxygen				15	1	1
				15	18.6	24
Water Current Profile				10		1 metre bins from 3.5 to 28.5 metres above bed

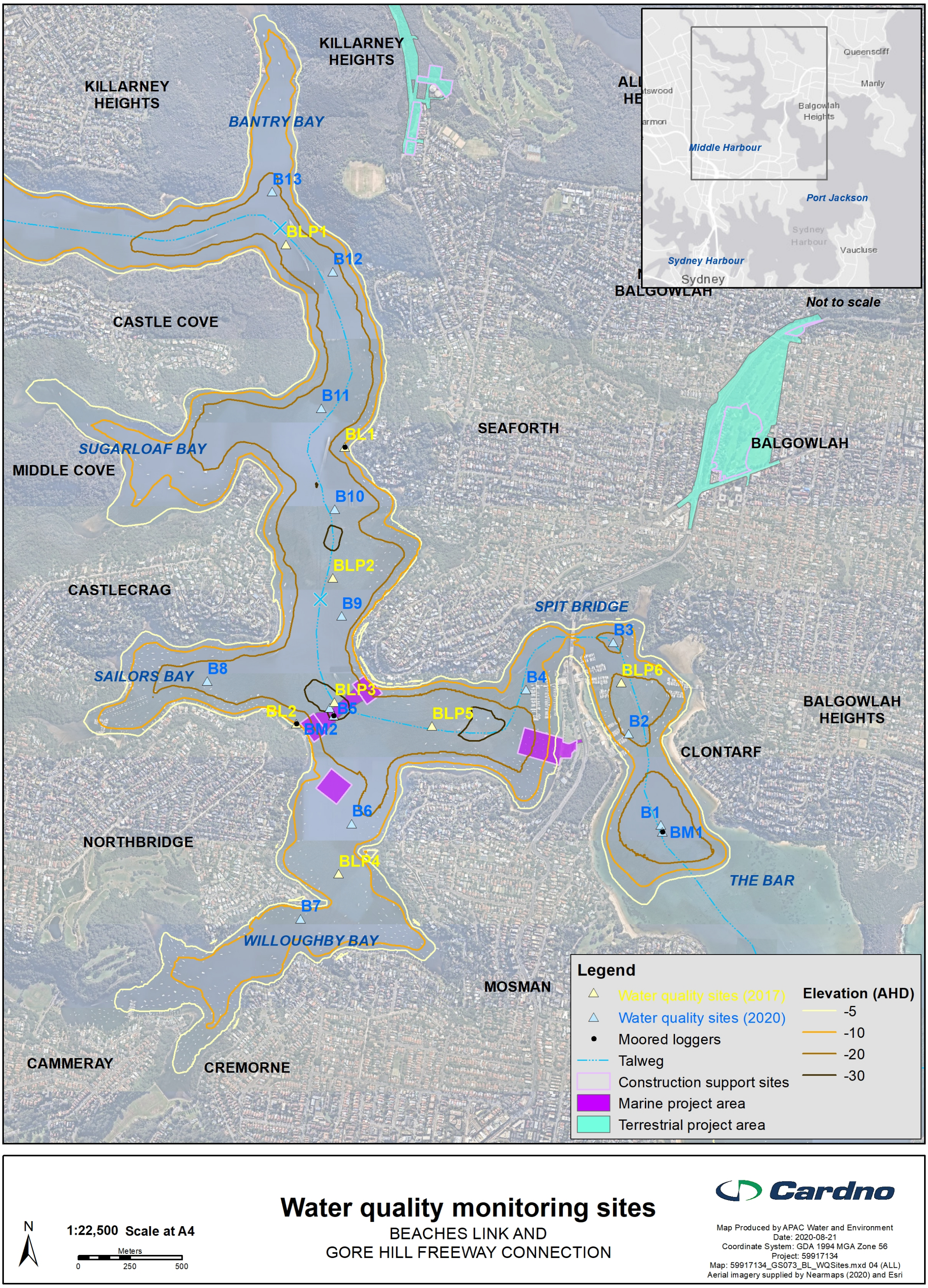


Figure 2-3 Water quality monitoring sites within Middle Harbour

2.3.3 Supplementary meteorological and oceanographic data

Meteorological and oceanographic data (refer to Table 2-3) were collated for the sampling periods. The data provided the physical context for the water quality response of the system and are a key input to inform the understanding of environmental processes governing water quality within Middle Harbour.

Wind speed and direction were obtained from the Australian Bureau of Meteorology (BoM) for the Sydney Harbour meteorological station at Wedding Cake West (station ID: 066196). Air temperature, daily rainfall and daily global solar exposure were obtained from the BoM Observatory Hill meteorological station (station ID: 066062). Daily global solar exposure was not available for Sampling Period 2.

Downwards shortwave radiation data were obtained from the United States National Centre for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2). Data were extracted from the CFSv2 global model grid, which has a resolution of 0.2 degrees (about 20 kilometres), at hourly temporal resolution. This model estimates the clear sky solar radiation hitting the land surface (ie assuming an absence of atmospheric attenuation due to cloud cover) as described in Saha et al. (2012).

Recorded and predicted harbour water levels were obtained from the BoM National Tidal Centre using water level records from the Fort Denison tide gauge operated by Manly Hydraulics Laboratory.

Table 2-3 Summary of Sydney Harbour meteorological and oceanographic data utilised in this investigation

Parameter	Station location	Data source	Frequency
Wind speed and direction	Sydney Harbour Wedding Cake West (Stn 066196)	BoM	30 mins
Air temperature	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Daily rainfall	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Daily global solar exposure	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Downwards short wave radiation	Latitude: -33.83° Longitude: 151.16°	CSFv2	Hourly
Recorded and predicted Sydney Harbour water levels	Fort Denison	NTC	10 mins

2.4 Dredging effects simulations

The bed of Middle Harbour within the immersed tube tunnel construction footprint includes a range of different sediment types, including soft surficial sediments and harder material beneath the bed of the harbour. To remove this material, the program of dredging works comprises a sequence of dredging operations. As described in Section 7 of Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling), the immersed tube tunnel placement would require removal of about 75,000 cubic metres of harbour bed material. The dredging program was designed to operate for about eight hours per day during daylight hours and would run for about 37 weeks. The dredging methodology and program (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)) has included a range of mitigation measures to reduce potential environmental effects.

Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) modelled the tidal dispersion of the suspended sediment concentrations (SSC) introduced into the water column by the dredging activities. The model focused on the dredging processes as the key source of suspended sediments entering the surrounding waters and its subsequent dispersion and settling into the waters of Middle Harbour and provided estimates of the dredging-related suspended sediments dispersion. In the following sections, the model results are referred to as “excess SSC” (milligrams per litre) to reflect that they only represent the dredging contribution to suspended sediment concentrations.

2.5 Ecosystem tolerance limits

The Western Australian Environmental Protection Authority Technical Guidance Document *Environmental Impact Assessment of Marine Dredging Proposals* (WA EPA, 2016) and McArthur et al. (2002) provide a useful approach for presenting predictions of the likely range of environmental impacts of dredging, which in turn, provides the basis for facilitating the transfer of these predictions into recommended conditions and environmental monitoring and management strategies. This approach was used in Appendix T (Technical working paper: Marine ecology) to assist with the assessment of impacts from the project. The effects of dredging were mapped in terms of zones of impact and influence.

To delineate these zones, the potential impact of dredging-related excess turbidity and excess sedimentation on habitats or biota, an assessment of estimated ecological tolerance limits for each habitat type or biota is required.

Tolerance limits for habitats are generally derived in two different ways:

> Tolerance limits for turbidity are derived from water quality monitoring data, arguing that resident flora and fauna are adapted to local conditions but would be stressed if exposed to conditions that regularly exceed normally prevailing background concentrations

> Tolerance limits for sediment deposition are derived from habitat-specific dose-response experiments and field observations reported in scientific literature.

Given dose-responses were unavailable for most of the species in the marine ecology impact assessment study area, tolerance limits for habitats were derived from marine water quality monitoring data. It was assumed that aquatic plants and primary producers are adapted to the natural turbidity variability up to the 95^{th} percentile and that above this value they may become stressed.

The natural variability in total suspended solids concentrations in the vicinity of the proposed immersed tube tunnel crossing location was determined from the available historic data, the SHERM outputs and additional data collected as part of the project-specific water quality monitoring program. Tolerance limits were defined by the 95^{th} percentile observed total suspended solids concentration minus the median total suspended solids concentration. These tolerance limits were then applied to the predicted dredging-related excess SSC to determine where potential effects may arise within the zones as follows (refer to Figure 5-1):

> Zone of High Impact: the dredged area and immediate vicinity where sediment is likely to be displaced. Defined as the project disturbance footprint. Impacts to benthic habitat and/or biota in these areas are predicted to be severe and often irreversible

> Zone of Moderate Impact: the area where dredge plumes combined with natural system variability exceeds the 95^{th} percentile of the natural system for more than 10 per cent of the time. Impacts to benthic habitat and/or biota within this zone are predicted, but the disturbed areas may recover after completion of the dredging and disposal operations and it is expected that there would be no long-term modification of the benthic habitats

> Zone of Influence: the area where dredge plumes combined with natural system variability exceed the 95^{th} percentile of the natural system for more than five per cent of the time but no impacts to benthic habitat or biota are expected.

2.6 Simulations of effects during project operation

2.6.1 Tidal flushing

Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) (refer to Section 2.4) conducted a series of hydrodynamics and conservative tracer dispersion simulations to assess the potential long term effects during project operation due to the presence of the immersed tube tunnels in Middle Harbour. The effects of water flows (or hydrodynamics) on water quality is often characterised by the flushing characteristics as indicated by the *e*-folding time (the time required for a concentration to fall exponentially to a factor of 1/*e* (67 per cent) of its initial concentration) that provides a useful measure of potential water quality responses. Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) used a series of conservative tracers introduced into the homogeneous (constant density) waters upstream of the immersed tube tunnel crossing location for these investigations. *E*-folding times were calculated from model outputs of time series of tracer concentrations at specific locations, particularly the deeper waters upstream of the tunnel crossing.

2.6.1 Dissolved oxygen and siltation

The SHERM results provided simulations of the effects of catchment runoff on the vertical stratification and these results are used to indicate the combined effects of tidal, wind and salt wedge conditions on water quality. Following a runoff event the saline recovery period may be characterised by its *e*-folding time, provided the salinity at the mouth of the estuary remains constant. The model results and the collected field data were used to highlight the effects of these processes on water quality, including dissolved oxygen and siltation. The potential effects of the immersed tube tunnels were assessed by comparing the modelled *e*-folding times prior to and after its construction and likely water quality implications inferred from the SHERM results and field data.

The harbour infill rate in the basin upstream of the immersed tube tunnel crossing sill was estimated via two methods. First, assessment of historical information derived from sediment cores and discussions with Professor Gavin Birch (Sydney University) and second, using the SHERM catchment model inputs to derive the loads to Middle Harbour, from which sedimentation in harbour basins was assessed.

3 Existing environment

3.1 Overview of water quality processes in Middle Harbour

Sydney has a temperate, humid climate with abundant sunshine and significant rainfall. Precipitation averages 1309 millimetres per annum varying from 156 millimetres in the wettest month of March to 60 millimetres in the driest month of September. The region is prone to droughts with extended periods of very low rainfall lasting several months. The regular rainfall-induced catchment runoff leads to significant loads of sediment, nutrients and other water borne constituents entering the waterway and affecting the quality of water within the broader Sydney Harbour estuary.

The wider Sydney Harbour estuary is comprised of four connected estuarine water bodies including Middle Harbour estuary in the north eastern part of the broader Sydney Harbour estuary (refer to Table 3-1). The broader estuary is influenced by ocean tides, episodic catchment runoff and wind events. The area is also subject to seasonal wind patterns characterised by the summer sea breeze cycle and occasional strong winds and heavy rain as intense low pressure systems propagate through the region.

Table 3-1 Summary of physical characteristics for relevant estuaries

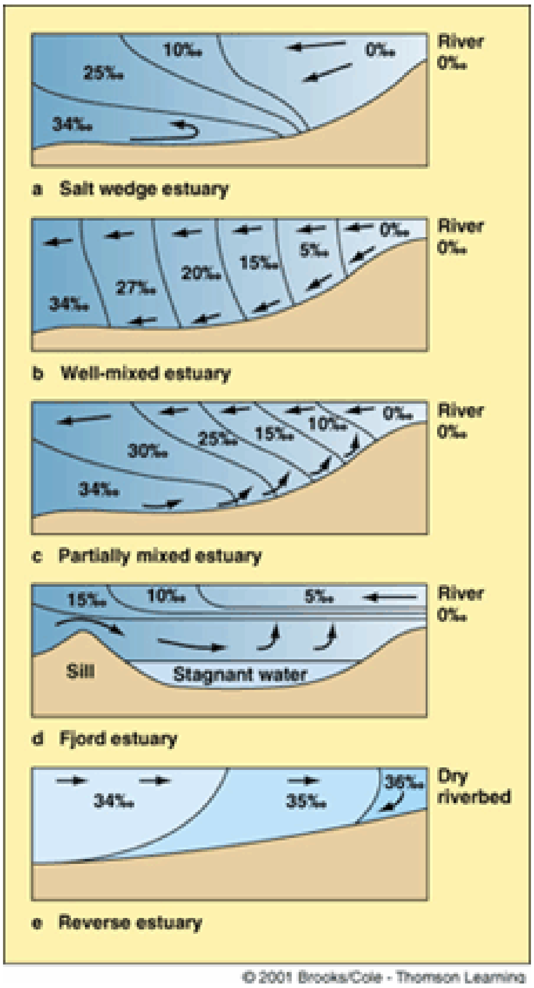
	Port Jackson	Middle Harbour	Lane Cove River	Parramatta River	Total Sydney Harbour Estuary
Entrance location	-33.83, 151.29	-33.82, 151.26	-33.84, 151.18	-33.84, 151.19	**-33.83, 151.29**
Catchment area (km^2)	55.7	77.0	95.4	252.4	**480.5**
Estuary area (km^2)	29.1	6.1	3.0	13.7	**51.9**
Estuary volume (GL)	376.4	81.9	12.6	69.7	**540.6**
Average depth (m)	13.0	13.4	4.2	5.1	**9.0**

Reproduced from NSW State Government (from http://www.environment.nsw.gov.au/estuaries/list.htm)

3.1.1 Mixing and physical processes

Mixing and dispersion of water masses introduced into the estuary is a key factor in determining the water quality response to catchment runoff, resuspension of bed sediments during stirring events, and ocean inputs. Using the Hansen and Rattray (1966) classification scheme the mixing characteristics vary between a well-mixed estuary during dry periods and a partially mixed estuary following intense rainfall runoff from the catchment (refer to Section 3.3.2). At specific locations upstream of sills (for example upstream of The Bar that forms the shallow entrance to Middle Harbour) the Hansen and Rattray fjord classification is also relevant but the intense tidal flushing leads to relatively short residence times and only short periods of stagnation conditions of near-bed waters. The deeper near-bed waters are subject to conditions that result in long residence times due to very slow mixing and exchange with overlying waters. During these periods, the rapid consumption of dissolved oxygen by microbes feeding on organic material previously deposited to the harbour bed leads to dissolved oxygen depletion of the near-bed waters. Rapid oxygen exchange with the atmosphere at the water surface and then vertical mixing maintains high dissolved oxygen content of the overall water column.

A range of conditions can lead to longer residence times of the deeper waters upstream of the sills. For Middle Harbour, the complex interactions between rainfall/runoff, mixing within the broader Sydney Harbour and exchange with ocean waters leads to seasonal variations in the temperature and salinity signature that in turn influences the salt wedge or fjord-like nature of the mixing of the Middle Harbour deep waters. Vertical stratification associated with the salt wedge in the deeper water can impede vertical mixing and the exchange of deeper waters with surface waters and lead to deteriorating water quality in the deeper waters.



Note ‰ refers to the traditional salinity unit of parts per thousand.

Figure 3-1 Generalised estuarine circulation classification scheme after Hansen and Rattray (1966)

Rainfall recurrence intervals are listed in Table 3-2 to highlight the importance of rainfall intensity for freshwater input and suspended sediments loads to the estuary. These daily rainfall recurrence intervals from a one month recurrence event up to 10 year recurrence were generated from an extreme value analysis of daily rainfall totals recorded at the BoM Observatory Hill station from 1858 to 2019.

Table 3-2 Average recurrence of daily rainfall totals: Observatory Hill 1858 to 2019

Recurrence interval	Daily rainfall (mm)
1 month	25.9
2 months	40.0
3 months	50.0
6 months	67.8
1 year	92.2
2 years	113.0
10 years	168.9

The quality of the waters within the broader Sydney Harbour estuary reflect the balance between catchment loads of varying quality (depending on the land use and practices within the catchment), ocean inputs and the tidal flushing that mixes the different water masses. Tidal flushing intensity diminishes from the ocean entrance at the Heads to the upstream extremities of the estuary near the river (Lane Cove and Parramatta Rivers) and creek (eg Scotts, Moores, Gordon, Bates Creeks that enter Middle Harbour) inputs. During frequent rainfall, the creek and river flows carry suspended particles and dissolved substances into the estuary causing the estuarine waters to become turbid. Following runoff, these particles are dispersed into the estuary by tidal and wind-induced currents and settle to the bed of the harbour where they can be resuspended by subsequent rainfall, wind and oceanographic events. The dispersion process effectively dilutes the introduced particles and dissolved substances and their concentrations diminish toward the pre-runoff concentration. In general, the turbidity varies along the estuary from clearer low turbidity oceanic waters near the mouth to the higher turbidity near the river/creek inputs. In addition, the temporal variability is characterised by higher turbidity following significant inflow and relatively low values during dry periods. These key processes that determine natural water quality and their influence on key aquatic habitats near the Middle Harbour mainline tunnel are shown schematically in Figure 3-2.

The catchment loads of nutrients and sediments support a diverse range of aquatic ecosystems within the estuary. In the vicinity of the Middle Harbour mainline tunnel the key habitats include intertidal and subtidal rocky reef, sparse fringing seagrass communities and soft-bottom biota in the deeper waters.

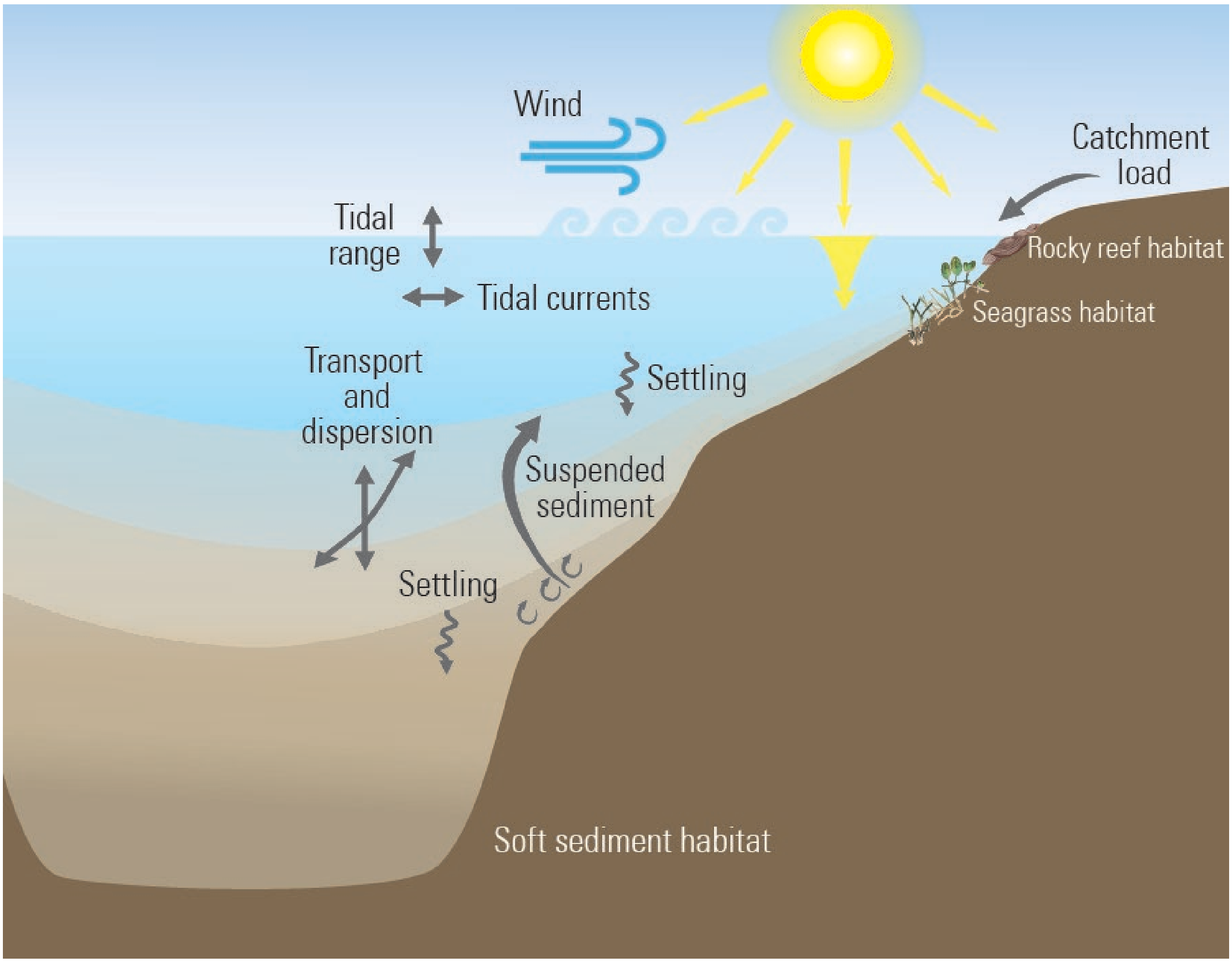


Figure 3-2 Water quality processes schematic

Suspended sediment concentrations provide a measure of particulate inflow, as well as resuspension of sediments. The presence of suspended sediments in the water column is important for the transport of pollutants attached to particles, and for issues relating to smothering of biota and alteration in aquatic habitat. Turbidity is a measure of light attenuation that is due to total suspended solids, and it provides a measure of suspended clay and silt particles, phytoplankton and detritus. High turbidity impacts the aesthetic quality of the water, along with reducing aquatic plant growth. Suspended matter can originate from point sources such as sewer outfalls, industrial sites and stormwater drains. Generally, most of the suspended matter deposited in estuaries and coastal areas comes from soil and stream bank erosion within the upstream catchment (ANZECC/ARMCANZ, 2000). For this reason, turbidity in most estuaries is highly dependent on flow, with very large increases noted during flood events. In rivers, total suspended solids concentrations generally increase considerably during the early part of a flood event as sediment is washed into the river from the catchment and deposited sediment is resuspended (ANZECC/ARMCANZ, 2000).

The key water quality variables that affect aquatic communities within an estuary are turbidity and total suspended sediments as these affect the underwater light regime that impacts on the photosynthesis of aquatic plants.

Dissolved oxygen, however, can also be an important variable for marine biota. The significance of dissolved oxygen concentrations in aquatic systems is summarised on the OzCoasts website (https://ozcoasts.org.au/indicators/biophysical-indicators/dissolved_oxygen/). Measures of dissolved oxygen refer to the amount of oxygen contained in water, and define the living conditions for oxygen-requiring (aerobic) aquatic organisms. Oxygen has limited solubility in water, usually ranging from six to 14 milligrams per litre. Dissolved oxygen concentrations reflect an equilibrium between oxygen-producing processes (eg photosynthesis), and oxygen-consuming processes (eg aerobic respiration, nitrification, chemical oxidation), and the rates at which dissolved oxygen is added to and removed from the system by atmospheric exchange (aeration and degassing), and hydrodynamic processes (eg accrual/addition from rivers and tides versus export to ocean).

3.1.1 Suspended matter, light and primary production

The turbidity at a particular location depends on a range of complex physical processes including intermittent suspended sediment inflows, interactions with bed material, local re-suspension and transport processes and proximity to sources of material.

Suspended sediments reduce light penetration through the water column and thereby limit pelagic (middle water column) and benthic primary production (the process of converting light energy into biomass). As the suspended sediment settles to the harbour bed it may smother benthic organisms and affect the type of organisms and plants that can exist in this environment.

Fluctuations in light and rates of sedimentation occur naturally in Middle Harbour due to regular resuspension of bed sediments by the tidal currents, wind-driven turbulence and runoff. Increases in sedimentation and turbidity can influence the health of sensitive receivers within both the water column and the benthic habitats.

This link between the suspended sediments, light and primary production is the key water quality process to be investigated as part of this impact assessment. The related effects on biota is reported in Appendix T (Technical working paper: Marine ecology).

3.2 Review of historical water quality information

3.2.1 Historical turbidity assessments

There is a range of existing and historical water quality information available for Middle Harbour and Sydney Harbour more broadly (Table 2-1). The information reported in these studies is summarised below to develop an understanding of the natural variability in turbidity and total suspended solids within the broader harbour.

For the shallow waters within Homebush Bay, Birch and O'Hea (2007) determined that during inflow events there is little variation between typical distributions of total suspended solids for bottom and surface waters. Hatje et al. (2001) analysed the temporal variations in total suspended solids at various locations along the Parramatta River Estuary. Their results suggested that anthropogenic influences such as increased urbanisation of catchments leads to more stormwater outlets with higher runoff discharge and increased sediment delivery. This results in an increase in turbidity variability at smaller temporal scales within the harbour waters.

Diurnal variability of the concentrations of suspended particulate matter has been assessed within the Parramatta River Estuary at 14 locations from Duck River to Port Jackson (Hatje et al., 2001, 2003). The key processes of bottom sediment resuspension and vertical water column mixing are known to influence the overall turbidity, whilst seasonal influences (eg wetter period in late summer) have some limited effect within the estuary (Hatje et al., 2001, 2003). A number of authors note that wind waves are a key contributor to sediment resuspension within the estuary while tidal resuspension of sediments is negligible (Birch and O'Hea, 2007; Taylor and Birch, 1999).

Robinson GRC Consulting (1999) monitored turbidity levels within the upper reaches of the Parramatta River Estuary over the period of 1990 – 1997. The mean turbidity values for the Parramatta River, downstream of the weir, ranged about 15 to 20 NTU during dry weather to over 50 NTU following wet weather, due to the influx of suspended sediment associated with bank erosion and overland flow. The mean annual turbidity for the surface waters immediately downstream of the Silverwater Bridge was recorded at 7.7 NTU while bottom waters had turbidities of 21.9 NTU. Turbidity values for the sampling station just downstream of the Gasworks Bridge were of a similar range, with surface waters recording a mean annual turbidity of 13.3 NTU and bottom waters 21.5 NTU (Robinson GRC Consulting, 1999).

Bishop (2007) assessed the impacts of bottom sediment resuspension with regard to turbidity for the Upper Parramatta River Estuary (between Ermington and Rydalmere). The study concentrated on the effects of boat generated waves (wash waters). This section of the river is heavily utilised by purpose-built low-wash boats, however, other vessels also commonly pass through this reach and it was shown that turbidity can be directly linked to boat wash. Whilst it is stated that there is no significant effect on the sedimentology, the distribution of sediment particles was shown to affect water quality, thereby altering the local ecology (Bishop, 2007).

Laxton (1997) and Birch and O'Hea (2007) conducted water quality sampling and analyses to investigate total suspended solids and the chemistry of suspended particulate matter at numerous locations along the Parramatta River. Laxton (1997) presents a statistical summary of total suspended solids and turbidity (presented here in Table 3-3) for the upper Parramatta River and Duck Creek based on monthly water quality sampling from 1990 to 1996.

Table 3-3 Laxton (1997) total suspended solids and turbidity for Upper Parramatta River and Duck River

Statistical parameter	Turbidity (NTU)	TSS (mg/L)
90%	64.5	34.4
Median	11.9	7.6
10%	5.0	3.8

Birch and O'Hea (2007) collected water samples at ten sites along three transects in Homebush Bay under three weather conditions: calm (25 June 2004), calm/heavy-rain (18 August 2004), and high-wind/heavy-rain (2 October 2004). A summary of total suspended solids and turbidity values measured during the sampling periods is presented in Table 3-4.

Table 3-4 Birch and O'Hea (2007) total suspended solids and turbidity for Homebush Bay

Conditions		Turbidity (NTU)	TSS (mg/L)
Calm (Quiescent) Conditions	Mean	7.2	7.0
	Range	1.4 to 10.3	3.2 to 18.5
High Precipitation	Mean	29.4	17.2
	Range	13.9 to 48.7	7.8 to 41.2
High Wind/Heavy Rainfall	Mean	56.8	20.8
	Range	3.3 to 138.3	11.2 to 41.6

The above studies focused on the upper Parramatta River. Further downstream, monthly reports of turbidity data are available for the Darling Harbour area through the *Barangaroo Monthly Water Quality reports* (Lend Lease, 2017). These reports summarise results of water quality monitoring at Barangaroo South during the period from April 2012 to December 2017. The monthly minimum, maximum and mean turbidity values from the monitoring are summarised in Table 3-5. These data indicate the clearer waters of this reach of the Sydney Harbour as distinct from the more turbid waters of the shallow upper estuary areas from Homebush Bay and further upstream towards Parramatta.

Table 3-5 Summary of Barangaroo monthly water quality turbidity (NTUt) report: April 2012 to December 2017

Statistical parameter	Monthly minimum	Monthly average	Monthly maximum
Maximum	3.2	8.4	61.2
90^{th} percentile	1.9	4.6	25.3
Median	0.7	2.4	13.2
10^{th} percentile	0.0	1.6	5.7
Minimum	0.0	0.7	3.5

Total suspended solids and corresponding turbidity data from the CMA water quality monitoring program have been classified by their location into the Middle Harbour sites (MH2 to MH6, refer to Figure 2-3) and the Sydney Harbour sites (PJ1, PJ2, PJ3, PJ5, PJ8, P5, P6, LC5 and LC6). These two data sets were then analysed to derive percentiles of total suspended solids and turbidity (refer to Table 3-6). The results show the waters of Middle Harbour and generally clearer – with lower total suspended solids and turbidity range – than waters within the main Sydney Harbour.

Table 3-6 Catchment Management Authority total suspended solids and turbidity data statistics

Statistical parameter	Turbidity (NTU) Sydney Harbour	Turbidity (NTU) Middle Harbour	TSS (mg/L) Sydney Harbour	TSS (mg/L) Middle Harbour
Maximum	22.3	7.0	25.7	13.2
95th percentile	15.6	3.0	17.9	4.4
90th percentile	6.4	2.6	8.1	3.7
50th percentile (Median)	2.5	1.1	3.3	1.7
10th percentile	0.9	0.3	1.3	0.6
5th percentile	0.8	0.2	1.0	0.3
Minimum	0.4	0.1	0.7	0.1

The data for these two areas were also used to derive a relationship between total suspended solids (mg/L) and turbidity (NTU) using linear regression analysis (Figure 3-3). This relationship is based on a relatively small data set comprising low turbidity and total suspended solids values typically collected primarily during fair weather. The analysis showed a reasonable correlation in Middle Harbour, with a coefficient of determination of $R^2 = 0.72$ for the limited range of samples. For the Sydney Harbour sites, the broader range of values gave a stronger correlation and $R^2 = 0.94$. The relationships shown in these figures are utilised in the following to convert measured turbidity (NTU) values to total suspended solids (milligrams per litre) concentrations. For the Middle Harbour sites the relationship is total suspended solids = 1.38 x NTU + 0.25.

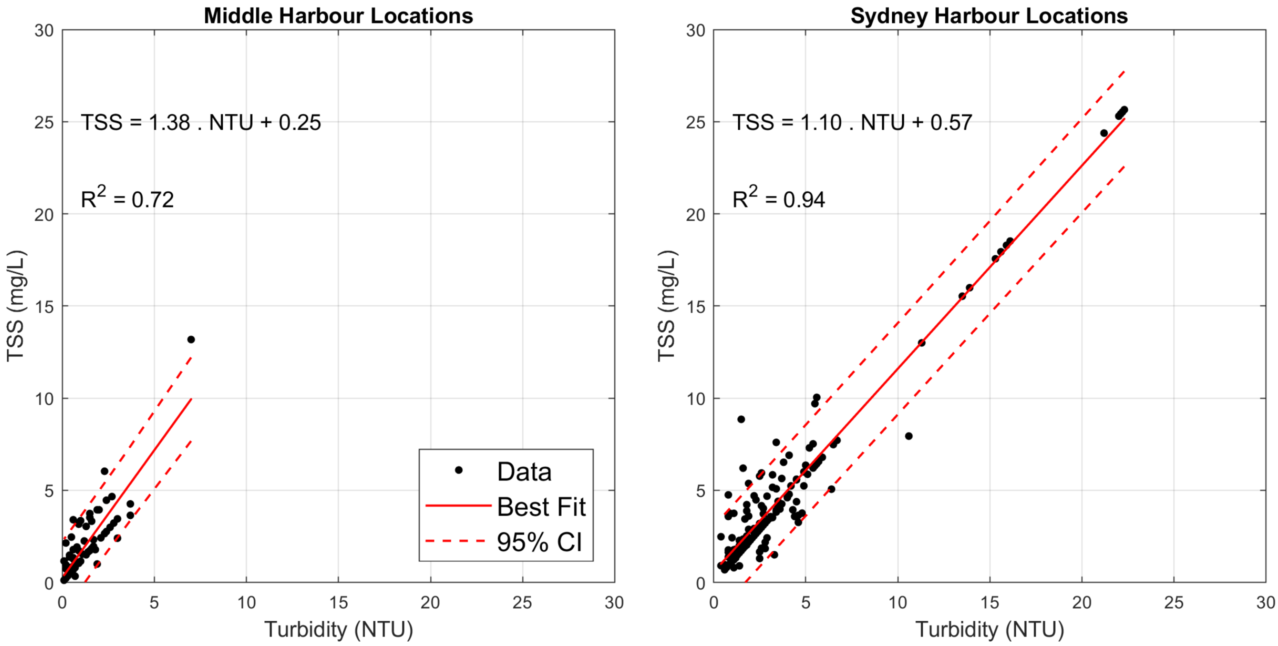


Figure 3-3 Total suspended solids vs turbidity relationship based on CMA water quality data

3.2.2 SHERM outputs

To assist in the characterisation of natural variability, results from the existing SHERM Hydro high resolution model were used to assess the hydrodynamics. A period over the three months July to September 2011 was selected that includes a number of significant inflow (rainfall) events that represent the extent of natural variability. The modelled salinity time series and a snapshot long section of isohalines (lines of constant salinity) along the centre of the Middle Harbour are shown in Figure 3-5. An indicative snapshot of the system on 23 August 2011 indicates the partially mixed nature of the system with the salt wedge propagating upstream following the small inflow event some two days prior to the snapshot. The time series figure indicates the typical response to freshwater inflow events and subsequent saline ingress to the estuary during post event recovery to higher salinity values.

This process is captured by the *e*-folding time that identifies the time required for mixing of water at a particular location (eg Middle Harbour at the Beaches Link mainline tunnel alignment) with water from a downstream location (eg The Bar near the entrance to Middle Harbour) and provides a useful measure of potential water quality responses. The *e*-folding time estimated from the saline recovery following the modelled events of 20 to24 July 2011 and 20 August 2011 was about nine days for the deeper waters and about seven days for the surface waters. This *e*-folding time calculation method assumes the salinity at the mouth of the estuary (represented by salinity at The Bar) remains constant during the saline recovery period. Over the nine days of deep water saline recovery the salinity at The Bar increased by about 1 psu (practical salinity unit) resulting in longer *e*-folding time estimates than the actual expected and hence provided an upper limit.

The SHERM water quality box model, WQBox, simulation results for total suspended solids at the study area are shown in Figure 3-6 for the surface and bottom layers for the one year period April 2012 to April 2013. The figure also shows the daily rainfall recorded at the BoM rain gauge at Observatory Hill in Sydney, as an indicator of catchment runoff.

The 12 month simulation occurs over a period of average total rainfall with four discrete major rainfall-runoff events, including April 2012 (165 millimetres over three days), June 2012 (125 millimetres over two days), February 2013 (177 millimetres over seven days) and March 2013 (142 millimetres over two weeks). Using the information on average recurrence presented in Table 3-2, the daily rainfall total of 87 millimetres that occurred on 19 April 2012 approximates a one year daily rainfall recurrence.

The typical scenario of higher total suspended solids in response to the rainfall and catchment inflows is clearly visible in Figure 3-6. The time series of total suspended solids indicates that low background suspended sediment concentrations during prolonged dry periods are similar for all vertical layers. High rainfall and catchment flow events generate spikes in total suspended solids and the rainfall event of April 2012 resulted in total suspended solids peak of 30.0 milligrams per litre. Figure 3-4 indicates typical levels of turbidity in Middle Harbour after heavy rainfall.

Table 3-7 shows only a small magnitude difference between the 5th percentile total suspended solids (about seven milligrams per litre) and the median total suspended solids (about 10 milligrams per litre), which indicates a relatively low level of statistical variability during dry periods.

The post event recovery period (that is, the time for conditions to return to values similar to the values prior to the event) varies depending on the magnitude of the rainfall event and the preceding conditions. Larger rainfall events show an average recovery time of about 25 days while for smaller rainfalls events, recovery time is in the range of five to 10 days.

Table 3-7 SHERM total suspended solids (mg/L) statistics derived from the box (depth 12 metres AHD) covering the Beaches Link mainline tunnel

Statistical parameter	Surface	Mid-depth	Bottom
Maximum	30.0	18.0	17.6
95th percentile	18.1	16.2	16.1
90th percentile	15.9	14.6	14.6
50th percentile (Median)	9.9	9.3	9.0
10th percentile	7.4	7.4	7.2
5th percentile	7.3	7.1	6.9
Minimum	6.9	6.9	6.6

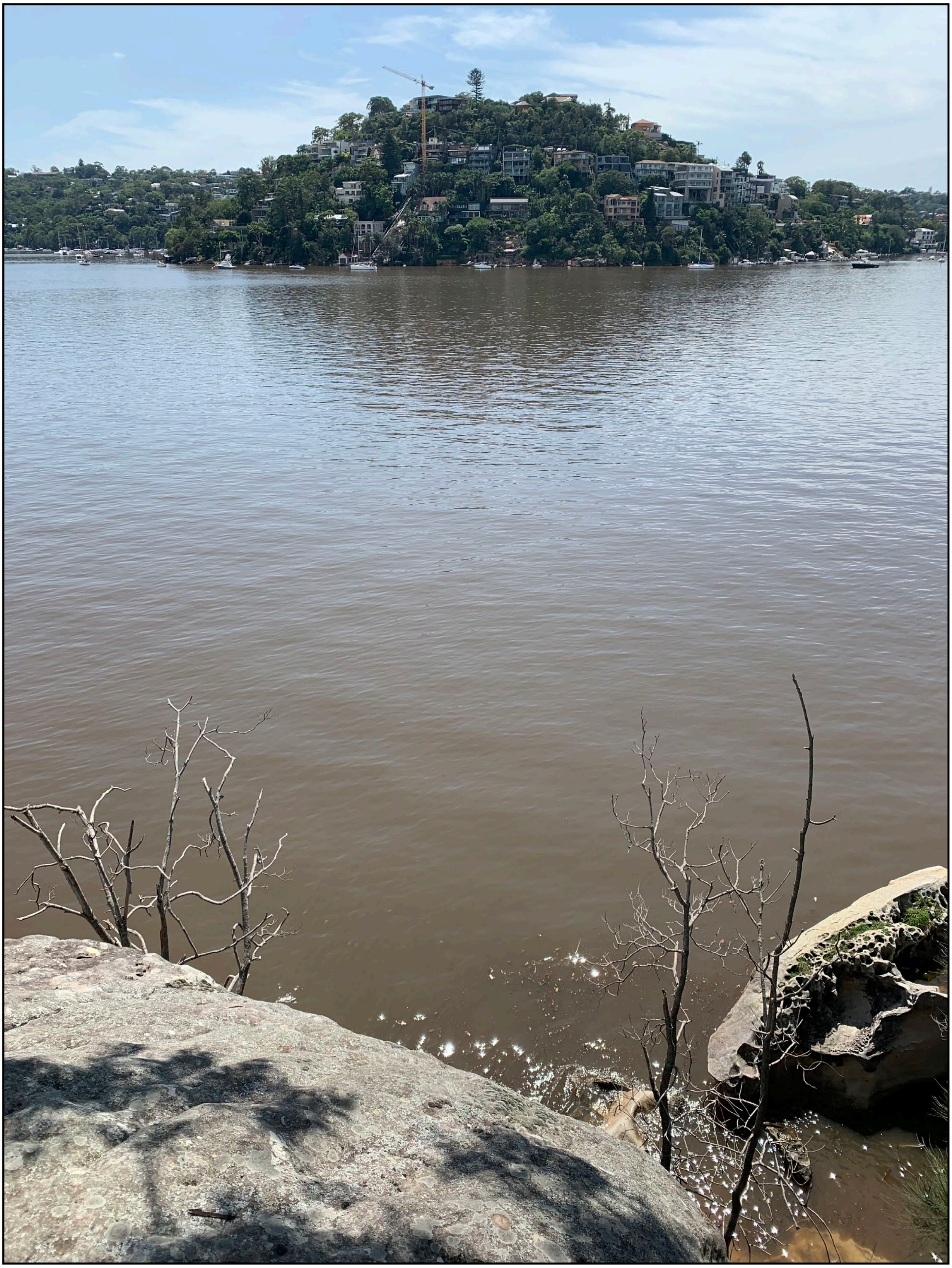


Figure 3-4 Evidence of increased turbidity at Clive Park (looking north) after heavy rain in February 2020

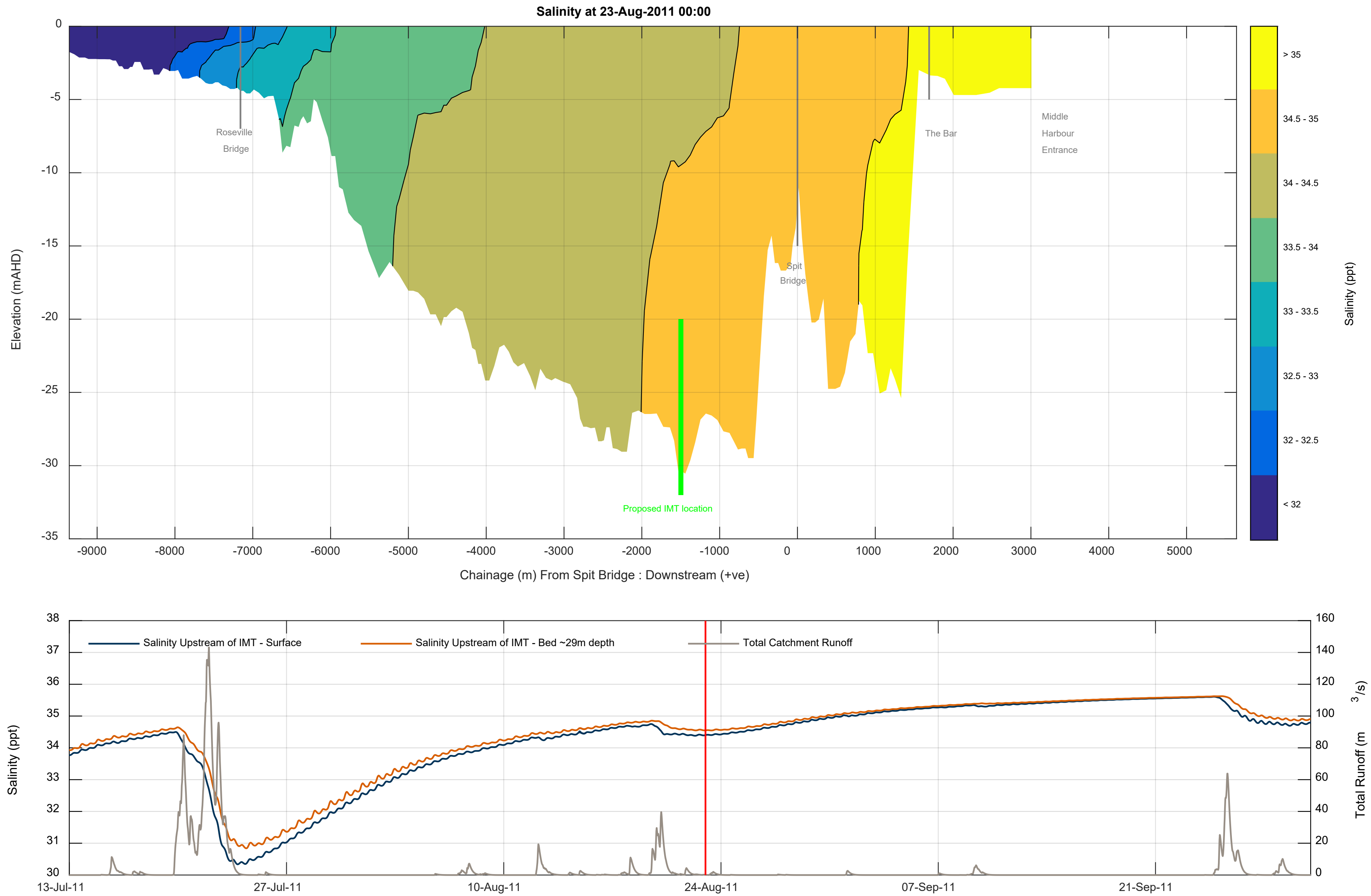


Figure 3-5 SHERM high resolution water quality model salinity results (reproduced from LLS)

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Figure 3-6 SHERM WQBox model total suspended solids (mg/L) in box model cell 22 that includes the immersed tube tunnel location

3.3 Results of field data collection for Sampling Period 1 (December 2017 to January 2018)

3.3.1 Conditions during data collection period

Rainfall, solar radiation and air temperature conditions during Sampling Period 1 are presented in Figure 3-7. Sampling Period 1 was drier than average, with monthly total rainfall of 47 millimetres and 37.8 millimetres for December and January respectively, compared to the long term monthly mean values of 101.7 millimetres and 117.5 millimetres. Rainfall was recorded on 29 of the 61 days during the period, with the average rainfall day of 2.9 millimetres. The largest rainfall event occurred on 9 January 2018, when 18.6 millimetres fell over a 24 hour period.

Downwards short wave solar radiation (DSWR) and daily global solar exposure (DGSE) are presented in Figure 3-7. Over the 61-day period, about 20 days received less than 20 megajoules per square metre of DGSE indicating moderate to high cloud cover on those days. Conversely, on the 21 cloud free days with subsequently intense solar radiation, DGSE was typically 30 megajoules per square metre and shortwave radiation (DSWR) peaked at about 1000 watts per square metre.

In terms of air temperature, Sampling Period 1 was hotter than average, with an average daily maximum of 27.8 °C and 27.9°C for December and January respectively, compared to the long term averages of 25.2°C and 26.0°C. December experienced four days exceeding 35°C, with a maximum temperature of 38.3°C on 20 December 2017. January experienced one day exceeding 35°C, with a maximum recorded temperature of 43.4°C on 7 January 2018.

Figure 3-8 shows that winds during Sampling Period 1 generally followed the daily sea-land breeze cycle with higher winds in the afternoon (peaking at about 25 to 35 kilometres per hour), followed by calmer periods during the evening. Winds were predominantly north-easterly, interspersed with periods of stronger southerlies. A maximum wind speed of about 60 kilometres per hour was recorded on both 14 and 20 December 2017. A noticeably high wind period was recorded during the deployment from 14 to 16 January 2018 when strong south to south westerly winds exceeding 30 kilometres per hour persisted for over 72 hours.

Tides during Sampling Period 1 displayed the typical fortnightly spring/neap cycle, with periods of particularly large spring tides experienced during early December, early January and late January, as indicated by the daily average tidal range. Spring tides at this time of year are generally stronger (that is, high tides are higher and low tides are lower) due to the Earth’s position in its elliptical orbit being closer to the sun (in an orbital phase called perihelion). These spring tides were further exacerbated by the presence of a “supermoon” (the phenomenon whereby a full moon or a new moon approximately coincides with the closest distance that the Moon reaches to Earth in its elliptic orbit).

Consequently, the astronomical tide reached close to the local long term Highest Astronomical Tide (HAT) of 1.1 metres AHD on seven occasions during Sampling Period 1. Figure 3-8 shows tidal residuals of +0.1 metres to +0.3 metres during these periods resulted in the extremely high tides recorded at Fort Denison. Peak tide levels of 1.35 metres AHD, 1.36 metres AHD and 1.15 metres AHD were recorded on 6 December 2017, 3 January 2018 and 31 January 2018, respectively. Figure 3-8 shows that the daily tide range during these periods was generally about two metres.

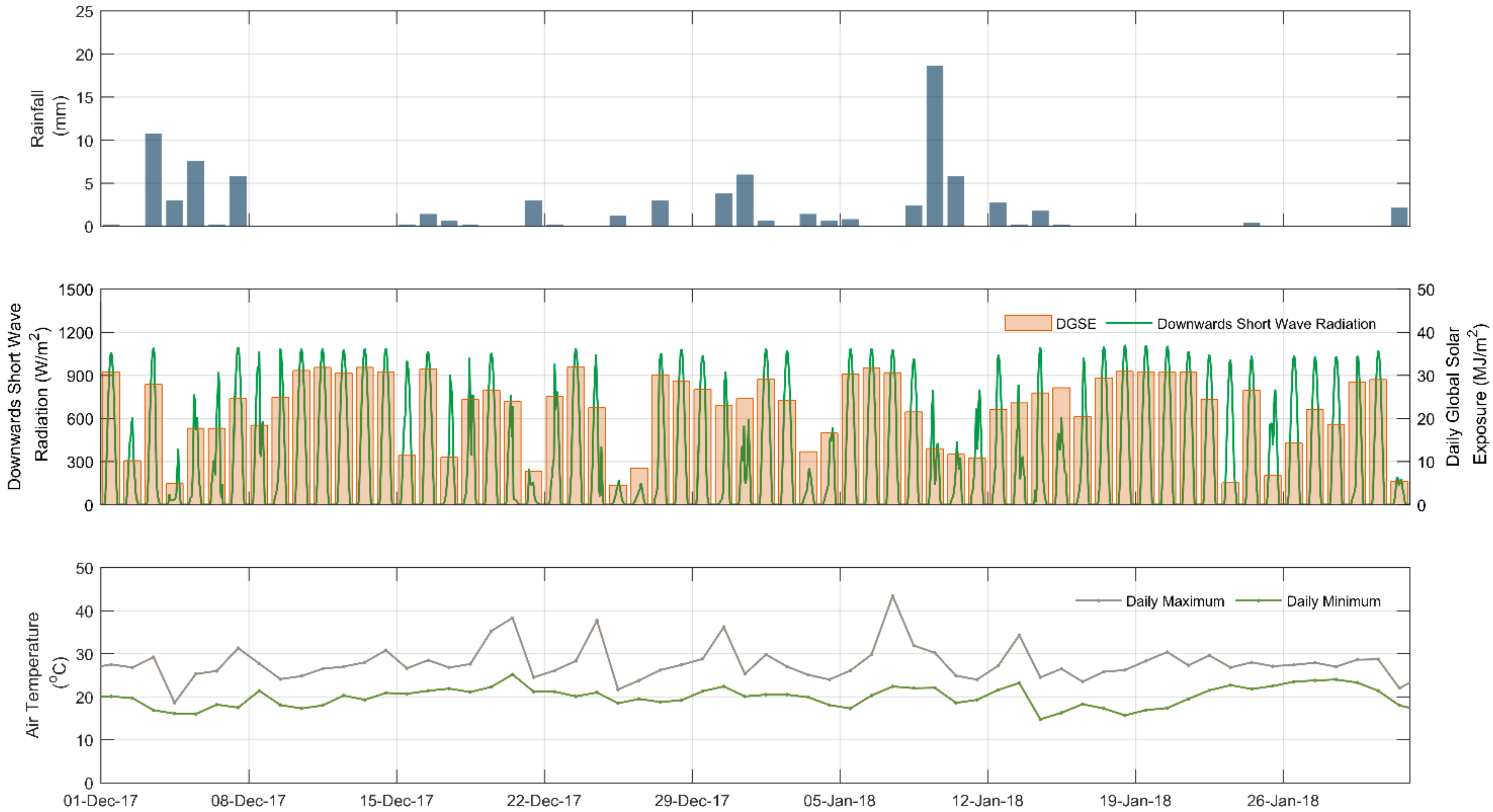

Figure 3-7 Rainfall, solar radiation and air temperature during Sampling Period 1

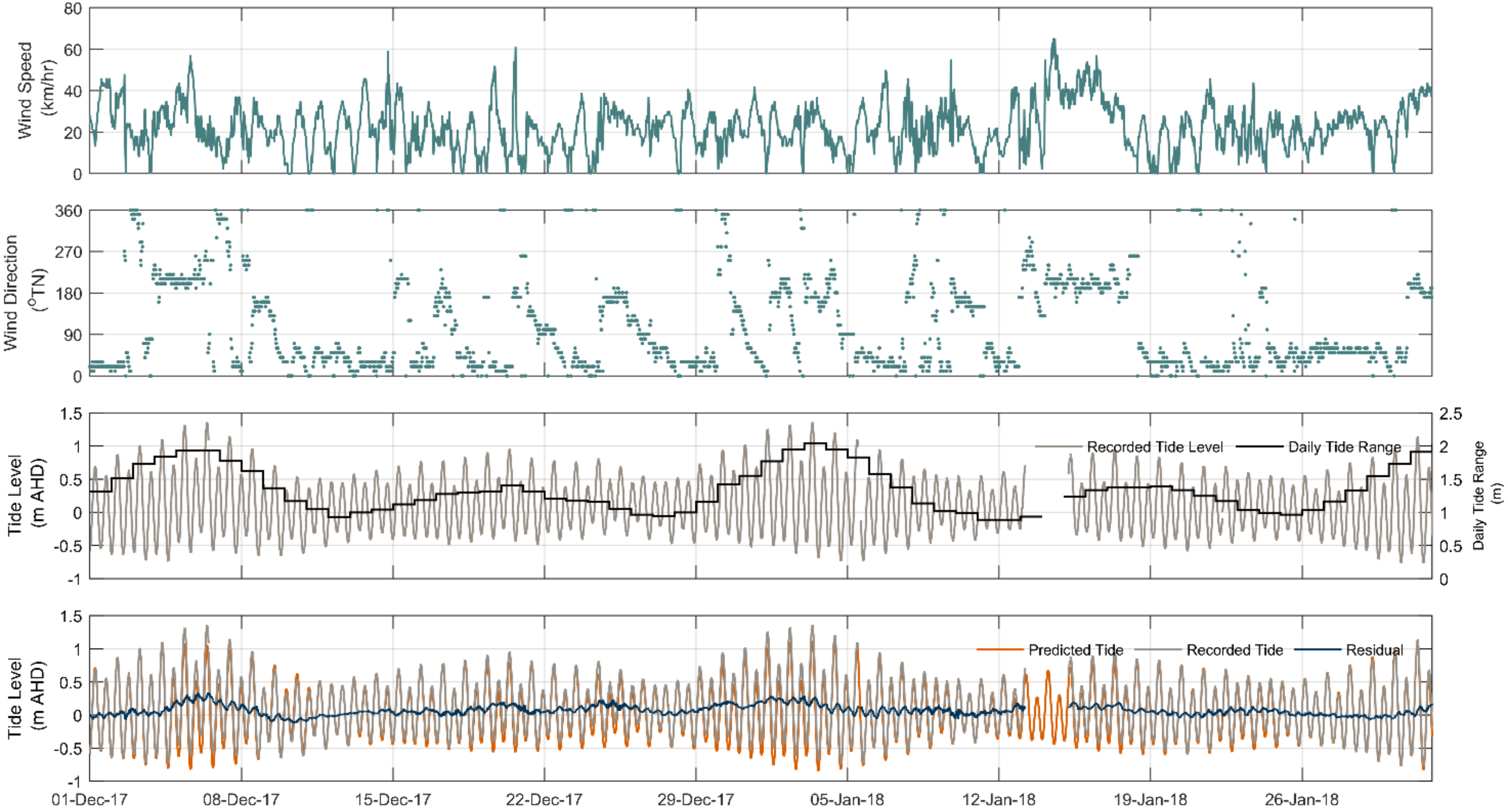

Figure 3-8 Wind and tide conditions during Sampling Period 1

3.3.2 Salinity and turbidity

As highlighted in Section 3.1.1, Sampling Period 1 was drier than average and the influence of this low rainfall is evident in the monitoring water quality parameters. Data collected at moored logger locations BL1 and BL2 shows measured time series of near-bed turbidity, salinity, temperature, alongside water levels and rainfall (Figure 3-9). Note the logarithmic scale on the turbidity figure to highlight the variability across the range of values. Figures showing the data collected at both sites are presented in Annexure A.

There was very little variation in turbidity over the two months, with the maximum hourly average less than three NTU. A very small increase in turbidity was evident from 17 January to 20 January 2018.

Turbidity recorded via vertical profiling was compared to the total suspended solids derived from laboratory analysis of additional water samples collected concurrently. No clear relationship could be derived from the measurement data set given the small magnitudes of the turbidity for the monitoring period.

Water temperatures ranged from 21°C to 26°C, gradually increasing over the sampling period, as the warmer weather continued into the summer period. This temperature range was consistent for both moored logger sites.

The near-bed salinity values ranged between 34.4 and 35.6 practical salinity units. Following a rainfall event on 9 January 2018, salinity decreased by about 0.7 practical salinity units. Following this event it remained dry for the second half of January and the salinity gradually increased by about 1.0 practical salinity unit over the three-week period.

Turbidity was found to be relatively consistent across the two moored logger sites, BL1 and BL2, over the two-month monitoring period (refer to Table 3-8, Figure 3-9 and Annexure A). Generally, values were less than five NTU with a median value less or equal to 0.5 NTU (refer to Table 3-8, Figure 3-9 and Annexure A). A large proportion of the turbidity values were very low and within the sensor accuracy (±2 NTU). Data from BL2 is provided in Table 3-8 below due to its location at the proposed crossing location at Middle Harbour. Raw data for BL1 is provided in Annexure A.

Table 3-8 Instantaneous turbidity statistics (in NTU) at Middle Harbour site BL2, located at the proposed crossing site, for Sampling Period 1

Statistical parameter	Ambient turbidity (NTU)
95th percentile	1.0
90th percentile	0.9
50th percentile (median)	0.5
10th percentile	0.3
5th percentile	0.3
Number of good samples	5360

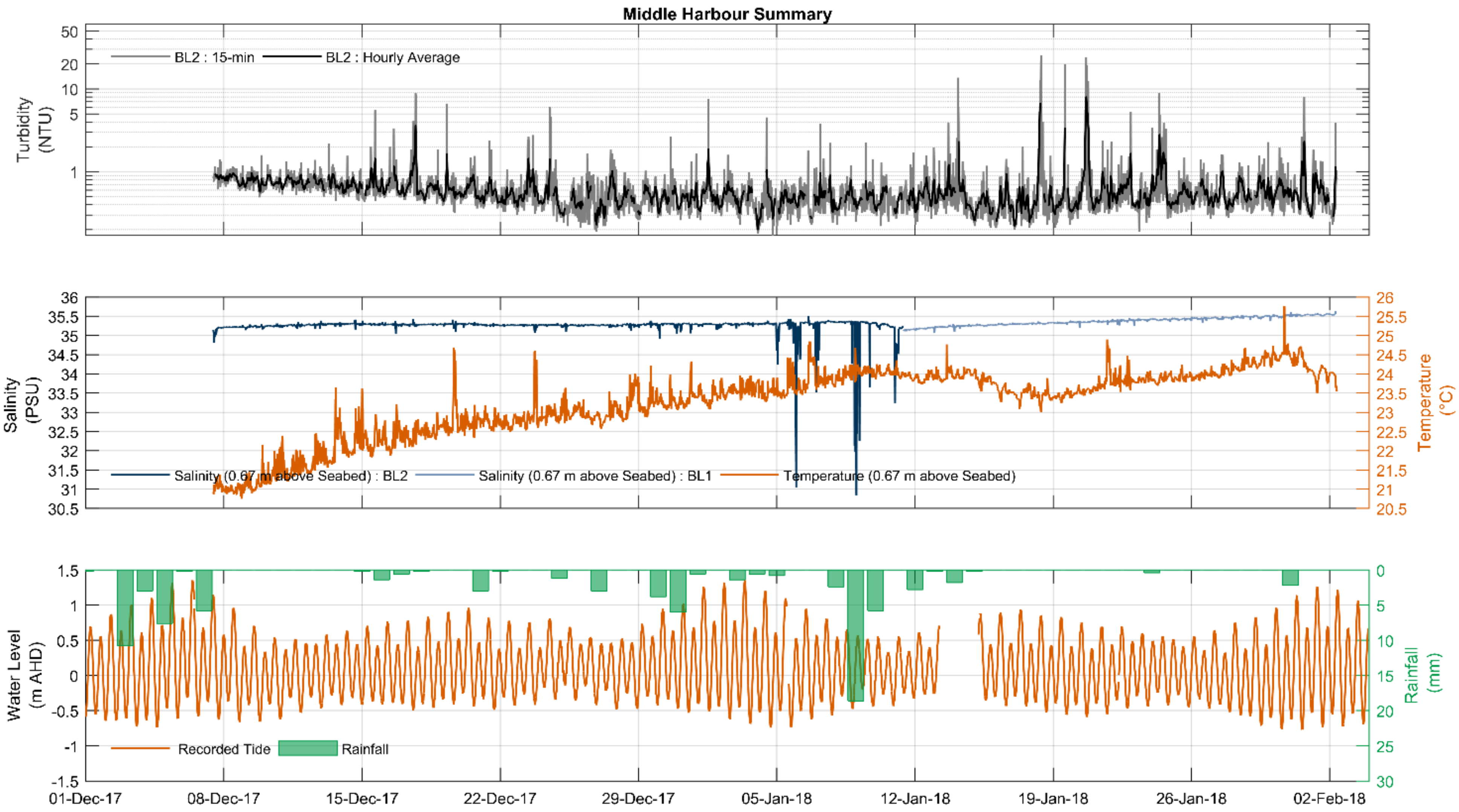

Figure 3-9 Turbidity (BL2), salinity (BL1 and BL2), temperature (BL2), water level and rainfall time series from moored logger sites during Sampling Period 1

3.3.2.1 *Vertical structure of Middle Harbour*

To investigate the vertical and longitudinal structure of the waters in Middle Harbour, water quality profiles were collected at six sites along the centreline of Middle Harbour, as well as the two moored logger locations, on 18 January 2018 and 30 January 2018. The vertical profile depths ranged from nine to 32 metres along the sites that were aimed to sample at the deepest point of the cross section. Vertical profiles of turbidity, salinity, density, PAR (measured and modelled), dissolved oxygen and chlorophyll-*a* are presented against depth below the water surface for site BLP2 (upstream of the sill that will be created by the crossing) in Figure 3-10. Data for all eight profile sites are presented in Annexure A.

The 18 January 2018 sampling occurred just over a week after a few relatively small rainfall events during the second week of January. The 30 January 2018 sampling followed a dry period of two weeks when no rain fell and it would be expected that the saline oceanic waters would progress upstream as a salt wedge through this period.

There is evidence of the spatial variation between the eight sites and temporal variation between the two sampling days. As with near-bed turbidity measured by the moored loggers, the profile turbidity was consistently very low, less than 3 NTU, at all sites, for both sampling days. In the deeper sites there appears to be a benthic boundary layer about four metres thick where the turbidity and other water quality variables show persistent character.

Chlorophyll–*a* was often higher deeper in the water column and generally higher during the 18 January 2018 sampling. On 18 January 2018, dissolved oxygen shows a weak vertical gradient from about 7.0 milligrams dissolved oxygen per litre at the surface to about 6.5 milligrams dissolved oxygen per litre near the bed of the harbour at 27 metres depth. On 30 January 2018, the surface water dissolved oxygen was still about 7.0 milligrams dissolved oxygen per litre but the near-bed value had decreased to 3.5 milligrams dissolved oxygen per litre.

The PAR profiles indicate good light penetration through the water column as is expected with the clear waters. The euphotic depth, where light decreases to one per cent of its surface value, was typically greater than 15 metres depth.

Temperature and salinity, or TS, characteristics provide a useful means of tracking water masses. For the profiles collected 12 days apart it appears there are three distinct layers in which the TS signature shows a range of features that can be used to infer water exchange and mixing. The profile at site BLP2 (Figure 3-10) indicates a surface layer to a depth of about six metres, a middle layer from six to 22 metres and a four metre thick deeper benthic layer from 22 metres to the bed of the harbour at 26 metres.

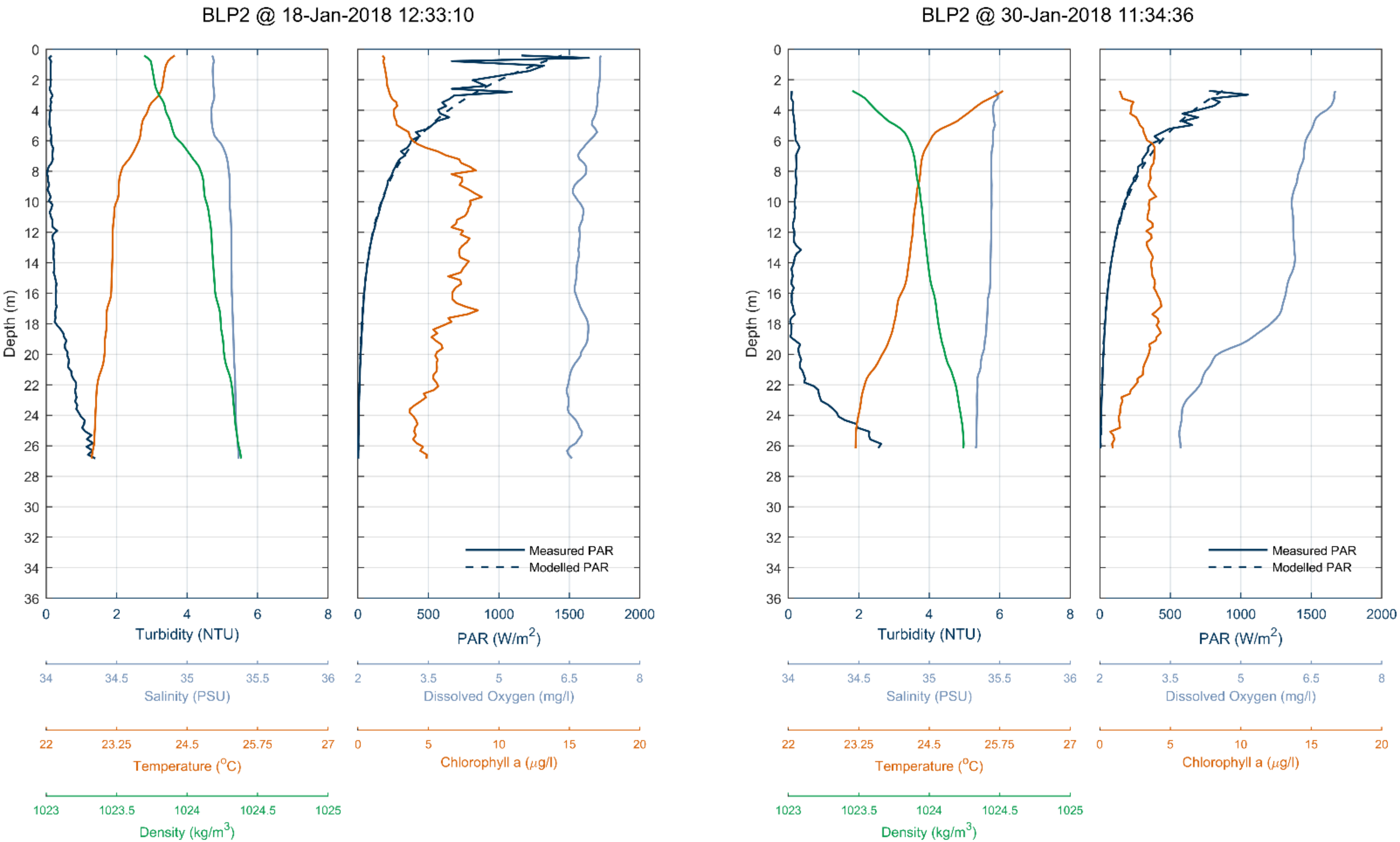

Figure 3-10 Vertical profiles of water quality parameters at Site BLP2 on 18 and 30 January 2018

The TS signature (refer to Figure 3-11) of the deep layer remains very similar with a slight warming between the two dates indicating that this water has remained within the reach for some period during the intervening 12 days. The middle layer TS signature shows the presence of new water of warmer temperature and higher salinity on 30 January 2018. Salinity on 30 January 2018 shows higher values in the middle layer overlying lower salinity deep waters. Normally this would indicate an unstable salinity and water density gradient but in this case the density was also being influenced by the higher temperature. The surface layer also indicates different TS characteristics on 30 January 2018. The shift in middle layer water from 18 to 30 January 2018 indicates the exchange with the warmer and more saline ocean water replacing the waters within this layer on 18 January 2018.

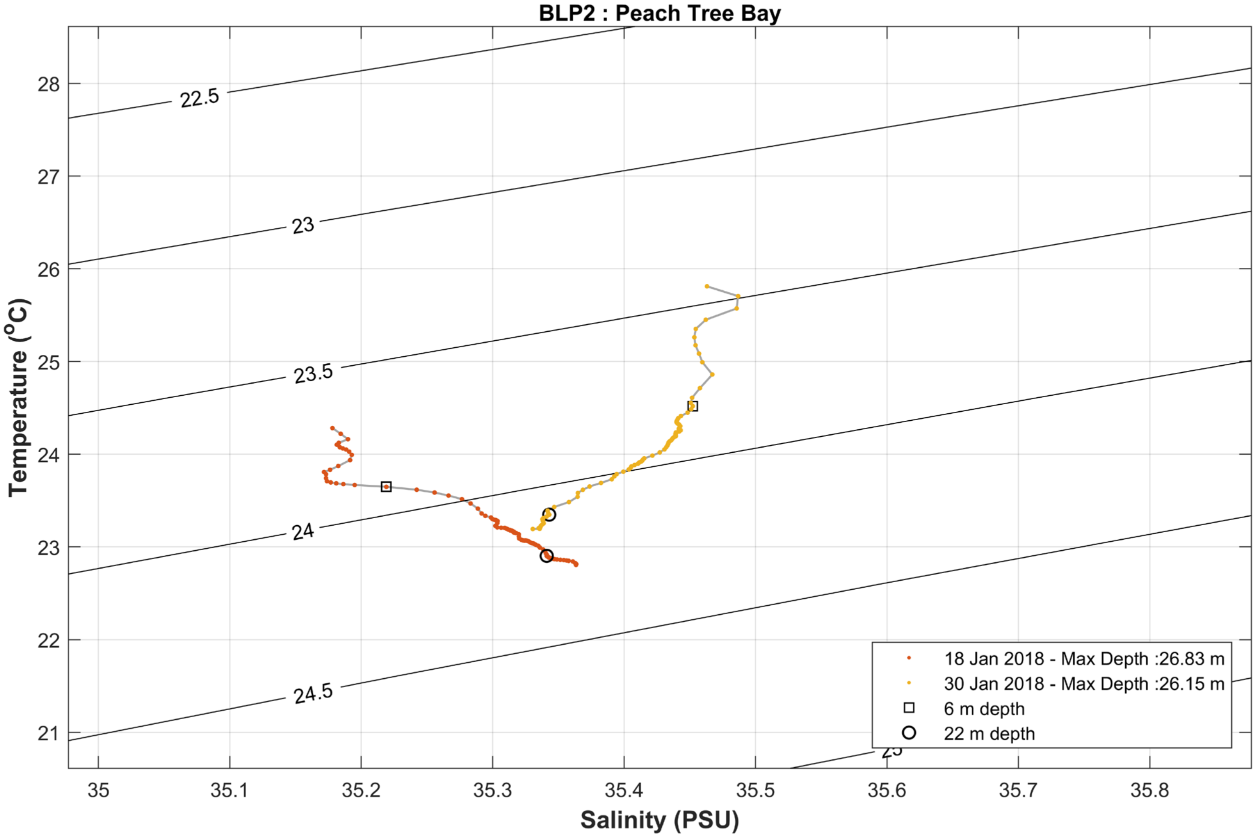

Figure 3-11 Temperature/salinity diagram for profile data at Site BLP2 on 18 and 30 January 2018

The partially mixed nature of the system on 18 January 2018 can be seen with recent upstream freshwater inflows sitting on top, as well as slightly fresher water in the deeper areas upstream. This marine water salt wedge extends into Middle Harbour as evident at and just upstream of the Spit Bridge. Stratification is likely to be impeding the vertical mixing within the benthic boundary layer and thereby limiting the vertical water exchange.

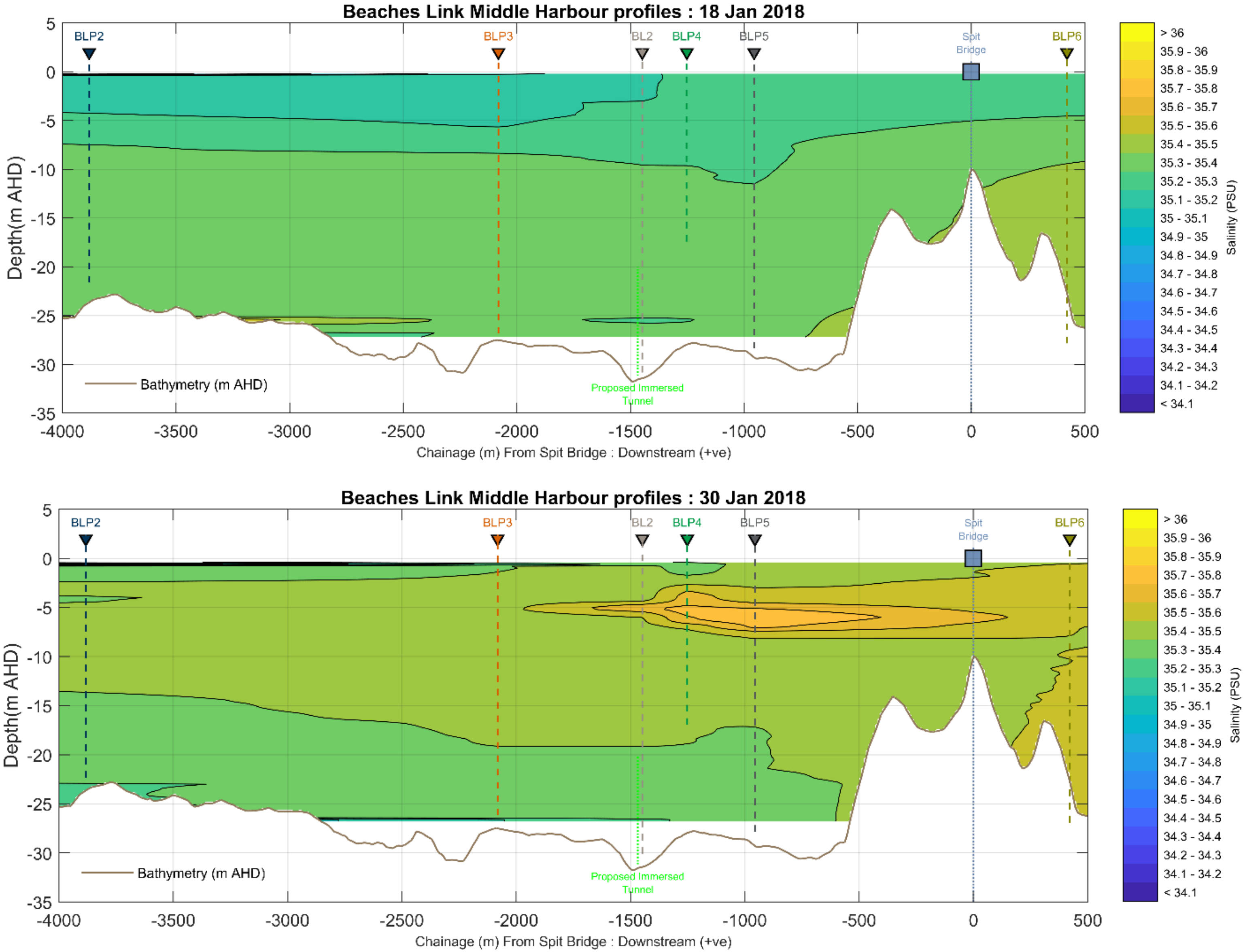

Figure 3-12 Salinity along Middle Harbour on 18 and 30 January 2018 derived from the six profiles indicated above the figure

The long section snapshot of dissolved oxygen on 30 January 2018 (refer to Figure 3-13) shows the higher dissolved oxygen (about seven milligrams per litre) in the middle layer between three and 10 metres depth. The deeper sections of this long section, nearer to the harbour bed, were much lower (less than 3.5 milligrams per litre). It is likely that these low values reflect the microbial consumption of dissolved oxygen and organic material at the harbour bed and influencing the benthic boundary layer. This high oxygen demand at the harbour bed results in the reduction of dissolved oxygen levels in the overlying waters. As indicated in the profiles and long section, the dissolved oxygen decreases from seven milligrams per litre to low values as the deeper waters upstream of the sill reside in this area for a period, possibly a few days to a week sufficient to allow the near-bed volume of water to be gradually depleted of dissolved oxygen.

Generally, the rapid vertical mixing and water exchange lead to rapid recovery from these low dissolved oxygen periods. The lower dissolved oxygen values evident in deeper areas of the long section indicate that vertical stratification, potentially associated with the fjord-like salt wedge exchange, may be impeding the vertical mixing of the deep waters. The continuous nature of the tidal exchange and intermittent fresh events suggests this situation may occur during the late summer/autumn period when the freshwater input maintains lower salinity harbour waters.

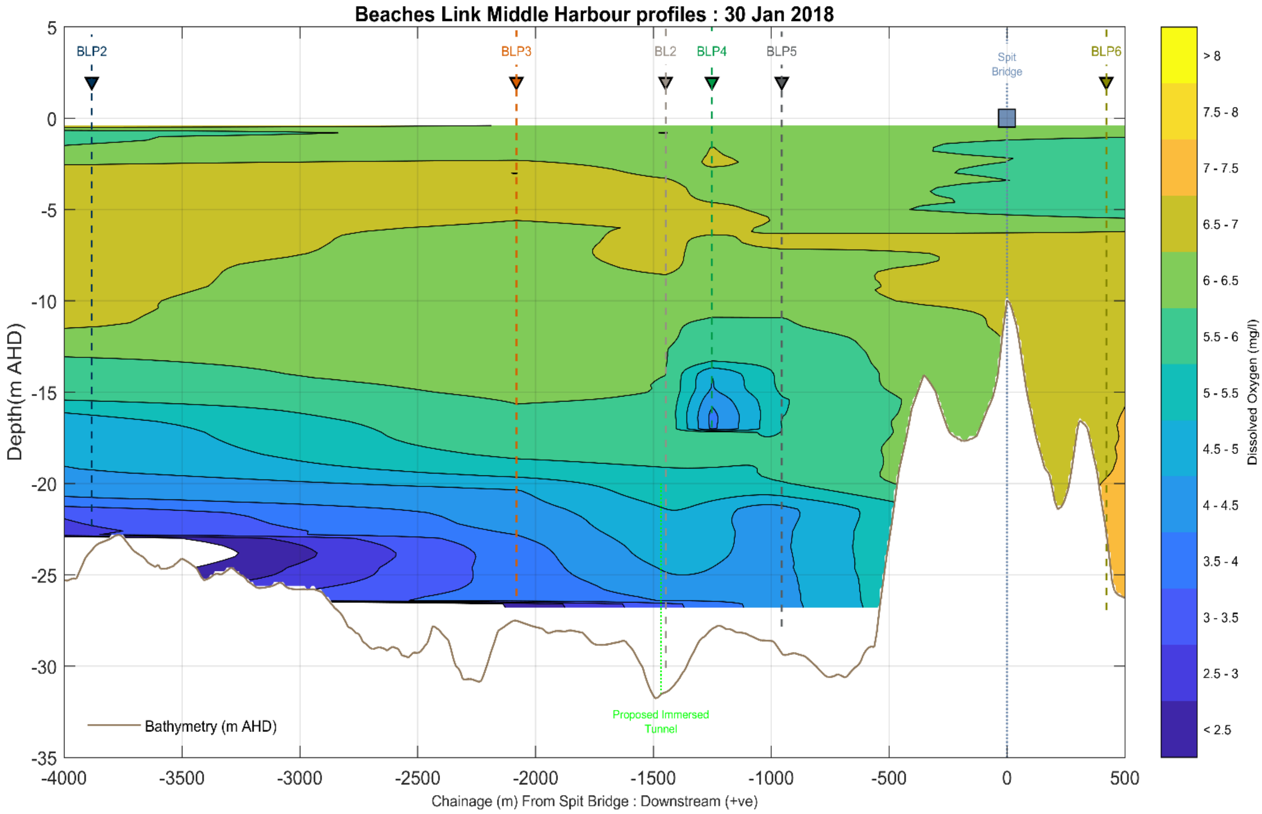

Figure 3-13 Dissolved oxygen concentration along Middle Harbour on 30 January 2018 derived from the six profiles indicated above the figure.

3.3.3 Light extinction

The photosynthetically active radiation (PAR) underwater light data collected at the moored logger sites (refer to Figure 3-14 and Annexure A) and the vertical light profiles were used to determine the light extinction coefficient. The extinction coefficient expresses the rate at which light is dispersed and absorbed by suspended particles as it propagates down through the water column. Applying the exponential decay of light with depth expressed by the Beer-Lambert law a curve fitting routine was applied to the PAR profile to derive the extinction coefficient and surface light values. The fitted curve is shown in the profiles in Figure 3-10 and results of the profile-derived values compared to the moored loggers estimates, at the time of the profile, in Table 3-9.

The PAR values from the moored loggers tended to be slightly lower than the profile readings but the difference between the two depths were consistent between the instruments.

Turbidity and chlorophyll-*a* provide an indication of the suspended particles and micro-plankton that influence the light extinction. Modelling of the extinction coefficient as a function of suspended matter (total suspended solids in milligrams per litre) and chlorophyll-*a* (Chl-*a* in µg/L) concentrations typically uses a relationship for the total extinction coefficient, K, (Cardno, 2015):

$K = k_b + 0.08 \times \text{total suspended solids} + 0.015 \times \text{Chl-}a$,

Where the background clear water extinction, k_b, is about 0.1 m^{-1} and coefficients are derived from field data for the particular water body of interest.

Applying this relationship to the profile information indicates that for typical values of chlorophyll-*a* of four micrograms per litre and low total suspended solids of one milligram per litre (refer to Figure 3-14 and Table 3-9) that the chlorophyll-*a* forms a significant contribution to light extinction and conversely during turbid fresh events the total suspended solids (greater than 10 milligrams per litre) concentration dominates light extinction.

Table 3-9 Light extinction, turbidity and chlorophyll-*a* values derived from the vertical profiles and time-series from the moored loggers

Curve fit parameter	Site BL1		Site BL2	
Time/ Date	12:50 18/01/2018	11:49 30/01/2018	12:04 18/01/2018	11:04 30/01/2018
Profile derived parameters				
Depth at moored logger upper sensor (m)	5.89	5.44	6.97	6.44
Profiler PAR (Wm^{-2})	333	384	357	397
Depth at moored logger near-bed sensor (m)	7.21	6.69	8.20	7.71
Profiler PAR (Wm^{-2})	308	315	285	285
Extinction coefficient, K (m^{-1})	0.24	0.23	0.23	0.23
Surface light, I_0 (Wm^{-2})	1758	1480	1882	1611
Photic depth, z_p (m)	19.0	20.1	19.8	20.2
Profile curve fit coefficient of determination R^2	0.98	0.95	0.96	0.96
Turbidity at moored logger near-bed sensor depth (NTU)	0.2	0.1	0.3	0.3
Turbidity depth-average (NTU)	0.2	0.2	0.2	0.2
TSS depth-average (mg/L)	0.5	0.5	0.5	0.5
Fluorescence chlorophyll-*a* (µg/L)	5.4	3.8	6.7	3.4
Time series parameters				
PAR at moored logger mid-depth sensor (Wm^{-2})	293	300	282	324
PAR at moored logger near-bed sensor (Wm^{-2})	223	237	241	269
Extinction coefficient, K (m^{-1})	0.32	0.33	0.27	0.27
Turbidity (NTU)	0.3	0.3	0.3	2.0
Fluorescence chlorophyll-*a* (µg/L)	1.3	0.9	8.1	3.0

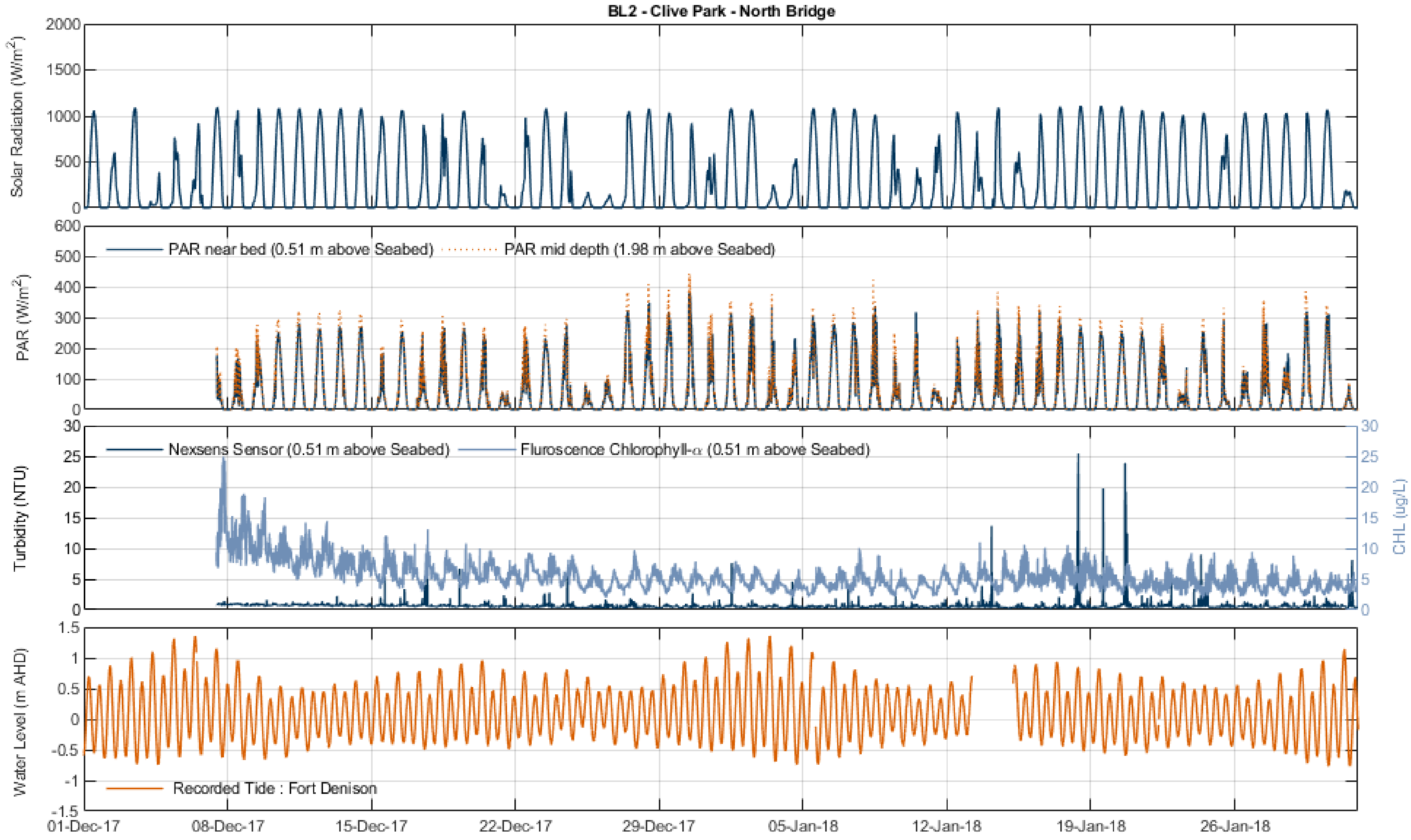

Figure 3-14 Surface radiation, underwater PAR, turbidity and chlorophyll-*a* and water level for moored logger site BL2 during Sampling Period 1

3.4 Summary of background variability in turbidity

The natural variability in total suspended solids in Middle Harbour is characterised by elevated concentrations during wet weather runoff events that decline to very low values during the subsequent dry periods. The duration of elevated turbidity conditions depends on the size of the rainfall/runoff event and intervening period since the previous rainfall event. Sydney's rainfall is distributed across the year and typically dry periods range from a fortnight to a few months. The magnitude and duration of the turbidity peak both increase with the increasing rainfall intensity of the event. Typically, an isolated one-month recurrence rainfall event produces a turbidity response that peaks at about 15 milligrams per litre for about one hour and decreases over the next two days to about five milligrams per litre whereas a one-year recurrence rainfall event produces a peak of about 30 milligrams per litre and declines over the next five to eight days.

When deriving an estimate of the natural variability in total suspended solids concentrations it is important to understand whether the data sets utilised include a representative sample of the underlying statistical distribution. In order to develop an estimate of the total suspended solids variability of the natural waters of Middle Harbour total suspended solids data sets from various sources that each represent different subsamples of the underlying distribution are summarised in Table 3-10. The three available data sets are characterised by the particular conditions during sampling. Comparing the three data sets suggest the SHERM results represent a higher estimate of low range total suspended solids (less than median) values, while the CMA and collected data do not include samples representative of high rainfall/runoff events.

Table 3-10 Summary of total suspended solids (TSS) and rainfall statistics from various data sources, for Middle Harbour

Statistical parameter	SHERM data TSS (mg/L)	CMA data TSS (mg/L)	Collected data TSS (mg/L)
Maximum rainfall recurrence event during collection	1 year	6 month	<1 month
Sampling interval	1 hour	~1 month	5 minutes
95th percentile	17.3	4.4	1.6
90th percentile	15.4	3.7	1.4
50th percentile (median)	9.8	1.7	1.0
10th percentile	7.5	0.6	0.7
5th percentile	7.4	0.3	0.7

The natural variability in total suspended solids was determined by combining subsets of the three data sets selected based on the one month sampling of the CMA data. A random selection of three values from the collected time series observations (two month duration) from moored loggers, the complete CMA data set (Harrison, 2013) at the two nearest Middle Harbour sites and the eight points of the modelled peak total suspended solids extracted from the eight events following rainfall events with recurrence intervals greater than one month. The results of this process, the estimated total suspended solids variability of the existing waters of Middle Harbour in the vicinity of the mainline tunnel alignment, are presented in Table 3-11. These values were used to support the impact assessment.

Table 3-11 Natural variability in total suspended solids percentile values in Middle Harbour near the immersed tube tunnel crossing location

Statistical parameter	Existing waters TSS (mg/L)
95th percentile	15.9
90th percentile	9.1
50th percentile (median)	1.7
10th percentile	0.6
5th percentile	0.3

3.5 Results of field data collection for Sampling Period 2 (April to June 2020)

3.5.1 Conditions during collection period

Weather conditions during the five-week sampling period conducted from 23 April to 1 June 2020 were generally drier than average but a relatively large event of strong winds and significant rainfall (greater than 50 millimetres in 24 hours) occurred in late May some six days prior to the completion of the field work (see Annexure B).

3.5.2 Dissolved oxygen and salinity

Following the rainfall event in late May (described above), the dissolved oxygen concentration within the deep basin upstream of the Spit Bridge sill decreased. Compared to the similar event in January 2018 (refer to Section 3.3.2.1), the temperature and salinity vertical profiles showed a much deeper mixing layer. The mixing layer included the part of the water column between the seabed and about 15 metres above it. Inflow waters were restricted to a surface layer some 10 metres deep (refer to Annexure B). Within the bottom layer, the dissolved oxygen declined at a rate of around one per cent dissolved oxygen concentration per day. This rate reflected the difference between the rate of depletion at the bed due to the sediment oxygen demand and the rate of replenishment of dissolved oxygen into the bottom from mixing with the surface waters.

The autumn sediment oxygen demand is likely to have been lower than the event in January 2018 due to the cooler water temperature (reduces microbial metabolism and oxygen demand) and relatively low amount of fresh organic material due to the low runoff during the preceding dry conditions. Further, the large volume of the relatively deep bottom layer in late autumn results in more effective replenishment of dissolved oxygen from the surface thereby maintaining dissolved oxygen concentrations at reasonably high levels within the deep water. The dissolved oxygen concentrations were continuing to decrease at the cessation of the field work on 1 June 2020.

Seasonal variability in the temperature and salinity characteristics and salt wedge/fjord-like behaviour (refer to Figure 3-1) leads to considerable variation in the flushing characteristics of the deep water. Flushing times were estimated at about 1.5 days (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)) although, under stratified conditions, water in the bottom boundary layer upstream of The Spit sill may reside for longer periods and thereby promote conditions more favourable to the depletion of dissolved oxygen in the bottom layer.

Based on average annual rainfall patterns (greater than 50 millimetres of rainfall in 24 hours occurs about three to four times per year, refer Table 3-2), the conditions leading to the dissolved oxygen depletion near the seabed to about 50 per cent saturation concentrations are likely to occur naturally a few times per year and particularly during the warmer late summer and autumn period. Conditions where dissolved oxygen concentrations reduce to lower than 50 per cent saturation are also likely to occur once or twice in a summer/autumn season. Extreme events of prolonged dissolved oxygen depletion to about two milligrams dissolved oxygen per litre could occur following a large rainfall event following drought, which has been suggested to occur about once every seven to 10 years.

3.6 Results of siltation estimates

Assessment of historical information derived from sediment cores and discussions with Professor Gavin Birch of the University of Sydney, indicated that the rate of siltation upstream of the tunnel crossing will likely increase by a maximum factor of 6.5/5.5 = 1.18, or to about 3.9 millimetres per year rather than the current estimate of 3.3 millimetres per year. There is likely to be some leakage of sediment over the tunnel sill leading to a smaller rate of sedimentation upstream. There would be a related decrease in siltation rate downstream of the tunnel sill. Moreover, the height of the immersed tube tunnel crossing sill above the bed of the harbour reduces from 9.2 metres at the deepest point to zero as it disappears into the north and south tunnel entrances. Assuming a parabolic harbour bed cross-section profile, it is expected that the increased siltation rate upstream of the sill would be to around 3.7 millimetres per year, or an increase of about 0.4 millimetres per year (four millimetres per decade) higher than the existing rate. Practically, present day harbour bed depth sounding instruments have an accuracy typically of about 20 millimetres; hence a change in sedimentation due the immersed tube tunnel crossing would be difficult to resolve within about 50 years.

A second estimate of sedimentation rate within Middle Harbour has been made by assuming all of the catchment derived total suspended solids contributes to sedimentation upstream of the natural sill located about 500 metres upstream of the Spit Bridge. Assuming that the sedimentation is equally distributed over the waterway area below negative one metre AHD, a dry bed density of 600 kilograms per cubic metre, then the current sedimentation upstream of the Spit Bridge was estimated using the SHERM model to be about 1.9 millimetres per year, on average.

A similar analysis using the waterway area and catchment inputs upstream of the proposed immersed tube tunnel crossing sill gives a slightly higher sedimentation rate of about 2.2 millimetres per year, on average. This equates to an extra three millimetres of sedimentation over a 10 year period. These values are area averaged, and are likely to be slightly higher in the deeper portions of Middle Harbour, and lower in the shallower reaches. It is also likely that a portion of the sediment would leak over the sill, leading to lower siltation rates.

4 Potential impacts

4.1 Construction

Potential impacts on marine water quality may occur during the following project construction activities:

> Dredging and excavating of harbour sediments
> Harbour construction activities
> Land based construction activities.

Dredging and excavating of harbour sediments and construction activities have the potential to impact marine water quality through the following key impact pathways:

> Increased turbidity as the dredge plume disperses into the harbour waters and the associated reduction in light that may restrict periods of growth of primary producers such as seagrass and rocky reef aquatic plants
> The settlement of suspended sediments generated by dredging and excavating on plant habitats causing smothering of benthic plants and organisms
> Increased turbidity associated with construction activities (ie piling, construction of temporary wharf facilities and vessel movements)
> Mobilisation of contaminants associated with the transportation and dispersion of disturbed sediments
> Direct impact on water quality from discharges, runoff, spills and leaks.

There are a range of water quality processes that influence turbidity and sedimentation within the natural environment (refer to Section 3.1). These same processes drive the transportation and dispersion of dredging-related excess suspended sediment concentrations (refer to Figure 4-1). However, dredging-related excess suspended sediment concentrations would lead to an increase in the frequency of occurrence of elevated turbidity and total suspended solids and potentially a persistence of the elevated total suspended solids over periods longer than the period to which the natural system is adapted.

Short intense bursts of elevated total suspended solids may also affect marine ecology. Sensitive habitats may respond to these stimuli differently. For example, seagrasses are adapted to very short bursts of intense turbidity that occur during significant freshwater runoff events and hence are unlikely to be sensitive to intense bursts associated with the excess dredging effects. They are more sensitive to prolonged periods of darker conditions and hence the frequency and duration of excess SSC are more likely to be of concern.

Harbour construction activities that have the potential to impact marine water quality associated with the project include:

> Construction activities that are carried out directly within the waterway or harbour, including dredging, excavating and piling activities for cofferdams as well as construction of construction support site infrastructure at Spit West Reserve construction support site (BL9). These activities have the potential to reduce water quality as well as the potential to disturb contaminated sediments
> Vessel movements that have the potential to generate localised plumes of excess suspended sediments associated with vessel wash in shallower waters, generally less than five to ten metres deep
> Potential for spills or leaks of fuels and/or oils from maintenance or re-fuelling of construction plant or equipment that could eventually discharge into waterways or directly to waterways (in the instance of harbour construction activities)
> The transport, treatment and/or temporary storage of dredged and excavated materials that are unsuitable for offshore disposal.

Land based construction activities that have the potential to impact marine water quality due to construction activities occurring immediately adjacent to marine water bodies include:

> Land based activities that lead to the exposure or handling of soils (including removal of pavement, vegetation clearance, stripping of topsoil, excavation, disturbance of contaminated soil, stockpiling and materials transport). This may result in soil erosion and off-site transport of sediment via air or runoff to receiving waterways. This could impact water quality, such as increased turbidity, lowered dissolved oxygen levels and increased nutrients

> Potential for spills or leaks of fuels and/or oils from maintenance or re-fuelling of construction plant or equipment or vehicle incidents that could be eventually discharged to waterways (if carried out on land).

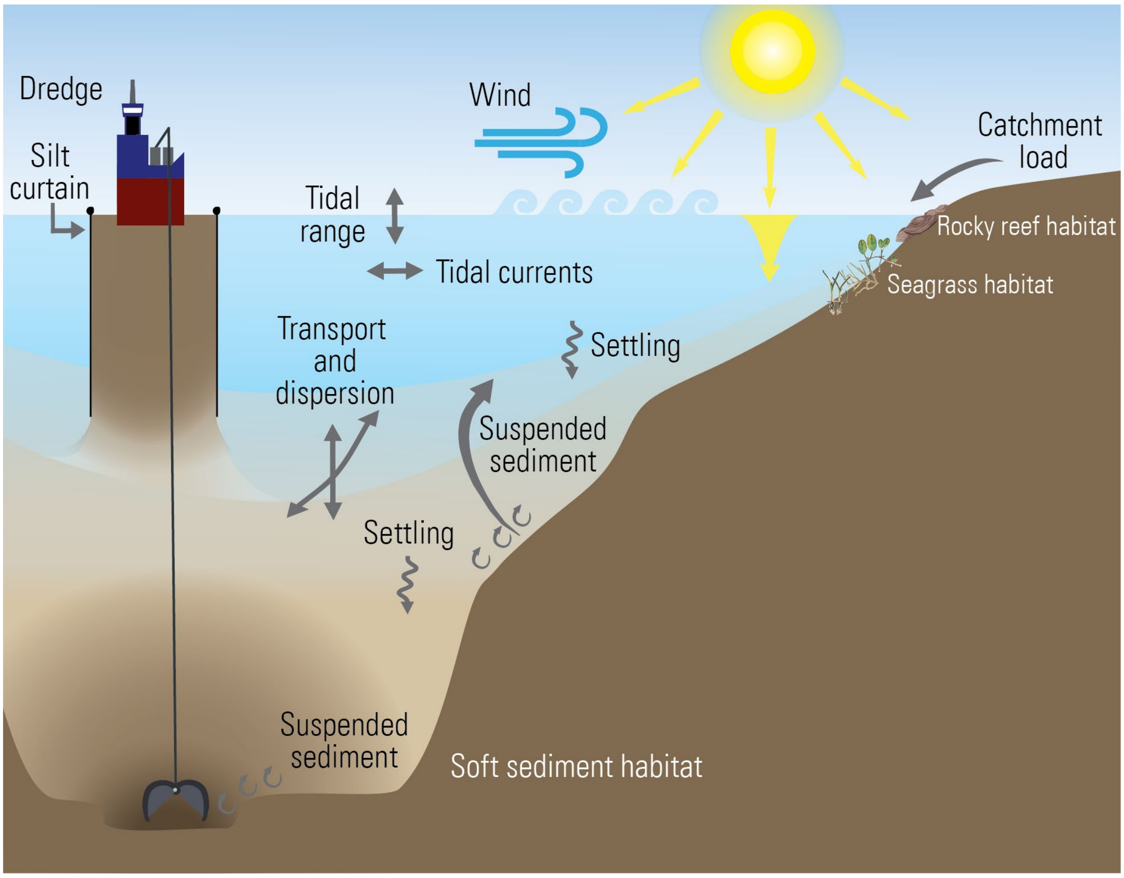

Figure 4-1 **Schematic showing the effects of dredging. NB Actual operations will include additional silt curtains around a moon pool on the dredge vessel and around nearby sensitive nearshore habitats**

Sediment sampling carried out for the project (Douglas Partners and Golder Associates, 2017; also refer to Appendix M (Technical working paper: Contamination)) found that selected contaminant concentrations within Middle Harbour sediments were above guideline criteria (where available). These contaminants were within the top one metre of sediments with minor detections of contaminants above guideline criteria from deeper sections. Contaminants above guideline criteria included:

> Polycyclic aromatic hydrocarbons (PAHs)

> Total recoverable hydrocarbons (TRHs)

> Organochlorine pesticides (OCPs)

> Tributyltin (TBT)

> Heavy metals

> Mercury

> Lead

> Silver

> Zinc.

Dredging and project construction activities have the potential to mobilise these contaminants. Dredging of these materials would be carried out using a backhoe dredge with a closed environmental bucket, mounted on a barge to remove the top layer of sediment that contains most of the high concentration material. Backhoe dredging operations would be completed within a floating silt curtain enclosure (or ‘moon pool’) that is secured to the dredge barge. This would comprise a fixed or floating boom upon which a shallow draft (two to three metres deep) silt curtain is attached to provide a controlled area for the dredge operator to work within. Additional containment of suspended sediments would be provided by the installation of deep draft silt curtains (ie silt curtains about 12 metres deep) situated at either side of the proposed project crossing location where the majority of the dredging will occur (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)). This method provides current best practice for removal of potentially contaminated sediments while minimising the leakage of fine material to the surrounding waters. Silt curtains would also be placed around sensitive nearshore habitats adjacent to dredging operations.

4.2 Operation

Secretary's environmental assessment requirement 6.10 (refer to Section 1.7) requires an assessment of potential impacts of the crossing of Middle Harbour on benthic ecology that could occur as a consequence of changes to tidal flushing. Tidal flushing upstream of the crossing has potential to be affected by the sill that would be created by the crossing. At the deepest point in the crossing alignment, the top of the immersed tube tunnel is projected to be at a level of 22 metres below mean sea level (~AHD) and about nine metres above the existing bed level of -32 metres AHD (refer to Figure 1-2 and Figure 1-3).

In the longer term, the sill created by the immersed tube tunnels has the potential to reduce water exchange and thereby increase residence times of the near-bed waters upstream of the sill (refer to Figure 4-2). Increased residence time of the deep water upstream may lead to longer periods of low dissolved oxygen concentrations in deep near-bed waters below the sill level (which varies between 16 metres and 22 metres, depending on the distance from the immersed tube tunnel connections to the subterranean tunnels near the shore) and/or increased siltation behind the sill. Lower dissolved oxygen concentrations may lead to nutrient release from the sediments and subsequent vertical mixing into the photic zone may stimulate additional algal growth near the surface.

Results of the project specific data collection indicated lower dissolved oxygen concentrations occur naturally within Middle Harbour deep waters and particularly in the basin formed by the existing sill at level -9.2 metres AHD located 500 metres upstream of the Spit Bridge (refer to Figure 4-2). The presence of an extra sill in Middle Harbour that would be created by the crossing has the potential to increase residence times of the deeper waters immediately upstream of the sill by about 30 per cent from 1.6 days to 2.4 days. It would also promote conditions more favourable to the depletion of dissolved oxygen in the bottom boundary layer, albeit in a relatively small volume of water affected by the sill created by the crossing.

The sill created by the crossing would likely increase the rate of mud siltation upstream of the crossing by three to four millimetres per decade (refer to Annexure C).

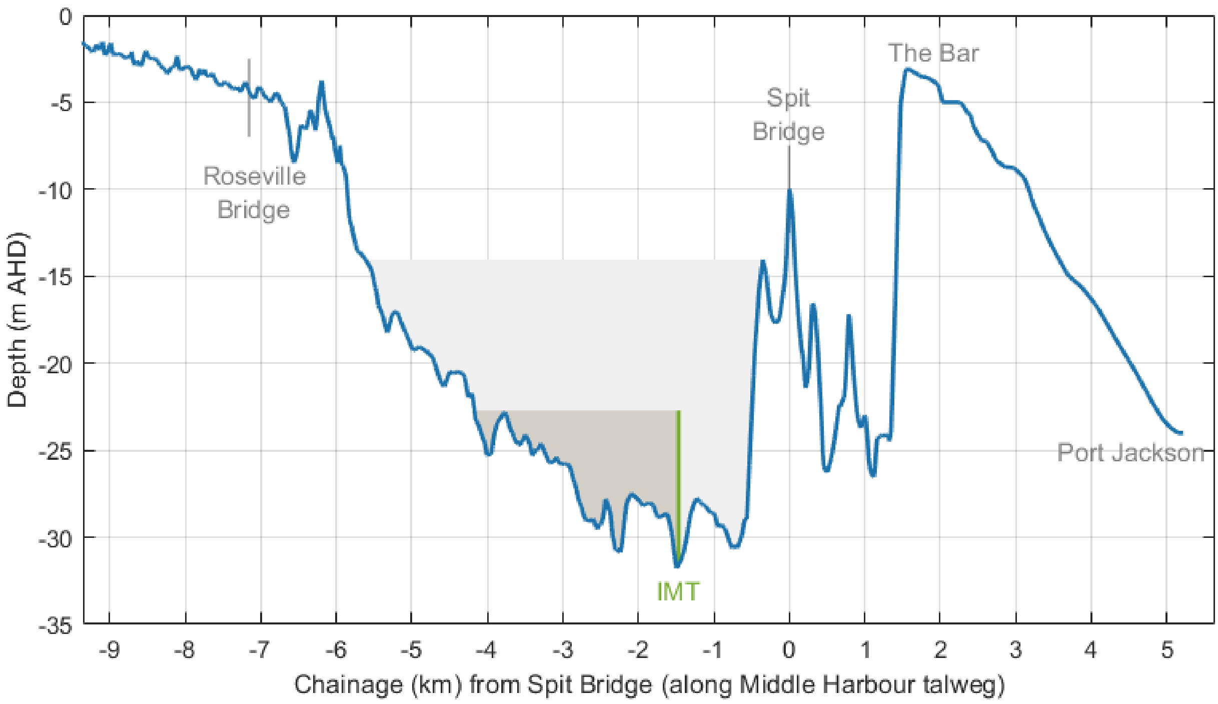

Figure 4-2 Long section of Middle Harbour indicating the existing system sills and the immersed tube tunnel crossing

5 Impact assessment

5.1 Construction

5.1.1 Increased turbidity

The potential impact of the excess SSC/turbidity generated by dredging activities was assessed using the approach outlined in Section 2.5. This approach developed tolerance limits (for turbidity/SSC) for resident marine flora and fauna that were derived from local water quality monitoring data. For Middle Harbour, a total suspended solids tolerance limit of 14.2 milligrams per litre was calculated from the data provided in Table 3-11. The tolerance limit was then applied to the predicted dredging-related excess SSC, provided by the plume dispersion modelling (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)), to determine the Zone of Moderate Impact and Zone of Influence.

Excess SSC percentage occurrence maps are presented in Annexure B of Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) for each key stage of the dredging program, comprising:

> Week 1 to 4

> Week 4 to 37

> Week 1 to 37 (entire program).

The Zone of Moderate Impact and Zone of Influence was determined for each of the above key dredging program stages. The outer extent of each of these zones were then merged to create an overall Zone of Moderate Impact and Zone of Influence for the project dredging activities.

The boundaries of the zones described above are shown in Figure 5-1. Water quality effects of the 37 weeks of dredging would be restricted to a small area that reflects the tidal transport of the dredge plume material, and would be within a distance of a few hundred metres of the dredging activities.

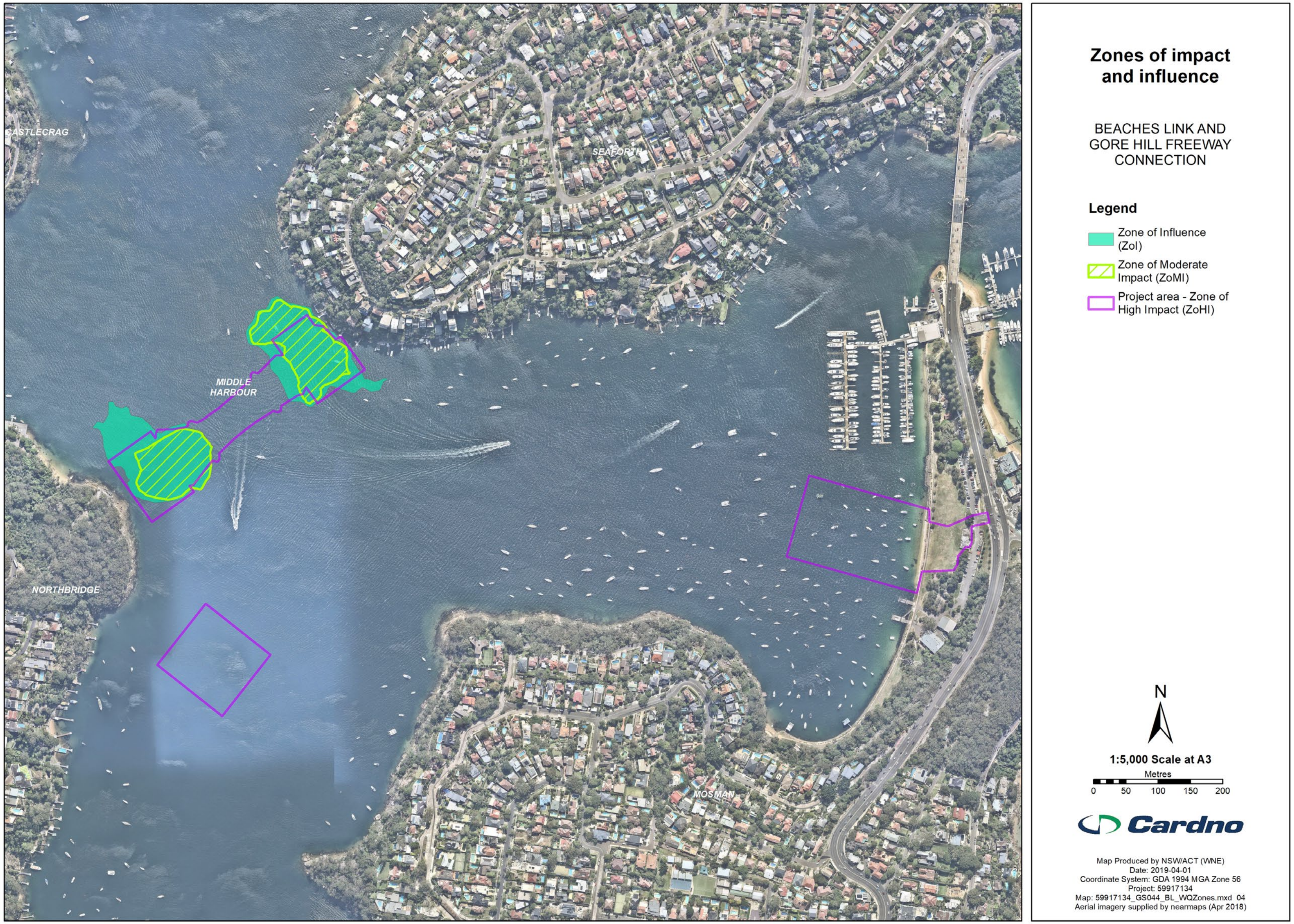

Figure 5-1 Zones of High Impact, Moderate Impact and Influence for the dredging program

The plume dispersion model (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)) calculated the excess SSC concentration in five vertical layers (from the water surface to harbour bed) and at each five minutes through the 37 week dredging period to produce a time-series of excess SSC. For the assessment of effects on water quality, the time-series excess SSC were extracted from the model at the water quality monitoring locations BL1 and BL2 (refer to Figure 2-3) and outputs were averaged over the depth and daily averages calculated.

The daily-averaged excess SSC for the 37 week dredge program at site BL2, immediately adjacent to the immersed tube tunnel crossing location, is presented in Figure 5-2. This shows patterns of excess SSC plumes generated in three to four-week periods that reflect the phases of the dredging program. An example of one of these periods from weeks 26 to 31 is presented in Figure 5-3 to highlight the short term variability demonstrated by the instantaneous five minute modelled values. This figure indicates the intermittent nature of the plume dispersion with excess SSC peaks occurring for short periods during the five to six hours of daily dredging operations across the five days shown.

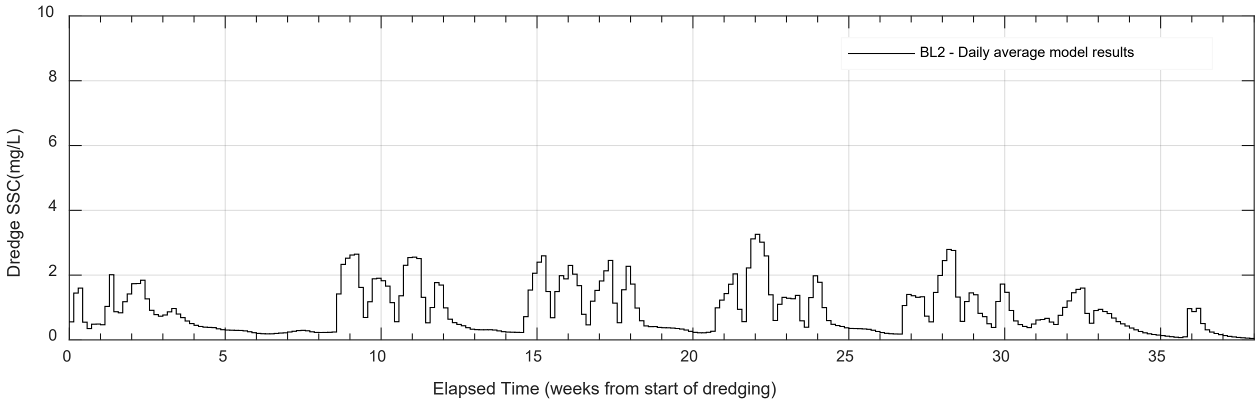

Figure 5-2 **Predicted dredge suspended sediment concentration (depth and daily averaged) at site BL2: Clive Park – Northbridge (from Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling))**

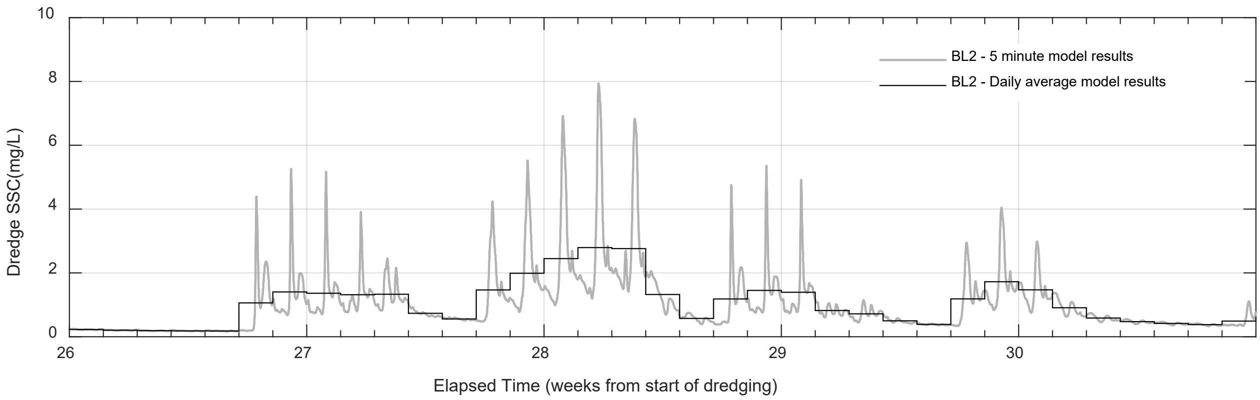

Figure 5-3 **Predicted dredge sediment concentration (depth and daily averaged, and depth averaged five minute interval), at BL2: Clive Park – Northbridge (from Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling))**

At site BL2, the 95th percentile excess SSC was 2.4 milligrams per litre and the median value 0.4 milligrams per litre as determined from the five minute values over the 37 week period of dredging. Assuming the excess SSC would occur in addition to the ambient water median concentration (1.7 milligrams per litre, refer to Table 3-11) then the suspended solids concentration 95th percentile would equate to a total suspended solids concentration of 4.1 milligrams per litre (2.4 milligrams per litre plus 1.7 mg/L). This is below the background 90th percentile concentration (9.1 milligrams per litre) and the tolerance limits for the marine environment.

The duration of excess SSC events was also predicted to be short with daily-average concentrations exceeding 0.5 milligrams per litre for about 30 days out of the 37 weeks of dredging and values exceeding one milligram per litre lasting less than five days. Effectively the median total suspended solids concentration during the dredging period would increase from 1.7 to 2.1 milligrams per litre, equivalent to the background 65th percentile.

Construction activities (ie piling, construction of temporary wharf facilities and vessel movements) would be likely to lead to mobilisation of harbour bed sediments within shallower waters and formation of short lived localised plumes that disperse rapidly into the ambient waters. These activities and the plumes generated would be likely to lead to elevated total suspended solids concentrations over small areas and for periods less than 10 minutes. These small plumes would be unlikely to lead to any measurable effects.

Land based construction activities occurring immediately adjacent to marine water bodies would be unlikely to result in transport of sediment via air or runoff to receiving waterways due to the small scale of land based works at Spit West Reserve construction support site (BL9). The risk of spills or leaks of fuels and/or oils from maintenance or re-fuelling of construction plant or equipment or vehicle incidents that could be eventually discharged to waterways should be managed through standard mitigation practices that would prevent their release (refer Section 6).

The results indicate that the dredging program and tunnel and onshore construction activities would likely have a minimal impact on marine water quality. The potential impacts of the changes in water quality on the marine environment are further discussed in Appendix T (Technical working paper: Marine ecology).

5.1.2 Sedimentation

The cumulative deposition of dredged sediments two weeks after the cessation of dredging is presented in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) Figures 7 9 to 7-13. The accumulated sediment shown in Figure 7-5 of Appendix P (Technical working paper: Hydrodynamics and dredge plume modelling) shows deposition of dredged sediments decreasing in thickness with increasing distance from the dredge source. A reasonably broad band of sedimentation of less than 0.5 centimetres would extend about four kilometres downstream and one to two kilometres upstream of the tunnel crossing dredging. Sedimentation of greater than 0.5 centimetres is predicted to be confined to an area within about 700 metres of the dredging and the area of more than one centimetre of sedimentation is predicted to occur within a few hundred metres of the dredge operations.

Historical estimates of the natural rates of siltation vary between 2.5 to three millimetres per year estimated from 30 metres of sediment accumulation in the harbour (Roy et al, 1981) and in Middle Harbour rates of two to 3.7 millimetres per year over dry/wet periods (Annexure C), equivalent to about three centimetres per decade. These very low rates are typical of NSW estuaries and benthic marine biota are generally able to adapt to these rates of change in bed level.

Sedimentation is difficult to measure in the field and the accuracy of current techniques is typically about two centimetres or greater. From a practical perspective, the effects of sedimentation after the 37 week dredging program are likely to be negligible and not measurable other than perhaps immediately adjacent to the dredge footprint (less than about 50 metres from the footprint). This level of sedimentation is unlikely to result in a measurable impact to the marine environment as it is well within the existing overall range of sedimentation.

5.1.3 Mobilisation of contaminants

Contamination data within the project area show levels of selected contaminants within the upper 0.5 to one metre of sediments that would exceed guideline criteria (where available) (Douglas Partners and Golder Associates, 2017). The behaviour of sediment-bound contaminants when resuspended into the water column is important for determining the potential for adverse environmental effects from dredging. In a study for the Sydney Metro City & Southwest project (Geotechnical Assessments, 2015), similar contaminants were found to occur as that found for the project by Douglas Partners and Golder Associates (2017) . In the study for the Sydney Metro City & Southwest project, Geotechnical Assessments (2015) carried out laboratory elutriation tests (by simulating resuspension of sediment in ambient seawater) for identified contaminants. These tests demonstrated that trace metals and all organic contaminants would likely remain bound to sediment particles and would be unlikely to dissociate and be released into the water column as dissolved phases. The minor component of contaminants that might be released to dissolved phases would be expected to re-adsorb to suspended particulate materials and resettle to the bed of the harbour.

A backhoe dredge with a closed environmental bucket has been proposed for removal of the upper 0.5 to one metre layer of sediment which has been shown by initial testing to be contaminated. A localised floating silt curtain would be attached to provide a controlled area or “moon pool” for the dredge operator to work within and additional deep draft silt curtains would be situated at either side of the proposed project crossing location where the majority of the dredging would occur (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)). These controls, in conjunction with the behaviour of sediment bound contaminants, means it would be unlikely that water quality would be substantially impacted by contaminants mobilised from dredging and construction activities. Silt curtains would also be placed around sensitive nearshore habitats close to dredging to further safeguard these. Dredge-induced accumulations of sediment in intertidal areas would be likely to be uncontaminated sediment dispersed during the dredging of deeper uncontaminated sediment (Douglas Partners and Golder Associates, 2017).

Potential impacts on marine habitat and biota as a result of the mobilisation of contaminants is further considered in Appendix T (Technical working paper: Marine ecology).

5.2 Operation

As discussed in Section 4.2, the longer term effects of the sill created by the immersed tube tunnels has the potential to increase the residence times of the near-bed waters upstream of the sill.

Section 6.2.3 of Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) investigated the change in tidal flushing of near-bed waters upstream of the sill and found the flushing characteristics in terms of the e-folding time would increase by about 30 per cent from about 1.6 days to about 2.4 days. The presence of an extra sill in Middle Harbour and the increase in residence times of the deeper waters immediately upstream of the sill would promote conditions more favourable to the depletion of dissolved oxygen in the bottom boundary layer, albeit in a relatively small volume of water affected by the sill.

Seasonal variability in the temperature and salinity characteristics and salt wedge/fjord-like behaviour (refer to Figure 3-1) leads to considerable variations in the flushing characteristics of the deep water. For the waters upstream of the sill at the assumed height of 9.2 metres above the bed of the harbour, the flushing times were estimated at about 2.4 days, although under stratified conditions, water in the bottom boundary layer upstream of the sill water may reside for longer periods (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)).

Based on average annual rainfall patterns, significant rainfall (greater than 50 millimetres in 24 hours) occurs about three to four times per year (refer Table 3-2). The conditions leading to dissolved oxygen depletion to about 50 per cent saturation concentrations are likely to naturally occur a few times per year and particularly during the warmer late summer and autumn period. Conditions where dissolved oxygen concentrations reduce to lower than 50 per cent saturation are also likely to occur about once per summer/autumn season.

The volume of water below the sill level of -16 to -22 metres AHD and the bed of the harbour at -32 metres AHD extends about one kilometre upstream of the proposed crossing. This volume represents only five per cent of the total water volume upstream of the tunnel sill. As with the existing conditions, any depletion of dissolved oxygen in the deeper water would be rapidly mixed vertically resulting in negligible effects on dissolved oxygen in the surface waters as a consequence of the project. In the deeper waters, the low dissolved oxygen events of the existing natural system are likely to last for a slightly longer period and attain slightly lower dissolved oxygen concentrations than in the present system. Such events are likely to occur about once or twice per year and last about two to five days in the deeper waters with negligible change to surface waters.

Both estimates of sedimentation derived from the sediment core observations and from catchment inflow estimates provide similar order-of-magnitude outcomes (refer to Section 3.6). The sill created by the crossing would likely increase the rate of mud siltation upstream of the crossing by three to four millimetres per decade. This rate is within the range of sedimentation rates within Middle Harbour and forms a negligible contribution to overall sedimentation.

The potential impacts of the likely slightly prolonged periods of low dissolved oxygen concentrations in deep waters and sedimentation to the marine ecology of Middle Harbour are discussed further in Appendix T (Technical working paper: Marine ecology).

6 Mitigation of impacts

In developing the design for the project, it was recognised that there would be potential for impact to the marine ecosystem of Middle Harbour. Based on the methods adopted for previous similar activities within the broader Sydney Harbour and experience with similar projects elsewhere, a number of measures for avoiding and minimising potential impacts to marine water quality and marine ecology were incorporated into the project design and proposed construction activities. The construction footprint was reduced as far as practicable to avoid areas of marine vegetation and habitat. Standard environmental management measures should be implemented at construction sites to minimise potential impacts to marine water quality and its flow on impacts on marine ecology. As discussed in Section 1.8, these should include:

- Treatment of tunnel wastewater via a treatment plant prior to discharge from construction sites to avoid adverse impacts to water quality in the harbour
- Installation of 10 to 12 metre deep-draft silt curtains around the dredge works during dredging
- Use of a backhoe dredge with a closed environmental bucket operated through a silt curtain to dredge the top layer of marine sediment (for details refer to Section 4.1)
- Installation of additional shallow silt curtains along the adjacent foreshore areas for added protection of sensitive nearshore areas
- Construction staging
- Management of contaminated sediments and acid sulfate soils.

These measures are discussed in Chapter 5 (Project description) and Chapter 6 (Construction work) of the environmental impact statement and would be further refined during further design development.

Following selection of the dredging contractor and proposed methods, a detailed plan for managing dredging activities, the dredge management plan, should be developed. The aim of the dredge management plan should be to outline the procedures to be adopted during dredging activities to minimise the area of impact to marine water quality, vegetation and habitat. Pre-dredging monitoring of the dissolved oxygen concentrations in the deeper waters should occur prior to the commencement of the dredging program to inform the dredge management plan and potential post construction mitigation requirements.

The dredge management plan should incorporate an adaptive management approach that utilises ongoing monitoring and assessment of triggers to provide early warning of potential ecosystem stress. Defined management responses to these indicators would be agreed in the development of the dredge management plan and likely include a triggered action response plan that defines the detailed monitoring program, data analysis, trigger assessment, reporting and decision framework for responding to any trigger exceedances.

The triggered action response plan should include a range of mitigation measures and may include adjustments to the dredging activities such as moving the dredge to other areas, changing the dredging method (eg dredging on ebb tide only), and ultimately cessation of dredging for a period to reduce stress to the environment. Additional strategies could include installation of silt curtains surrounding the nearshore seagrass patches. These responses should be tailored to the conditions observed and to minimise risks of any long term impact on the marine environment. The suspended solids/turbidity criteria should be derived from the information presented in Table 3-11 and the final dredging program proposed by the selected dredging contractor.

Based on the predictions of the effects of the proposed dredging program, it is likely that the proposed program would have negligible effects on the marine water quality of Middle Harbour. The analysis of the preceding sections provides a reasonable level of confidence that the proposed management measures with designated monitoring and triggered response activities would provide the safeguards for the protection of the marine environment.

The secondary impacts of marine water quality to marine ecology as a result of the project are discussed in Appendix T (Technical working paper: Marine ecology).

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ANNEXURE

A

MIDDLE HARBOUR WATER QUALITY SAMPLING: 5 DEC 2017 TO 31 JAN 2018

Cardno®

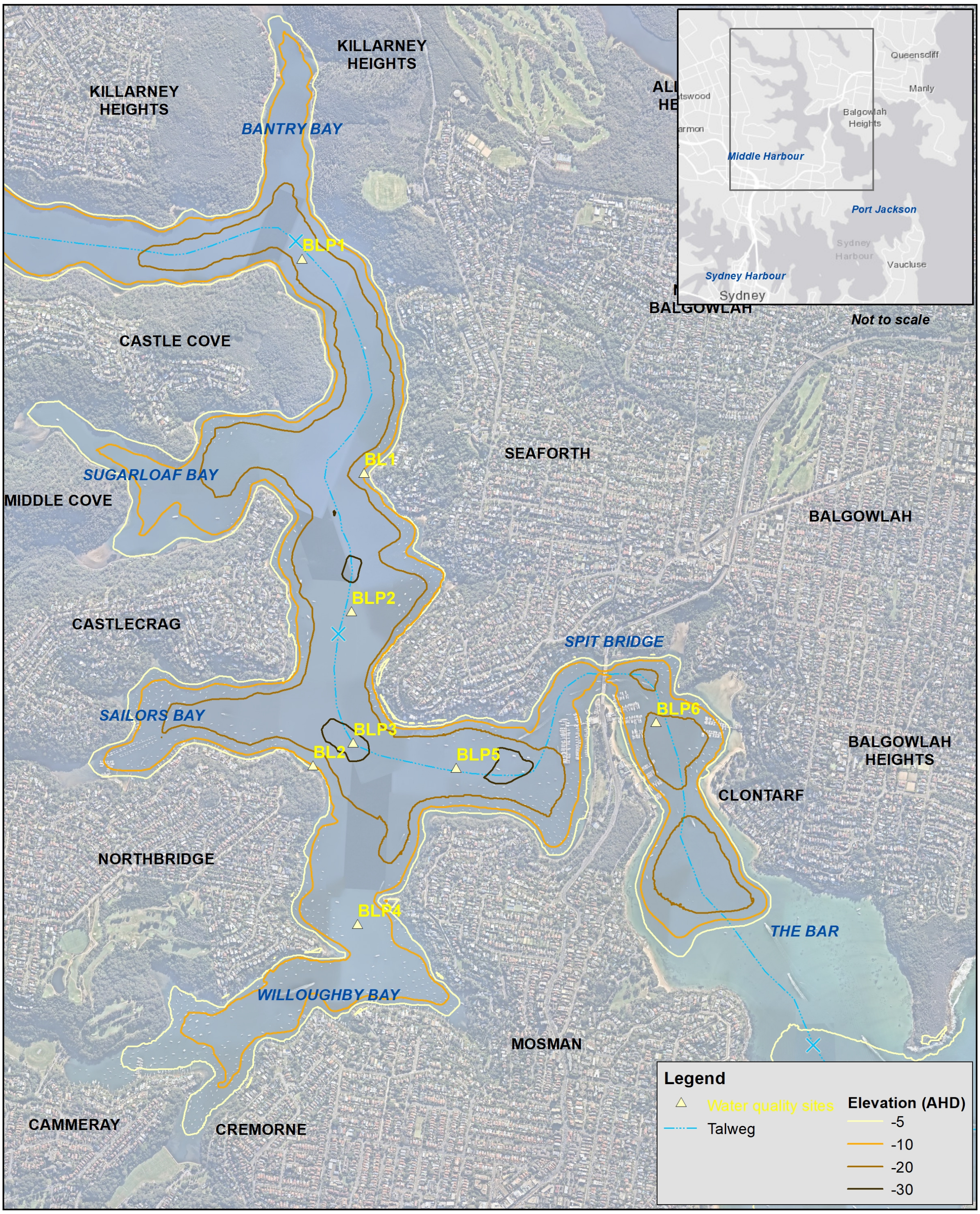
A Middle Harbour data collection: December 2017 to January 2018

Two water quality probes were set just above the seabed at sites BL1 and BL2 for an eight week monitoring period from 5 December 2017 to 31 January 2018. Vertical water profiles were collected at fixed monitoring sites BL1 and BL2, as well as six additional locations within Middle Harbour on 18 and 30 January 2018 (Table A-1, Figure A-1 to A-11). A Sea-Bird Scientific SBE 19plus V2 SeaCAT Profiler CTD combined with various sensors (Satlantic PAR, FLNTURT, SBE18 pH, SBE43 DO), recorded turbidity, PAR, CTD, chlorophyll a (Chl-*a*), pH and dissolved oxygen (DO) as it was lowered through the water column from the surface to the bed of the harbour.

Water samples were also collected at each profile location at a depth of about 1.5 metres below the water surface and analysed by laboratory ALS for total suspended solids (TSS) and Chl-*a* concentrations.

Table A-1 Location details of monitoring sites during the December 2017 field campaign

Profile / Sample name	Site name	Location
Pickering Point, Seaforth	BL1	336325 E, 6257958 N
Clive Park, Northbridge	BL2	336558 E, 6259297 N
Yeoland Point, Castle Cove	BLP1	336275 E, 6260277 N
Peach Tree Bay, Seaforth	BLP2	336501 E, 6258663 N
Seaforth Bluff, Seaforth	BLP3	336507 E, 6258062 N
Hallstrom Point, Northbridge	BLP4	336529E, 6257232 N
Beauty Point, Mosman	BLP5	336979E, 6257947 N
The Spit, Mosman	BLP6	337895 E, 6258157 N



N

1:22,500 Scale at A4

Meters
0 250 500

Water quality monitoring sites December 2017 - January 2018

BEACHES LINK AND
GORE HILL FREEWAY CONNECTION

Cardno

Map Produced by APAC Water and Environment
Date: 2020-07-09
Coordinate System: GDA 1994 MGA Zone 56
Project: 59917134
Map: 59917134_GS073_BL_WQSites.mxd 04 (2017)
Aerial imagery supplied by Nearmaps (2020) and Esri

Figure A-1 Water quality monitoring sites within Middle Harbour during 2017

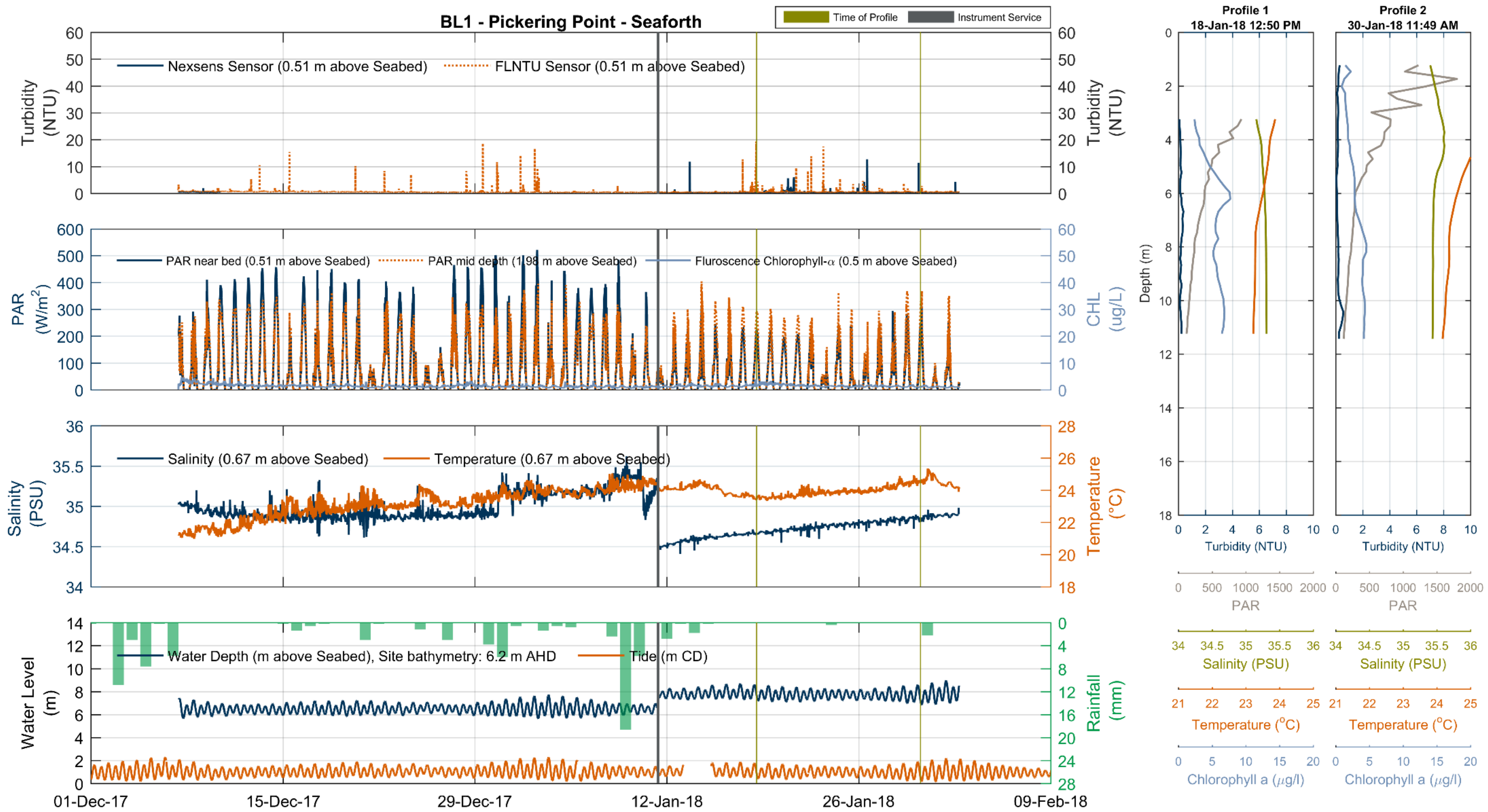


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Figure A-2 Water quality summary for BL1 - Pickering Point, Seaforth (5 December 2017 to 31 January 2018)

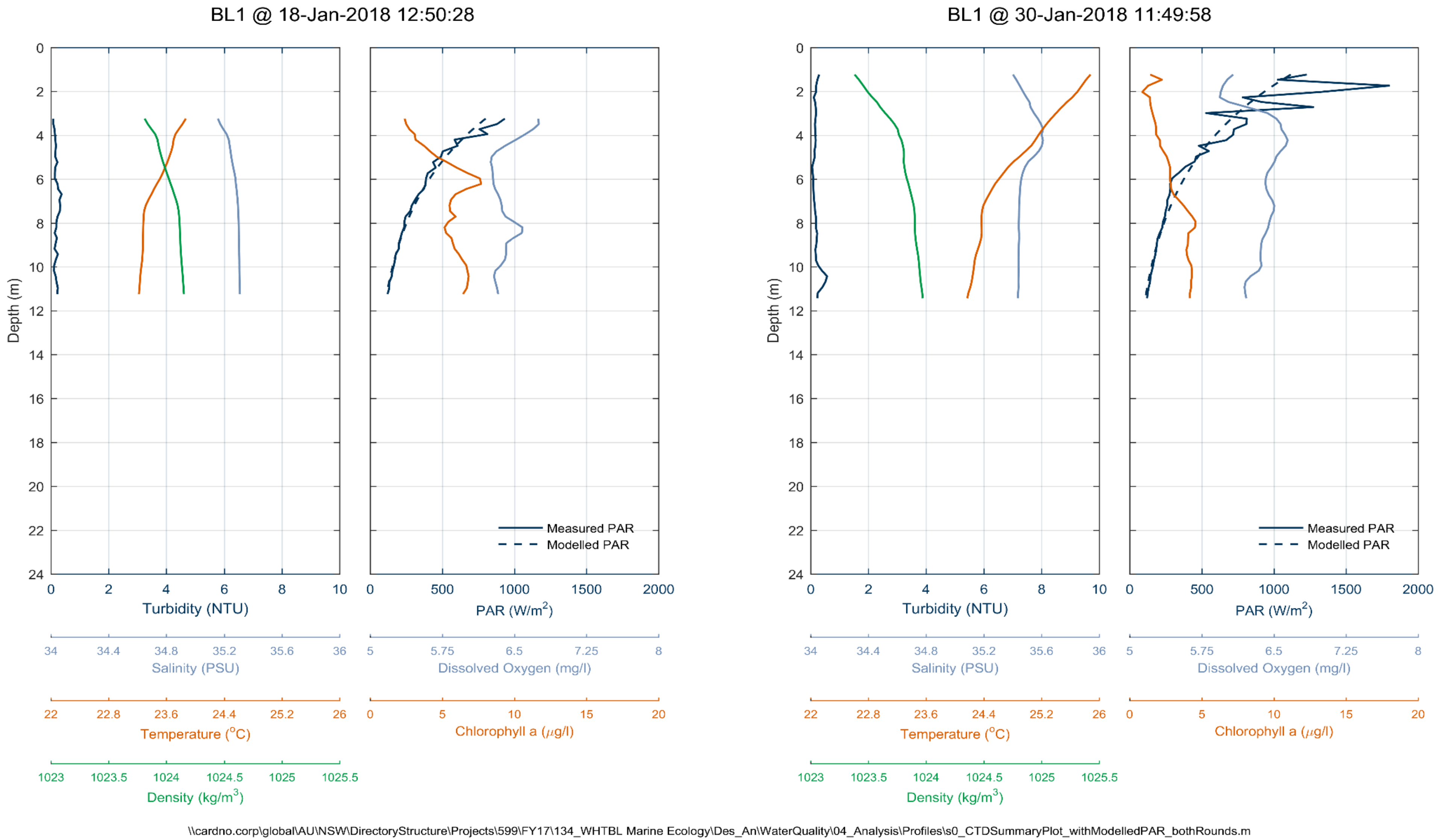

Figure A-3 Water quality vertical profiles for BL1 - Pickering Point, Seaforth (18 January 2018 and 30 January 2018)

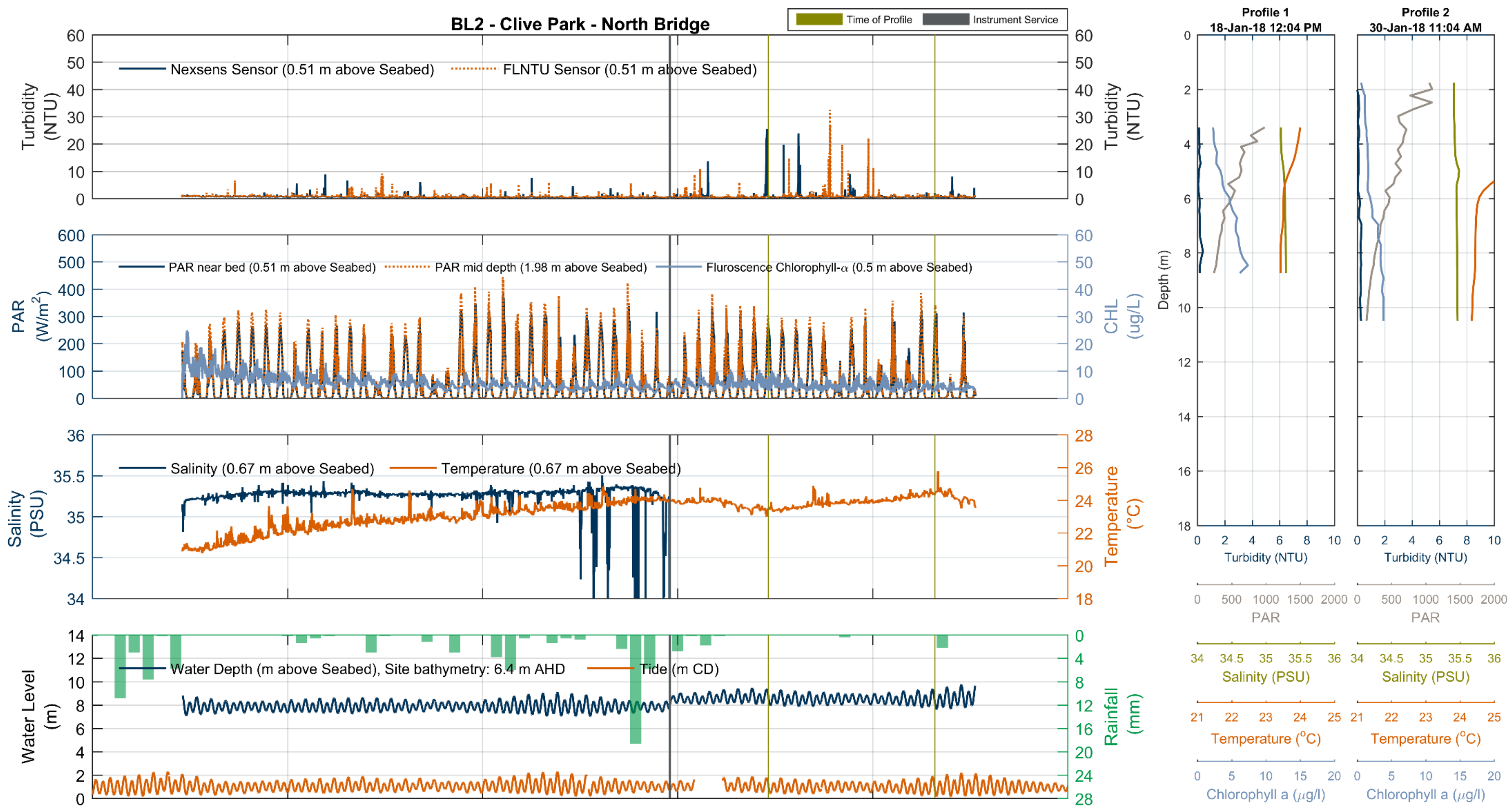

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Figure A-4 Water quality summary for BL2 – Clive Park, Northbridge (5 December 2017 to 31 January 2018)

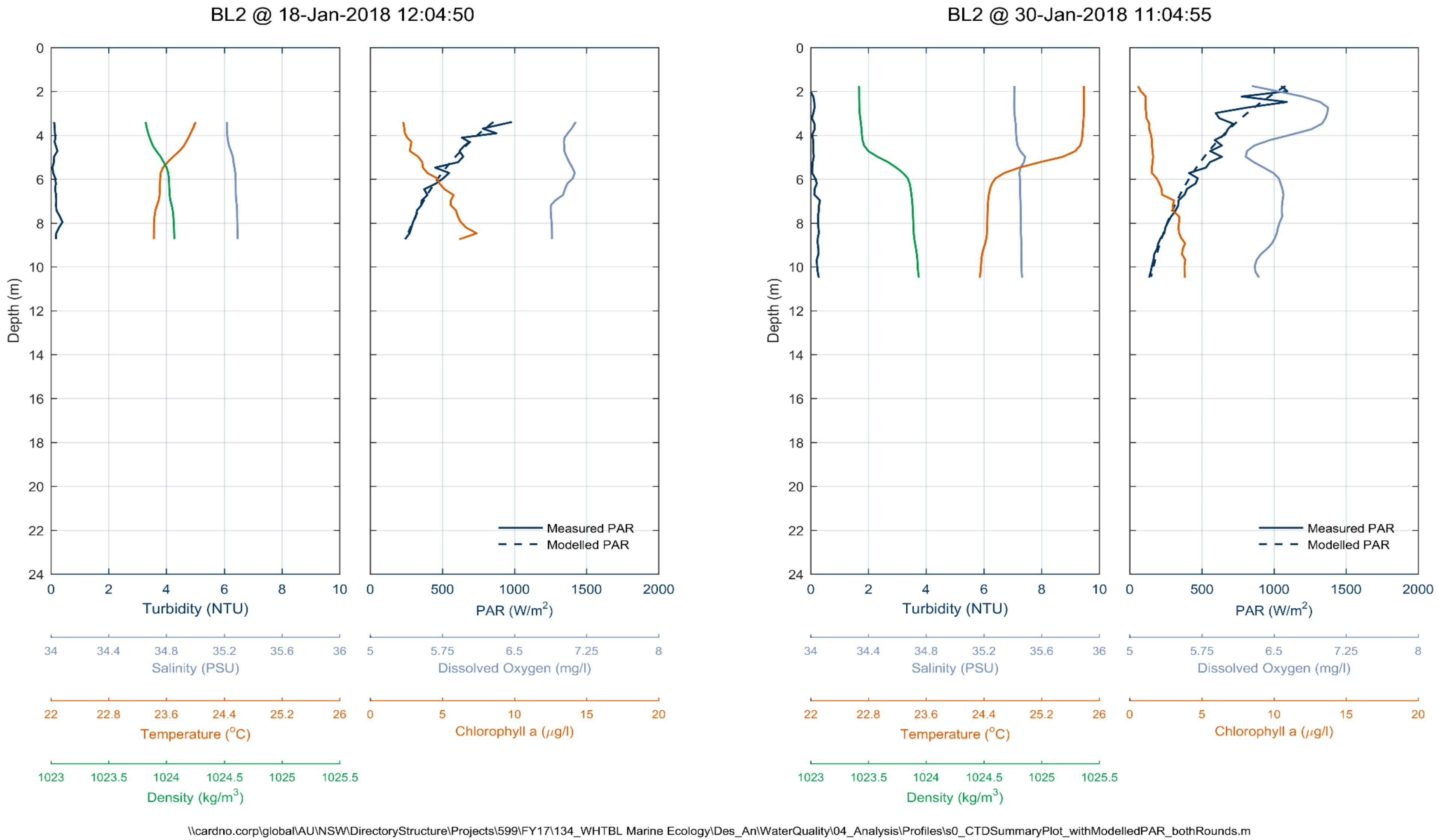

Figure A-5 Water quality vertical profiles for BL2 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)

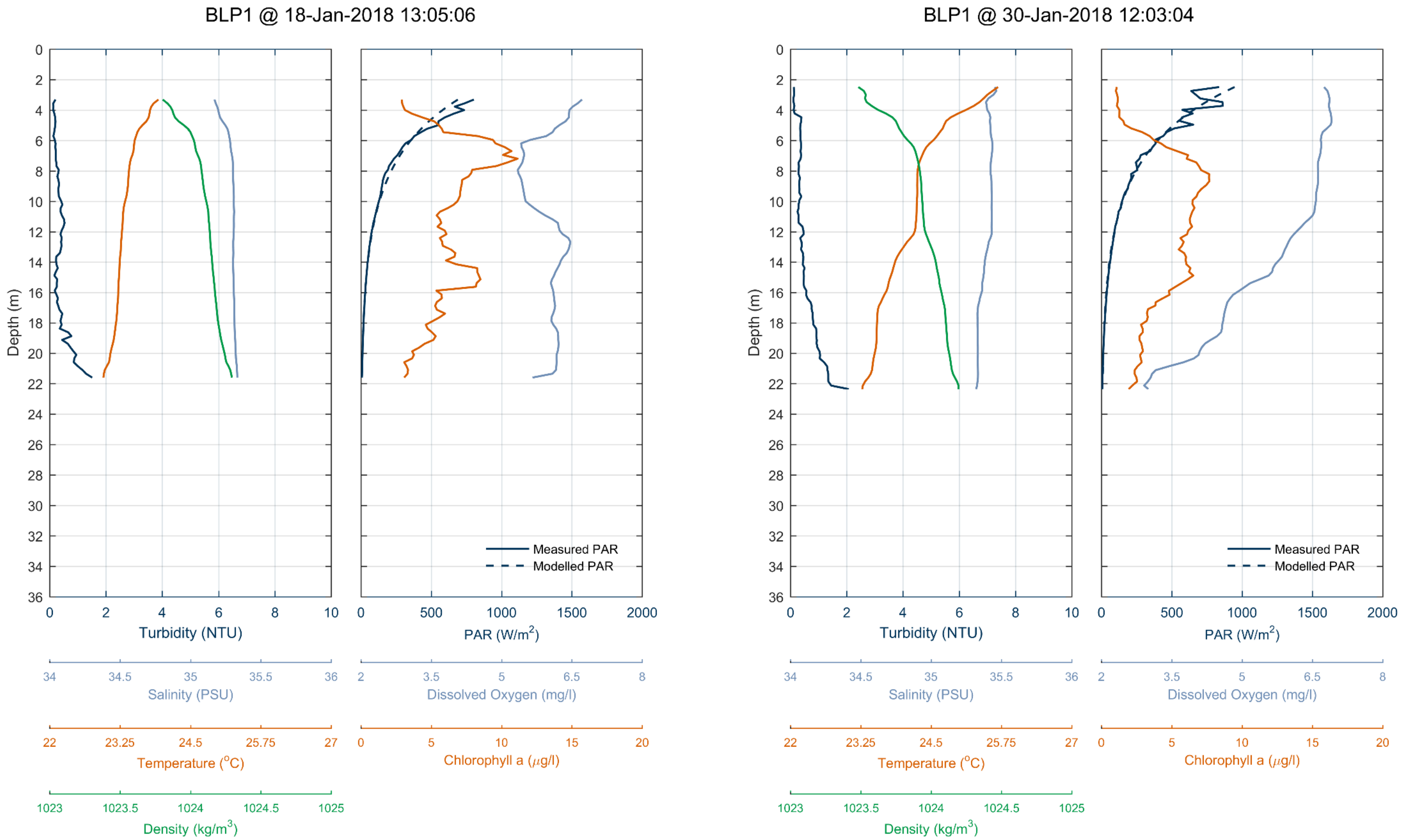

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Figure A-6 Water quality vertical profiles for BLP1 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)

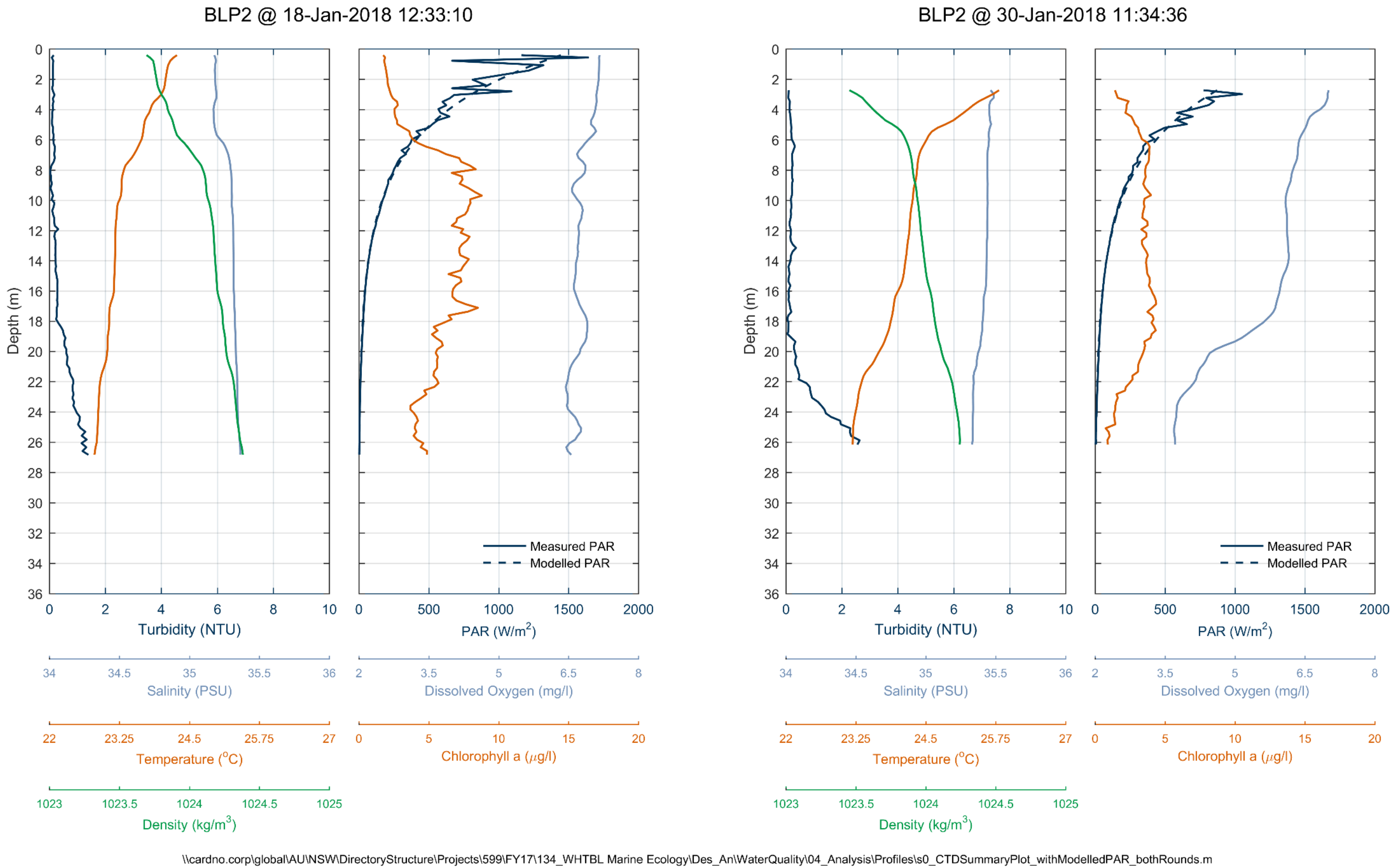

Figure A-7 **Water quality vertical profiles for BLP2 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)**

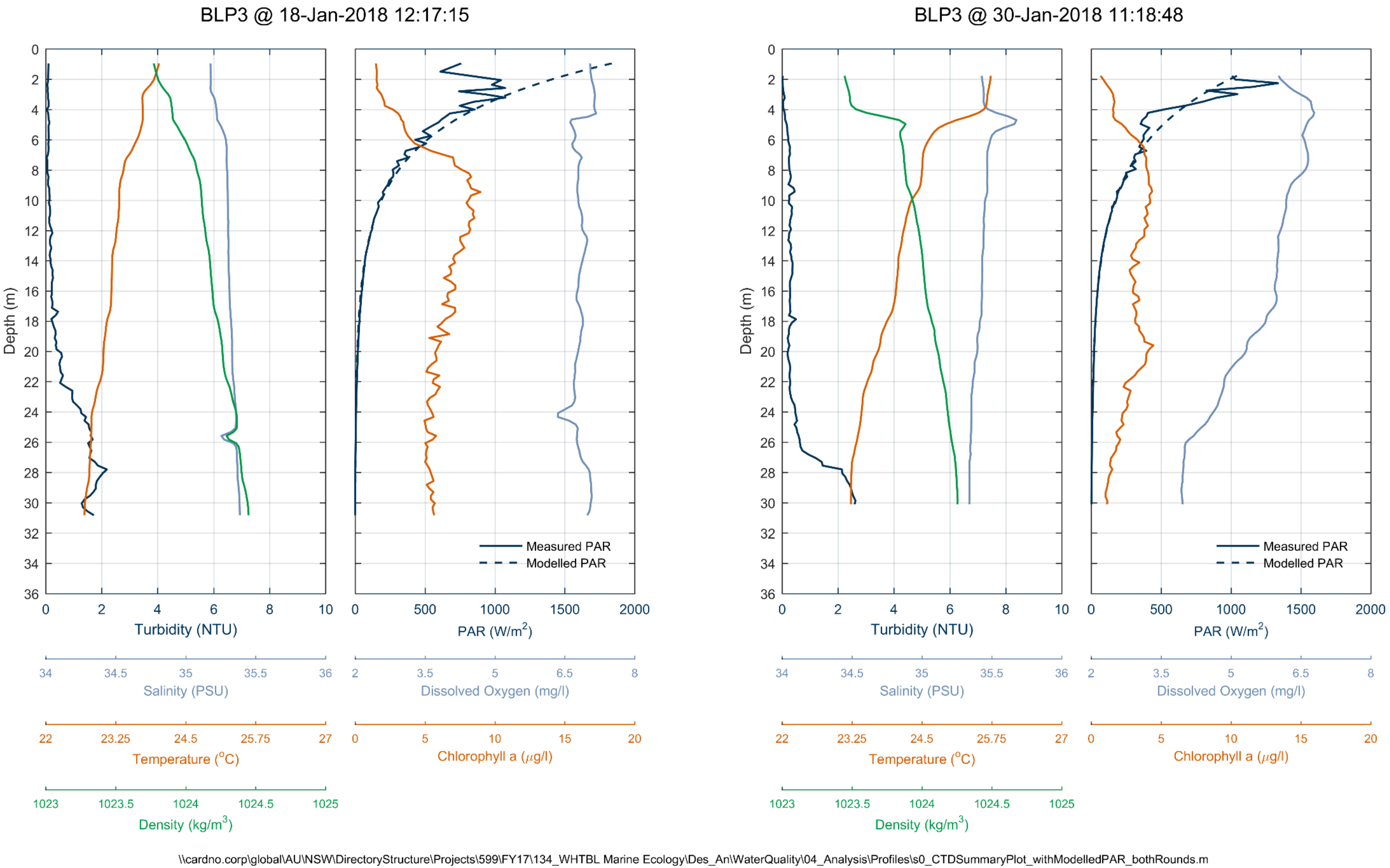

Figure A-8 Water quality vertical profiles for BLP3 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)

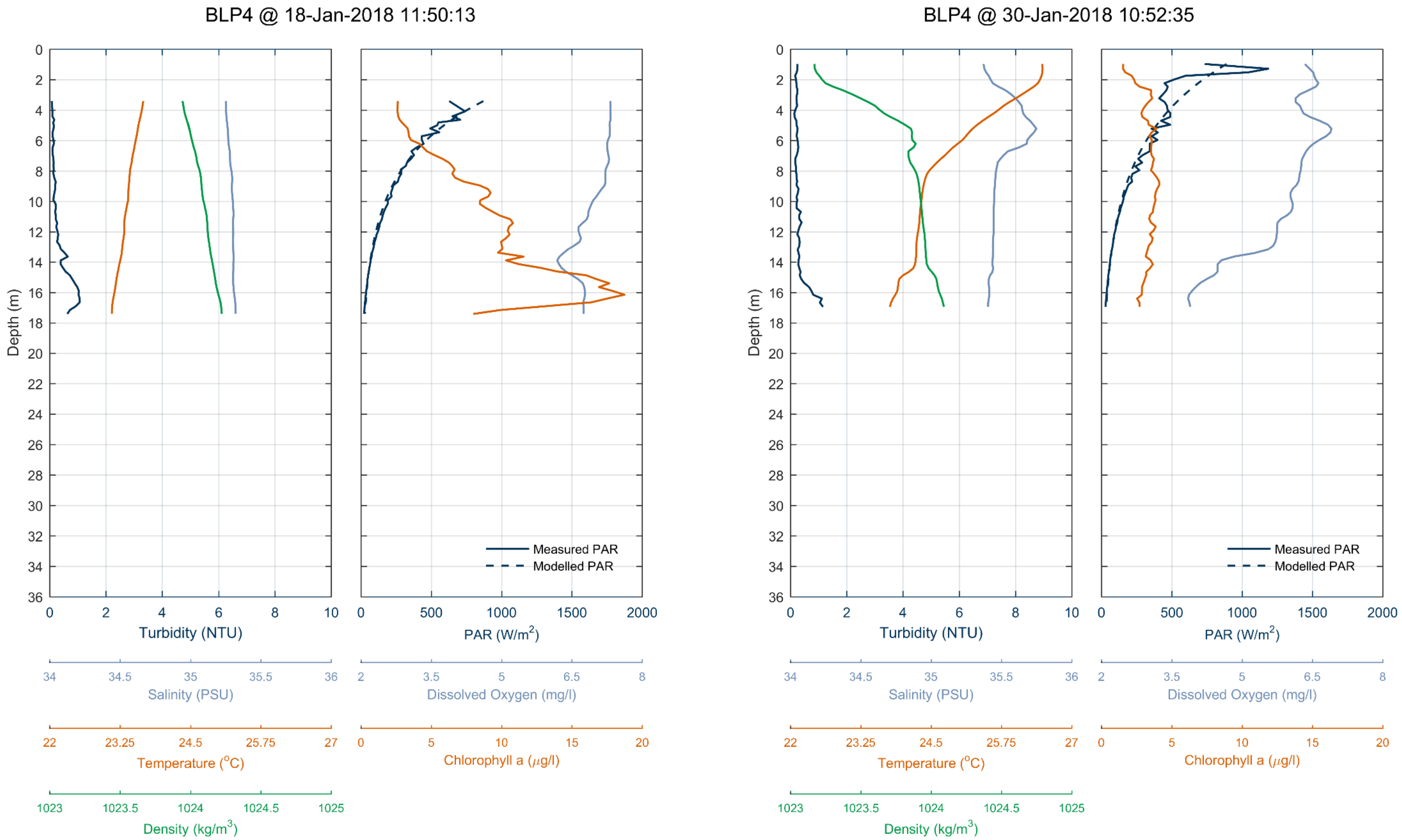

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Figure A-9 Water quality vertical profiles for BLP4 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)

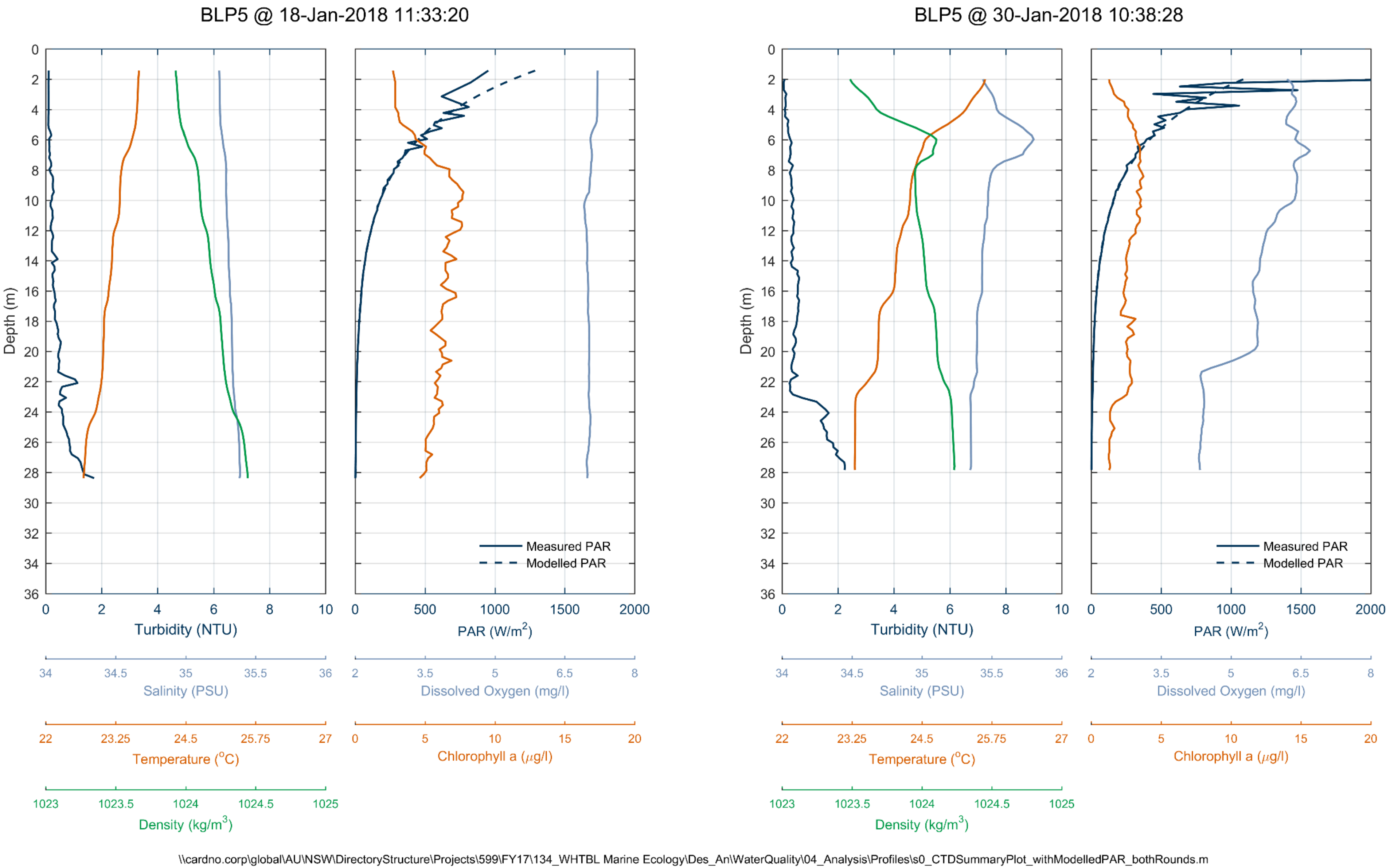

Figure A-10 **Water quality vertical profiles for BLP5 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)**

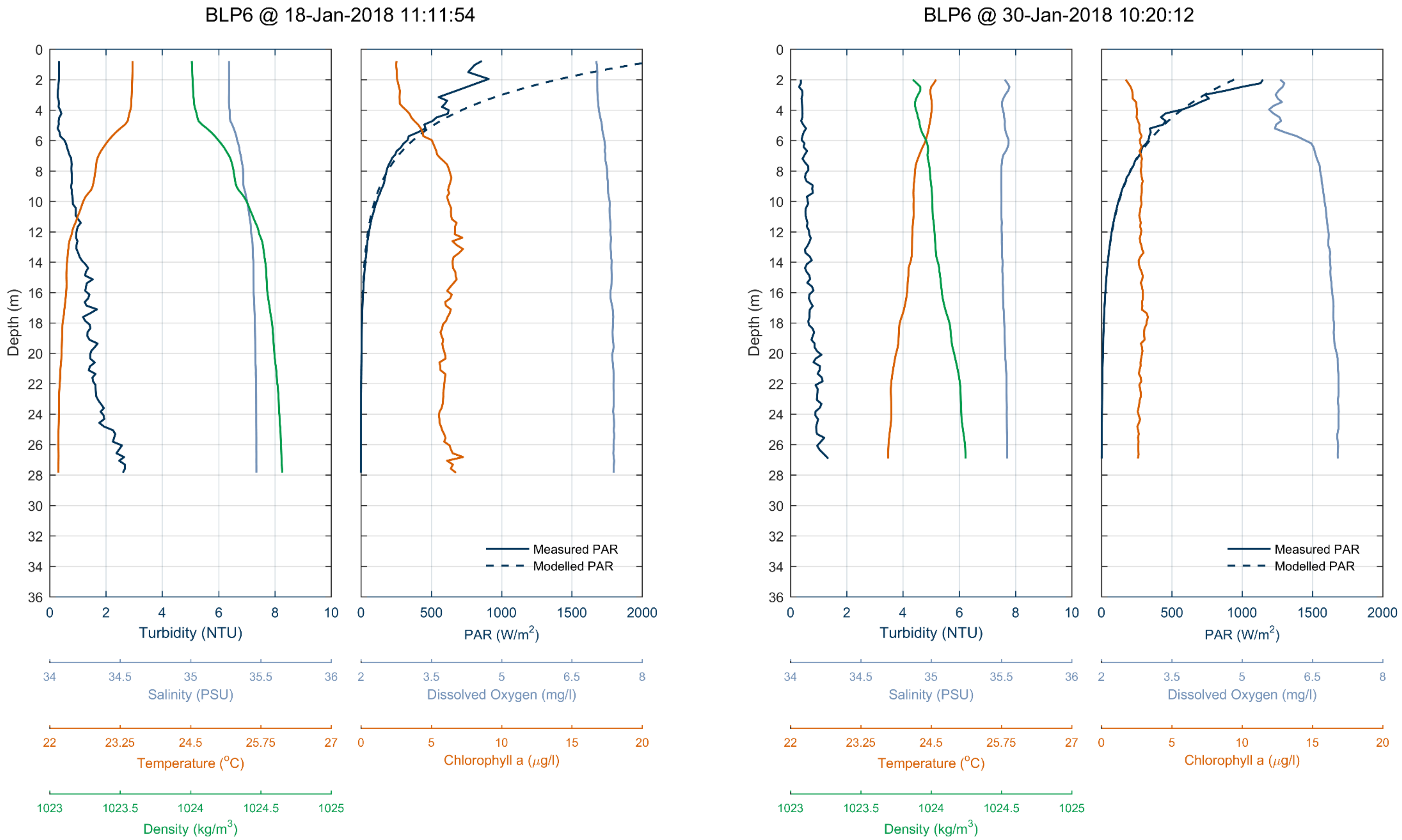

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Figure A-11 Water quality vertical profiles for BLP6 - Clive Park, Northbridge (18 January 2018 and 30 January 2018)

ANNEXURE

B

MIDDLE HARBOUR WATER QUALITY SAMPLING: 17 APRIL TO 1 JUNE 2020

Cardno®

B Middle Harbour data collection: 17 April to 1 June 2020

B.1 Introduction

This annexure describes the field data collected to understand dissolved oxygen variability in the deep waters upstream of The Spit near the proposed immersed tube tunnel crossing of Middle Harbour.

These data were collected in response to Item no. 6 10 in the Secretary's environmental assessment requirements:

6. 10 Identify and assess the impact of tidal flushing on the crossing of Middle Harbour. This assessment should also include details of any potential sediment accumulation and the impact this may have on marine populations that dwell on the harbour floor.

The Secretary's environmental assessment requirement Item no. 6 10 required an assessment of potential impacts of the Middle Harbour crossing on benthic ecology that could be a consequence of changes to tidal flushing. Tidal flushing upstream of the crossing has potential to be affected by the sill that would be created by the crossing (Figure B-1). The link between organic loads associated with summer rainfall runoff entering the harbour, transformations of the organic matter within the sediments and subsequent increases in microbial consumption can lead to lower dissolved oxygen (DO) water that may affect benthic ecosystems.

It was anticipated that the environmental conditions leading to natural low DO events in Middle Harbour are most likely to occur in late summer and early autumn. This is the period with high organic loading to the sediments, warm waters enhancing benthic microbial consumption of DO from the water column and periods of low mixing of deep water due to longer flushing times under stratified conditions following wet weather events. Data describing these conditions were collected from 17 April to 1 June 2020, in autumn. Investigations of potential accumulation of sediment are described in Annexure C.

B.2 Scope of works for April to June 2020 data collection

The aim of the data collection exercise from 17 April to 1 June 2020 was to understand natural variability in DO within the deep waters in the vicinity of the proposed crossing of Middle Harbour to inform an assessment of potential impacts of the sill that would be created by the crossing (Figure B-1). In particular, salinity and temperature measurements aimed to provide information on water residence time (tidal flushing) and natural variation in water quality in the deeper water upstream of The Spit following a period of wet weather inflow. Sampling involved a combination of water column profiles at sites at specific times and fixed sensor time series measurements at two sites. The measurements included the following:

> Vertical water column profiling of water quality (depth, temperature, salinity, chlorophyll-*a*, turbidity, DO and photosynthetically action radiation (PAR)) were collected at sites in the harbour during and following a period of wet weather inflow

> Fixed instruments at two moored sites were deployed for four weeks with two CTD/DO instruments (one near-bed and one near-surface) with a near-surface turbidity and Chl-*a* (fluorescence) instrument. One site included a bed mounted ADCP current meter

> Contextual weather and tide data were obtained from a number of sources.

Profiling and fixed probe data were combined and selected periods plotted to describe flushing processes and DO response to fresh water inflows and tidal flushing. Interpretive figures and tables were prepared.

This annexure summarises data collected in April to May 2020 and includes a brief interpretation of the data.

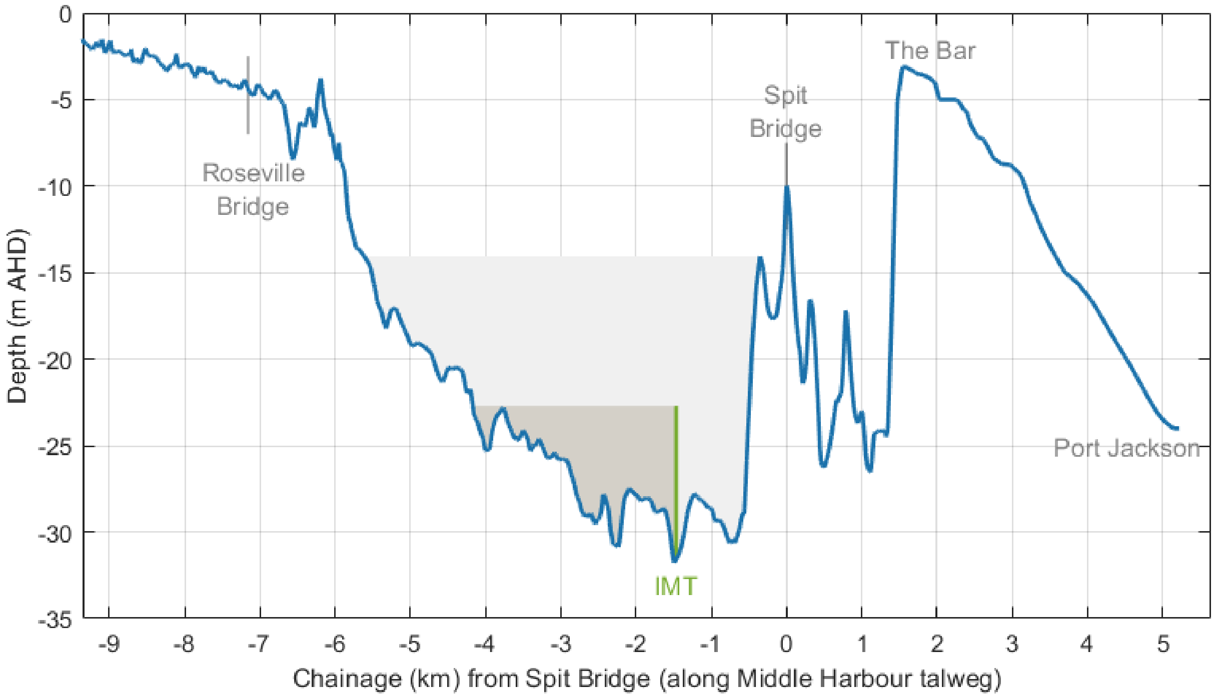

Figure B-1 Long section of Middle Harbour indicating the existing system sills and the proposed immersed tube tunnel (IMT)

B.3 Water quality mooring deployments

Two fixed water quality monitoring moorings comprised of a variety of sensors configured on a fixed harbour bed frame were deployed for the one-month monitoring period from 28 April 2020 to 1 June 2020. The moorings were deployed at the deepest part of the cross section at the proposed tunnel crossing location, site BM2, approximately 1.3 kilometres upstream of the Spit Bridge and approximately 1.2 kilometres downstream of the Spit Bridge, site BM1, in the deeper water off Clontarf Point and just upstream of the Middle Harbour entrance sand bar (Table B-1 and Figure B-2). Instruments included two Sea-Bird Electronics MicroCAT SBE37SMP-ODO instruments with integrated conductivity, temperature, depth and dissolved oxygen sensors and a WET-Labs EcoFLNTUSB with integrated fluorometric (chlorophyll-*a*) and optical backscatter (turbidity) sensors.

Table B-1 Location of water quality moored instruments and profiling sites

Site name	Harbour bed level (metres AHD)	Site coordinates
Moored instruments		
BM1	24	338093 E, 6257435 N
BM2	31	336505 E, 6257997 N
Profiling sites		
B1 (co-located with BM1)	24	338086 E, 6257467 N
B2	21	337930 E, 6257910 N
B3	21	337856 E, 6258352 N
B4	30	337434 E, 6258123 N
B5 (co-located with BM2)	32	336486 E, 6258035 N
B6	20	336591 E, 6257474 N
B7	16	336345 E, 6257014 N
B8	22	335894 E, 6258164 N
B9	27	336543 E, 6258479 N
B10	31	336510 E, 6258997 N
B11	26	336445 E, 6259485 N
B12	25	336501 W, 6260145 N
B13	22	336207 E, 6260532 N

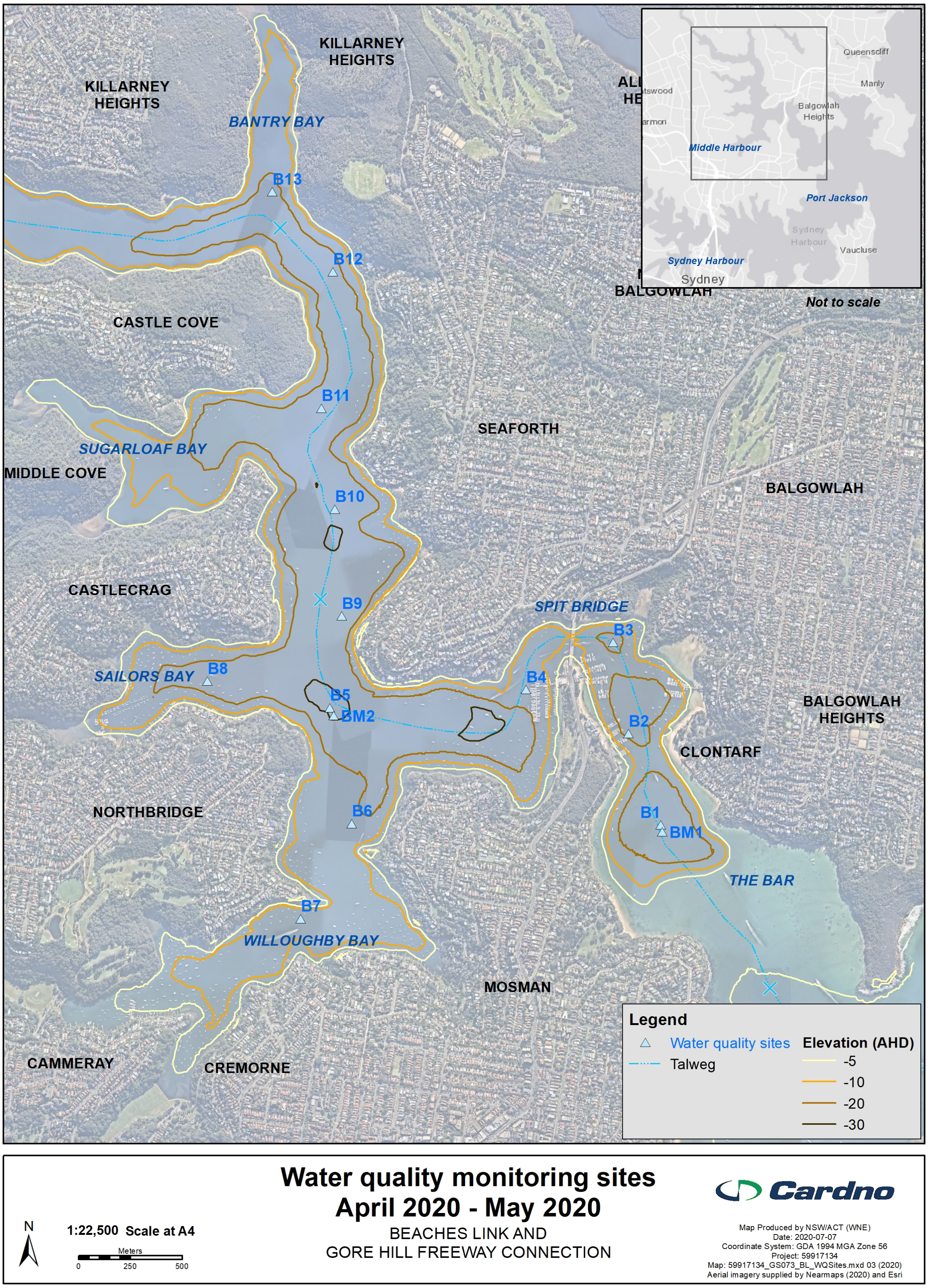

Figure B-2 Middle Harbour water quality monitoring sites sampled in April to May 2020

In addition to the water quality sensors a bed mounted current meter (Teledyne RDI 600kHz Sentinel ADCP) was deployed at the proposed crossing location, BM2, to monitor currents through the water column from near bed to near surface. The sensors and sampling frequencies are listed in Table B-2.

Table B-2 Moored instrumentation

Sensor	Sample interval (minutes)
WET Labs MicroCAT SBE37SMP-ODO	15
WET Labs EcoFLNTUSB	15
Teledyne RDI ADCP	10

B.4 Water quality profiling

Vertical water quality profiles were collected at the fixed monitoring sites BM1 and BM2, as well as at 11 additional locations within Middle Harbour (Figure B-2 and Table B-1). A Sea-Bird Scientific SBE 19plus V2 SeaCAT Profiler CTD combined with various sensors (listed in Table B-3) was used for these measurements conducted by lowering the instrument from a vessel vertically through the water column. During each day in the field, profiles were collected over two rounds to assess tidal variability (Table B-4).

Table B-3 Profiling sensor details

Sensor	Parameter	Range (units)
Seabird SBE 3F	Temperature	-5 to 35°C
Seabird SBE 4C	Conductivity	0 to 9 µS/m
Digiquartz	Pressure	0 to 200 psia
WET Labs EcoFLNTURT	Turbidity	0 to 200 NTU
Satlantic PAR	PAR	0 to 4500 µmol photons m-2 s-1
WET Labs EcoFLNTURT	Chl-*a*	0 to 75 µg/L
Seabird SBE 18	pH	0 to 14

Table B-4 CTD profiling sites and times. R1 = round 1 and R2 = round 2 profiles

Date	17 April 2020		23 April 2020		4 May 2020		12 May 2020		27 May 2020		1 June 2020
	R1	**R2**	**R1**	**R2**	**R1**	**R2**	**R1**	**R2**	**R1**	**R2**	**R1**
Site	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time
B1	13:46	15:41	9:43	11:56	10:40	12:54	10:19	12:42	9:34	11:54	9:10
B2	13:57		9:54	12:06	10:48	13:01	10:31	12:51	9:45	12:04	
B3	14:06		10:02	12:13	10:57	13:09	10:40	13:00	9:53	12:12	
B4	14:16		10:18	12:28	11:07	13:17	10:51	13:11	10:03	12:23	
B5	14:23	15:27	10:26	12:36	11:20	13:24	10:59	13:19	10:11	12:39	10:12
B6	15:58		10:33	12:48	11:45	13:39	11:15	13:34	10:24	12:54	
B7	16:06		10:38	13:00	11:51	13:45	11:23	13:40	10:31	13:01	
B8	14:31		10:45	13:08	11:58	13:53	11:31	13:48	10:40	13:09	
B9	14:40		10:52	13:15	12:05	13:59	11:40	13:56	10:47	13:17	
B10	14:49		11:37	13:21	12:11	14:11	11:41	14:04	10:54	13:24	
B11	15:00		11:09	13:34	12:18	14:17	11:56	14:12	11:01	13:32	
B12	15:10		11:18	13:41	12:24	14:23	12:06	14:21	11:09	13:39	
B13	15:17		11:25	13:48	12:30	14:29	12:13	14:29	11:15	13:46	
Tide Times Fort Denison	H: 04:16	1.54m	L: 02:22	0.51m	H: 05:14	1.76m	L: 06:30	0.47m	L: 05:38	0.05m	
	L: 11:02	0.59m	H: 08:24	1.55m	L: 11:43	0.35m	H: 12:30	1.30m	H: 11:39	1.32m	
	H: 17:15	1.32m	L: 14:25	0.50m	H: 18:00	1.66m	L: 17:52	0.76m	L: 17:05	0.75m	
	L: 10:53	0.77m	H: 08:43	1.73m					H: 23:37	1.78m	
7 Day Antecedent Rainfall mm (Spit Bridge)	3.0		0.0		14.0		5.0		74.5		

B.5 Supplementary meteorological and oceanographic data

Meteorological and oceanographic data (refer to Table B-5) were collated for the period of the field data collection. The data provided the physical context for the water quality response of the system and are a key input to inform the understanding of environmental processes governing water quality within Middle Harbour.

Wind speed and direction were obtained from the Australian Bureau of Meteorology (BoM) for the Sydney Harbour meteorological station at Wedding Cake West (station ID: 066196). Air temperature was obtained from BoM Observatory Hill meteorological station (station ID: 066062). Rainfall was obtained from Manly Hydraulics Laboratory for the Spit Bridge gauge operated for Northern Beaches Council.

Downwards shortwave radiation data were obtained from the United States National Centre for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2). Data were extracted from the CFSv2 global model grid, which has a resolution of 0.2 degrees (about 20 kilometres), at hourly temporal resolution. This model estimates the clear sky solar radiation hitting the land surface (ie assuming an absence of atmospheric attenuation due to cloud cover) as described in Saha et al., (2014).

Recorded and predicted harbour water levels were obtained from Manly Hydraulics Laboratory using water level records from the HMAS Penguin tide gauge.

Table B-5 Summary of Sydney Harbour meteorological and oceanographic data utilised in this investigation

Parameter	Station location	Data source	Frequency
Wind speed and direction	Sydney Harbour Wedding Cake West (Stn 066196)	BoM	30 mins
Air temperature	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Daily rainfall	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Daily global solar exposure	Sydney Observatory Hill (Stn 066062)	BoM	Daily
Downwards short wave radiation	Latitude: -33.83º Longitude: 151.16º	CSFv2	Hourly
Recorded and predicted Sydney Harbour water levels	Fort Denison	NTC	10 mins

B.6 Weather and sea level conditions during May 2020

Rainfall, solar radiation and air temperature conditions during the monitoring period are presented in Figure B-3. The deployment period was drier than average, with monthly total rainfall of 21.5 millimetres and 109.5 millimetres for April 2020 and May 2020, respectively – compared to the long term monthly mean values of 126.5 millimetres and 117.4 millimetres. The largest rainfall event occurred on 26 May 2020 in the final week of the monitoring period, when 57.0 millimetres fell over a 24 hour period. The monitoring period started after two months of higher than average rainfall, with monthly total rainfall of 407.0 millimetres and 173.5 millimetres for February 2020 and March 2020 respectively – compared to long term monthly mean values of 119.3 millimetres and 131.6 millimetres.

Downwards short wave solar radiation (DSWR) over the 61-day period peaked at less than 400 W/m^2 on 15 days indicating moderate to high cloud cover on those days (Figure B-3). Conversely, on the cloud free days with intense solar radiation, DSWR peaked around 700 W/m^2 at the start of the monitoring period, reducing to the late autumn peak of around 500 W/m^2 at the end of the period.

Air temperature during the deployment period was around average, with an average daily maximum of 24.4°C and 20.2°C for April 2020 and May 2020, respectively – compared to the long term averages of 22.5°C and 19.5°C. May 2020 experienced two days exceeding 25°C, with a maximum temperature of 28.5°C on 8 May 2020.

Wind speed, wind direction and sea levels during the period are shown in Figure B-4. Winds during the deployment period were generally moderate, without a predominant direction. A maximum wind speed of around 60 kilometres per hour was recorded on 24 May 2020 and a noticeably high wind period occurred from 22 to 26 May 2020 when strong south westerly to westerly winds exceeding 30 kilometres per hour persisted for over 72 hours.

Tides during the deployment displayed the typical fortnightly spring/neap cycle, with no particularly large spring tides experienced during the period. The period of high residual tides greater than 0.4 metres between 22 and 25 May 2020 with associated with strong westerly to south westerly winds (Figure B-4).

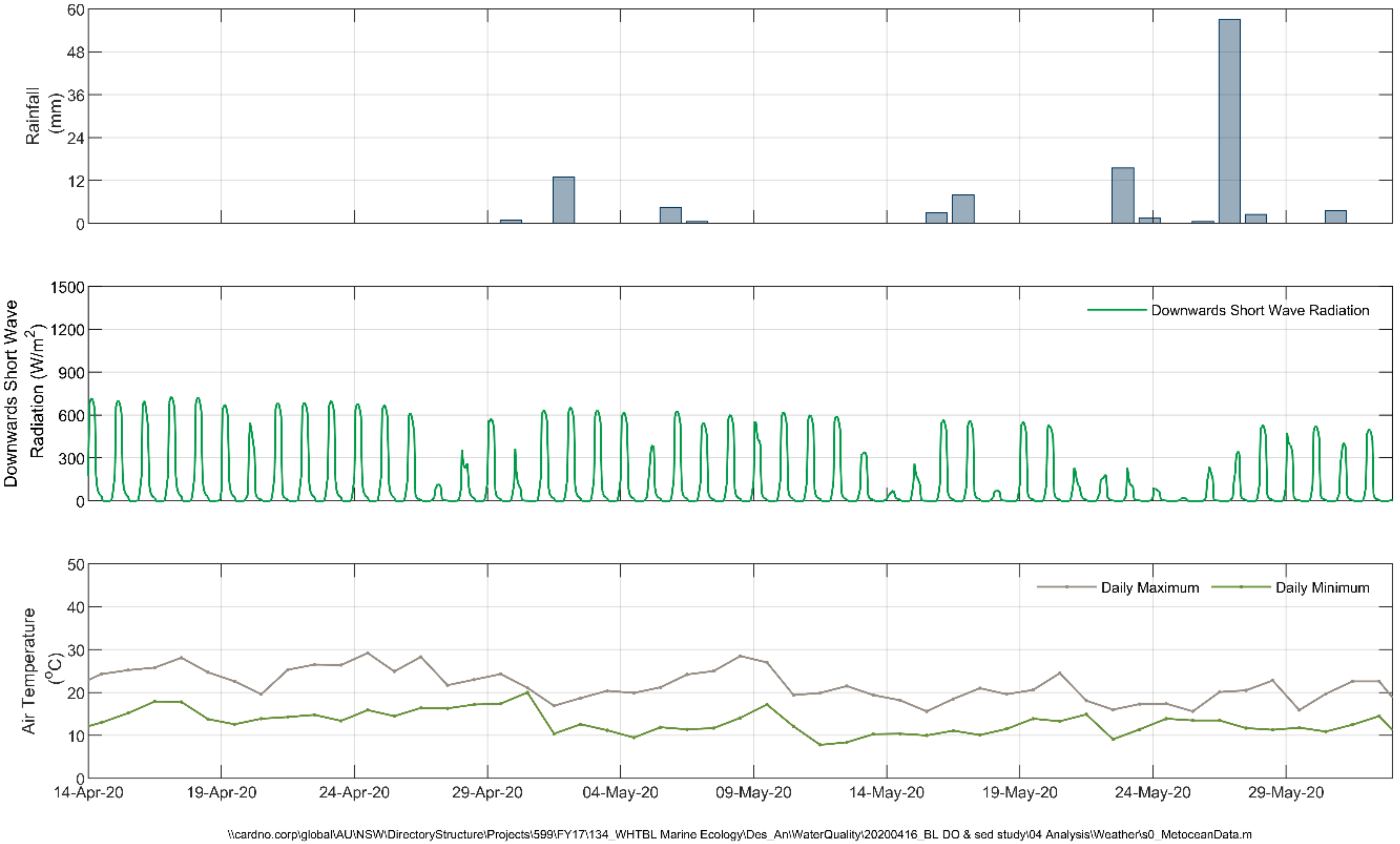

Figure B-3 Rainfall, solar radiation and air temperature during deployment period

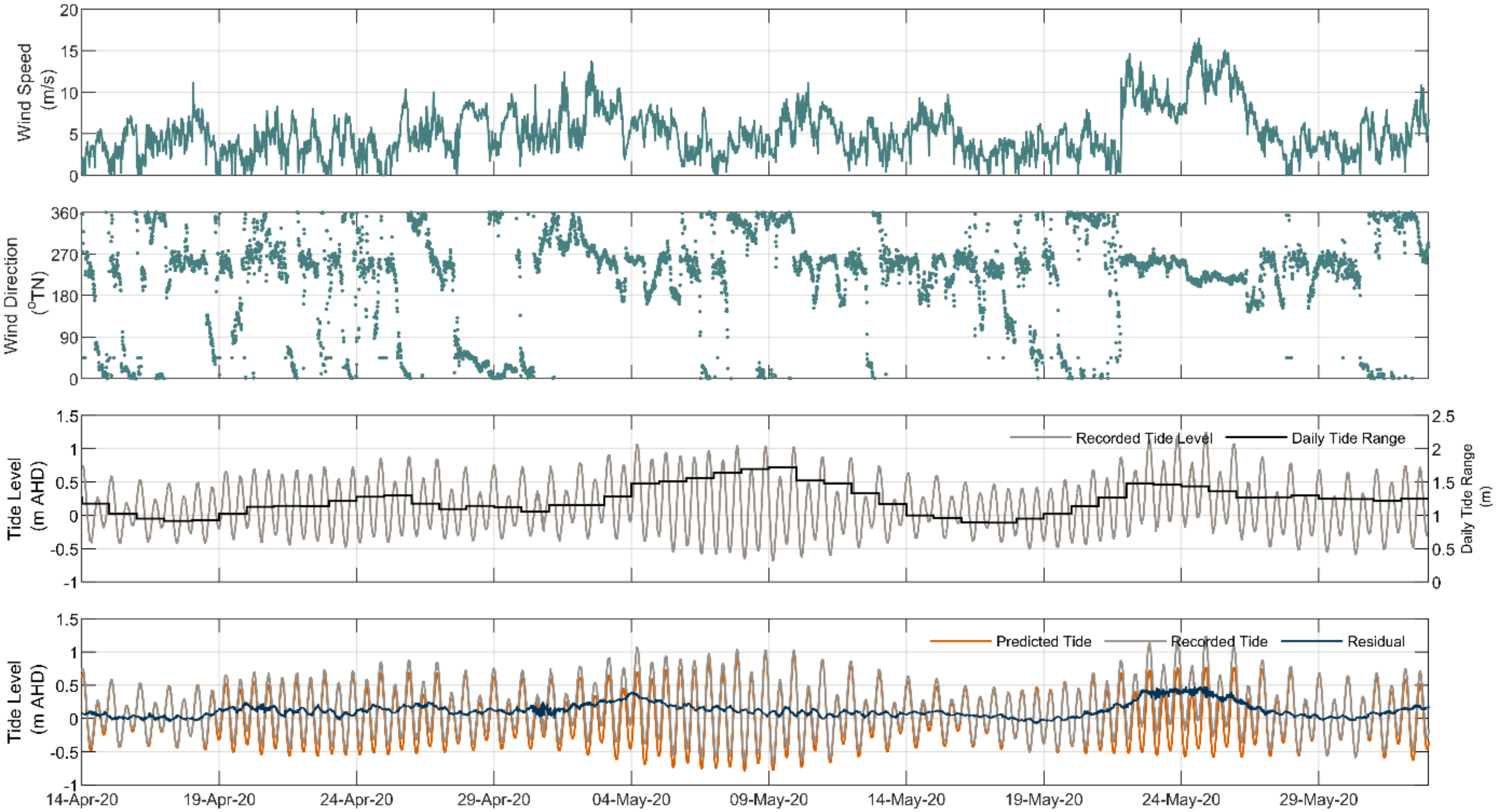

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Figure B-4 Wind and tide conditions during deployment period

B.7 Results

B.7.1 Time series – water quality instruments

As highlighted in Section B.6, the 61-day deployment period was drier than average and the influence of this low rainfall is evident in the water quality measurements. The time series of dissolved oxygen, salinity and temperature collected at sites BM1 and BM2 are presented in Figure B-5 and Figure B-6 along with water levels and rainfall.

Water temperatures ranged from 17°C to 21°C, gradually decreasing over the deployment, as cooler weather developed over late autumn. This temperature range was generally consistent for both monitoring sites, with water at site BM1 generally warmer at the start of the monitoring period and displaying greater temperature variability over the deployment due to the influence of tidally driven flows of ocean and catchment runoff water temperatures.

Salinity values ranged from 33.9 to 35.2 PSU with site BM2 displaying greater variability than BM1 over the deployment and with a larger gradient evident between the near bed and -5 metre LAT depths. The small salinity gradient evident at site BM1 indicates the higher mixing expected at this site. At site BM2, larger differences in measured salinity at the two deployment depths were observed. The largest salinity difference of 5.9 PSU occurred on 31 May 2020 with the -5 metre LAT depth measurement being 37.8 PSU and the near bed measurement being 33.9 PSU. This salinity gradient developed after the high rainfall recorded in the week prior to 26 May 2020.

Similarly, dissolved oxygen measurements at the two depths at site BM1 show good correlation, while larger differences are observed at site BM2. At the time of the instrument deployment on 28 April 2020 a vertical difference in dissolved oxygen concentration between the two depths at site BM2 was around one mg/L and this difference persisted until 1 May 2020. A gradual decrease in dissolved oxygen at the near bed depth at site BM2 was observed after the rainfall event occurring in the week prior to 26 May 2020. Over the seven days from 1 May 2020 to the instrument recovery on 1 June 2020 the dissolved oxygen concentration had decreased from 6.95 to 6.07 mg/L.

Turbidity and chlorophyll-*a* data collected at the -5 metre depth at sites BM1 and BM2 are presented in Figure B-7 and Figure B-8. The turbidity measurements at both sites show higher readings than measured by the vertical profiler at corresponding times and also display a diurnal trend. These discrepancies indicate that the measurements may be compromised. The chlorophyll-*a* concentrations are generally low at around 1 µg/l, with a peak observed at site BM2 of 4 µg/l after the rainfall event of 26 May 2020 and then remaining elevated at around 2 µg/l until 29 May 2020.

B.7.2 Time series – ADCP

The ADCP measured vertical profile of current magnitude and direction at site BM2 is presented in Figure B-9. The currents at this site display a tidal influence, with currents generally less than 0.2 metres per second except in the upper five to seven metres of the water column where wind driven currents appear to be dominant. These wind driven currents exceed 0.2 metres per second and are predominantly towards the east. As described in section B.6, strong south westerly winds persisted from 22 to 26 May 2020 corresponding to the period of stronger easterly currents in the upper water column.

The tidally driven currents display a complex structure, with higher currents generally occurring towards the surface although with current directions varying widely over the tidal cycle as a result of the complex bathymetry of the area.

B.7.3 Vertical profiles

Vertical profiles data was processed using the SeaBird Scientific utilities provided in SBE Data Processing tools and is summarised in Table B-6. Full vertical profiles for sites B1 to B13 are given for one of the six survey days (17 April 2020) are given in Figure B-14 to Figure B-26.

Table B-6 CTD processing configuration summary

Utility	Description
Convert	Convert raw instrument data to engineering units using the sensor calibration constants.
Filter	Apply low pass filters to conductivity, temperature (A 0.5) and pressure (B 1.0) data
Align	Align temperature conductivity and pressure data (advance 0.5 seconds)
Derive	Calculate derived parameters: water depth (sea water, lat = -33.87), density, salinity, specific conductance

Figures of all profiles conducted over this period of field data collection are presented below and the date, site name and time (see Table B-4) used to reference each figure.

B.7.4 Extinction Coefficient derived from vertical PAR profiles

A computation to derive the extinction coefficient for the standard exponential light decay model has been performed on the measured PAR profiles conducted as listed in Table B-4 using the method described in Section 3.3.3. The calculated light extinction coefficient was consistent for these profiles with a range of 0.22 to 0.47 and an average of 0.29, corresponding to an average photic depth during the period of 15.9 metres. These values are similar to the those measured in January 2018.

B.7.5 Post inflow event deep water dissolved oxygen

To highlight the effects of the significant inflow event of 26 May 2020 on deep water dissolved oxygen concentrations, the time series measurements at sites BM1 and BM2 for the 10-day period 23 May to 1 June 2020 are presented in Figures B10 to B13. Prior to the rainfall on 26 to 27 May 2020, conditions were characterised by strong south westerly winds blowing for some four days in excess of 30 kilometres per hour. Over 50 millimetres of rain fell on 26 to 27 May 2020 towards the end of this wind event.

Dissolved oxygen in the deep water (Site BM2 Bottom in Figure B10) shows a gradual decrease of around 0.12 mgL^{-1} per day over the six days from 26 May 2020 to the end of the deployment on 1 June 2020. The near surface measurements at both sites and the deep water at site BM1 show similar dissolved oxygen concentrations indicating the rapid mixing and tidal advection at BM1 and through the surface layer down to around 10 metres depth at the upstream site, BM2.

Salinity and temperature through this six day period show the typical salt wedge recovery following the inflow event. During flood tides dense saline water from Port Jackson flows over The Bar and into the deeper waters in the basin between The Bar and the Spit Bridge (20 metre deep basin). It appears this dense water influx at each flood tide is mixed within the basin and does not propagate upstream over The Spit sill (depth 10 metres), see Figure 3-1 for the partially mixed estuary. Low salinity in the surface at site BM2 indicates the catchment runoff mixes with the estuarine waters forming a surface layer that flows downstream and mixes with the higher salinity ocean waters. In the deeper water upstream of The Spit sill the very low mixing and exchange at site BM2 is clearly indicated by the almost constant salinity and temperature signals (see black line in Figure B10) coinciding with the decreasing dissolved oxygen.

The water currents during the period (Figure B11) show a complex shift in driving forces between winds, freshwater inflow, the tides and what appear to be baroclinic oscillations caused by the interaction of vertical stratification, topographic features and key driving forces. Figure B12 shows the near bottom currents (4.5 metres above the bed in water depth of 31 metres AHD) are relatively low, less than 0.1 metres per second and direction with variable current direction generally reflecting the tidal forcing. It appears that the dense bottom water is advected back and forth within the deep basin with little vertical mixing. The tidal excursion in the deep water is around one kilometre at the average speed of 0.05 metres per second. Closer inspection of the salinity and temperature signals during this period show a very slight decrease in salinity and an increase in temperature suggesting a very small amount of vertical diffusion of salt and temperature.

The vertical profiles taken on 27 May 2020 and 1 June 2020 at site BM2 in the deep basin show the effects of rapid mixing with a series of step-like structures in the surface layers down to about 15 metres depth and linear change below to the bed. Dissolved oxygen shows a linearly decreasing zone from around 10 metres depth, equivalent to the sill upstream of The Spit. At site BM1 downstream of The Spit, the layering of the salinity and temperature and high concentrations of dissolved oxygen indicate the rapid vertical mixing and advection at this site.

These data clearly indicate the longer retention times of water in the deep basin upstream of The Spit and resultant depletion of dissolved oxygen in the deep waters following the rainfall and inferred runoff event on 27 May 2020. There is evidence of low mixing causing the linear gradient in the layer between the bed of the harbour and about 10 metres deep although it appears that an e-folding time for the replenishment of the deep waters is likely to be greater than five days. This particular event occurred in late autumn when the benthic metabolism rates are generally declining as the cooler winter conditions. It is suggested that the rate of decrease of dissolved oxygen would be greater following a similar (greater than 50 millimetre rainfall) event during the warmer summer or early autumn period.

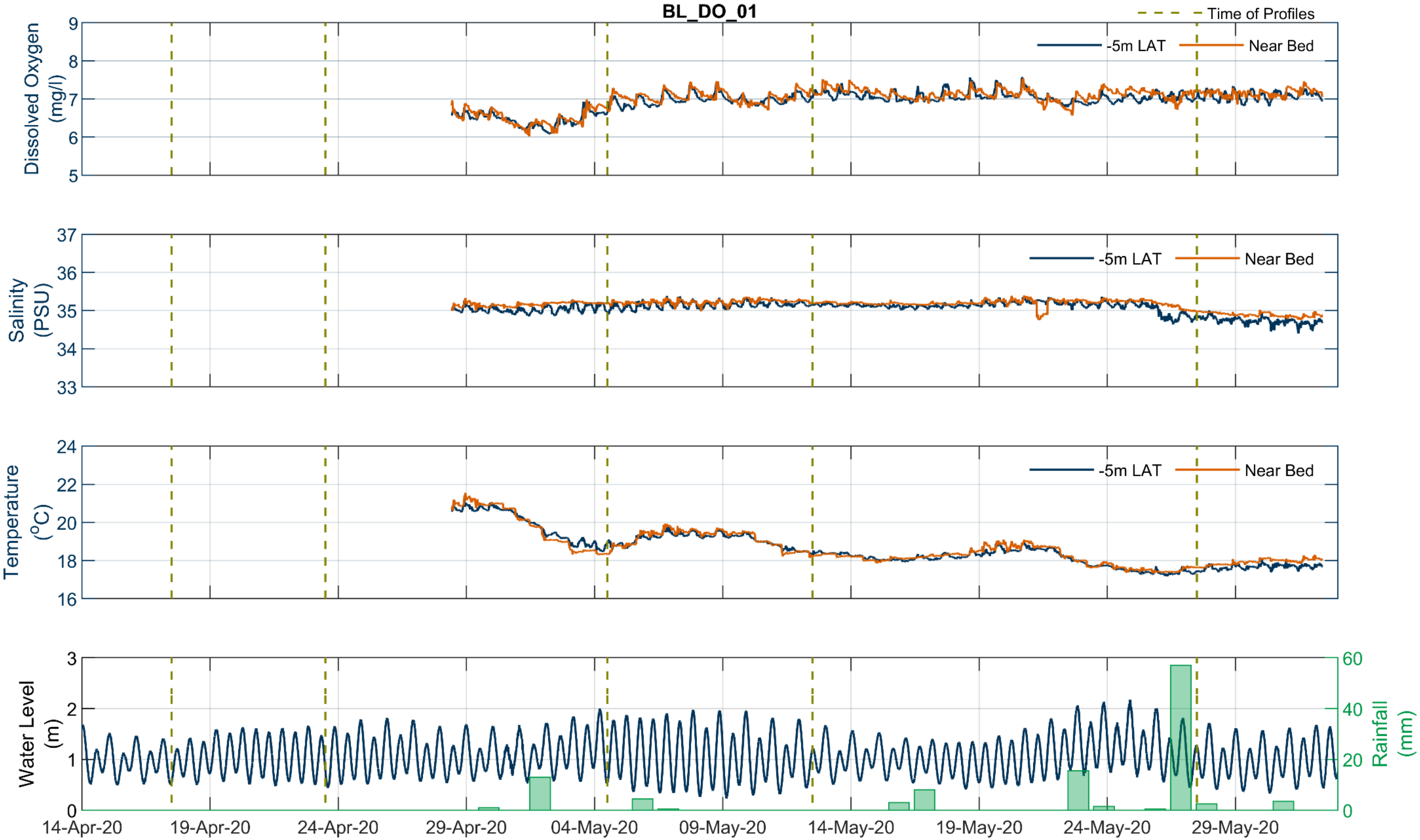

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Figure B-5 BM1 water quality time series

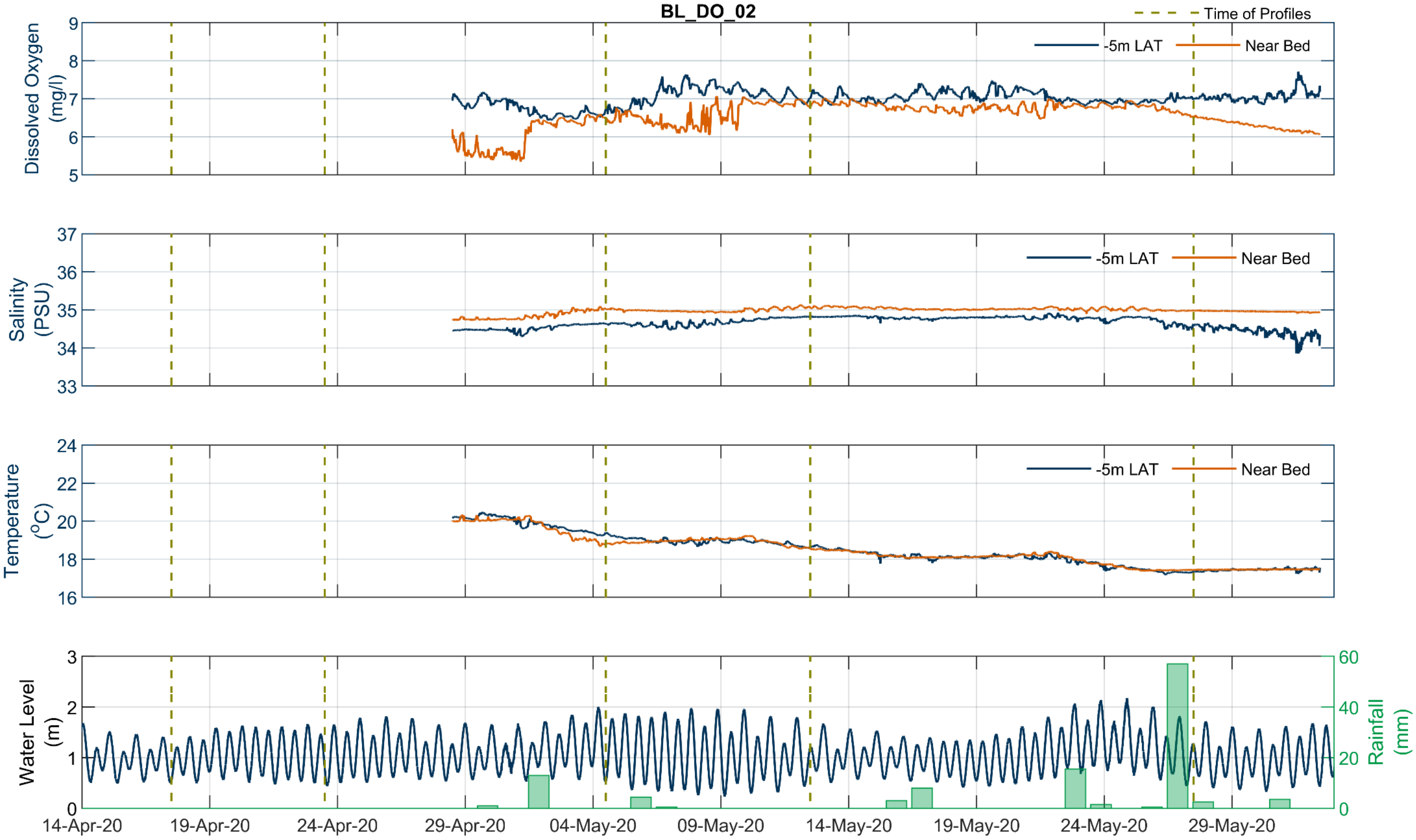

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Figure B-6 BM2 water quality time series

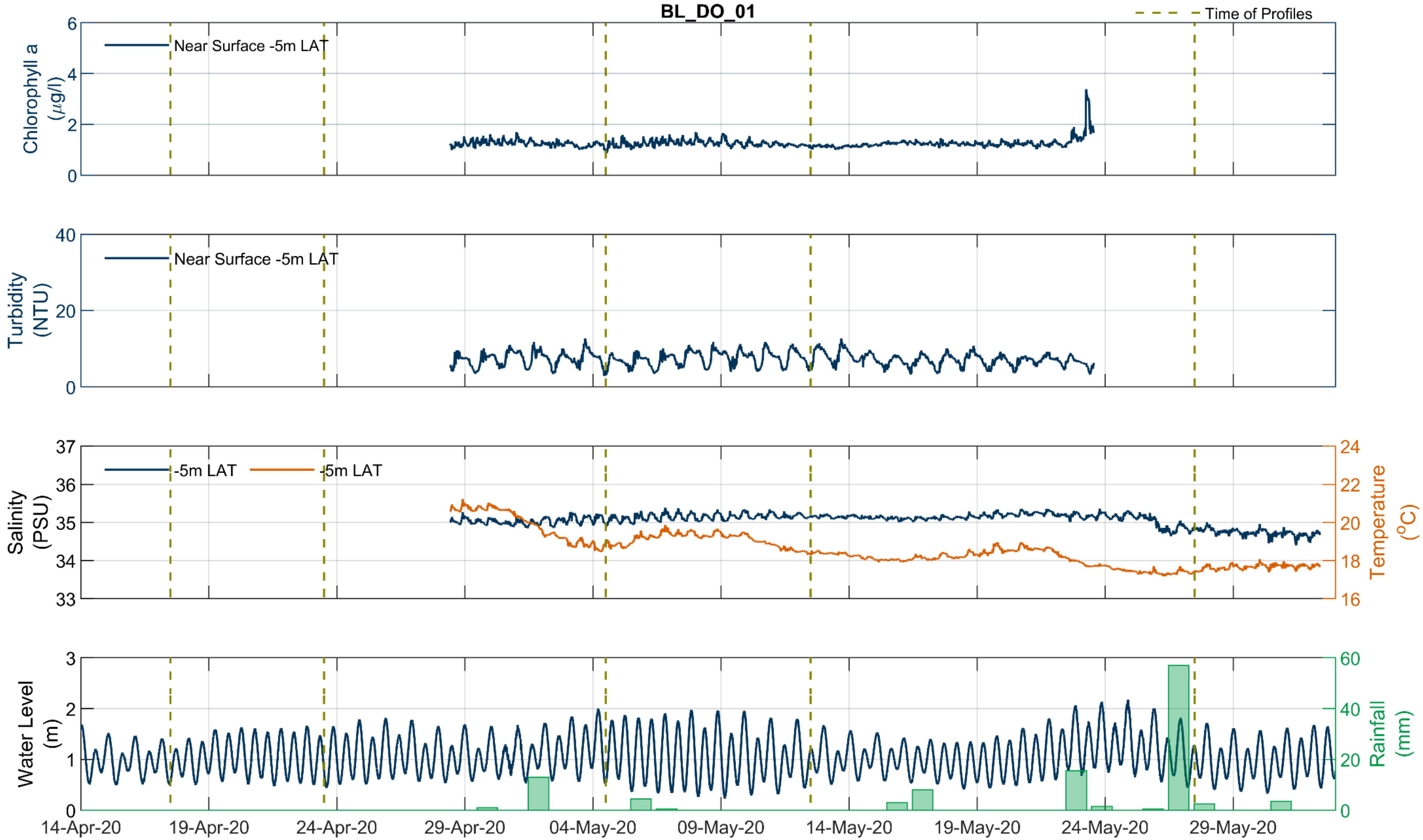

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Figure B-7 BM1 turbidity and fluorescence (chlorophyll-*a*) time series

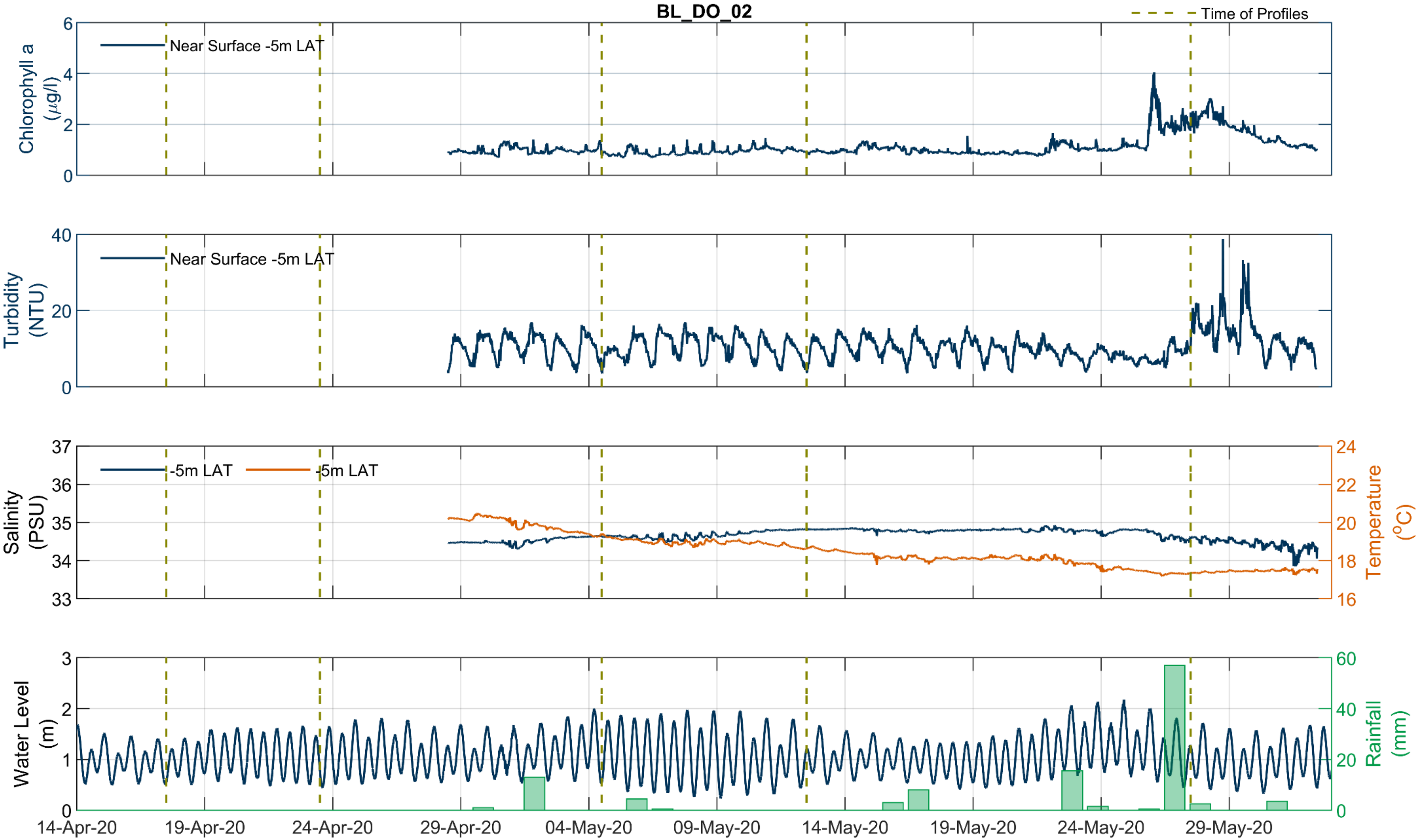

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Figure B-8 **BM2 turbidity and fluorescence (chlorophyll-*a*) time series**

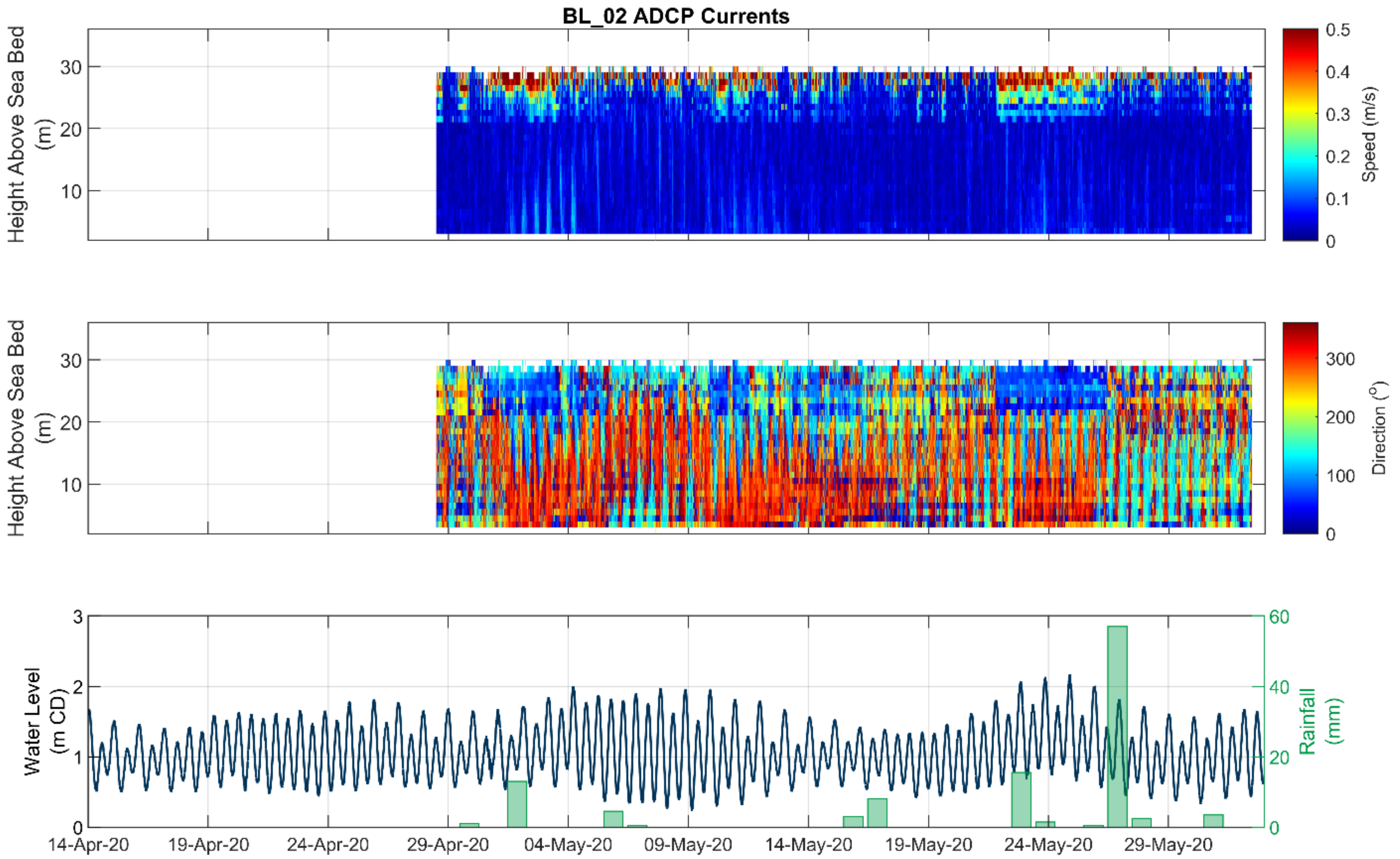

Figure B-9 BM2 ADCP time series

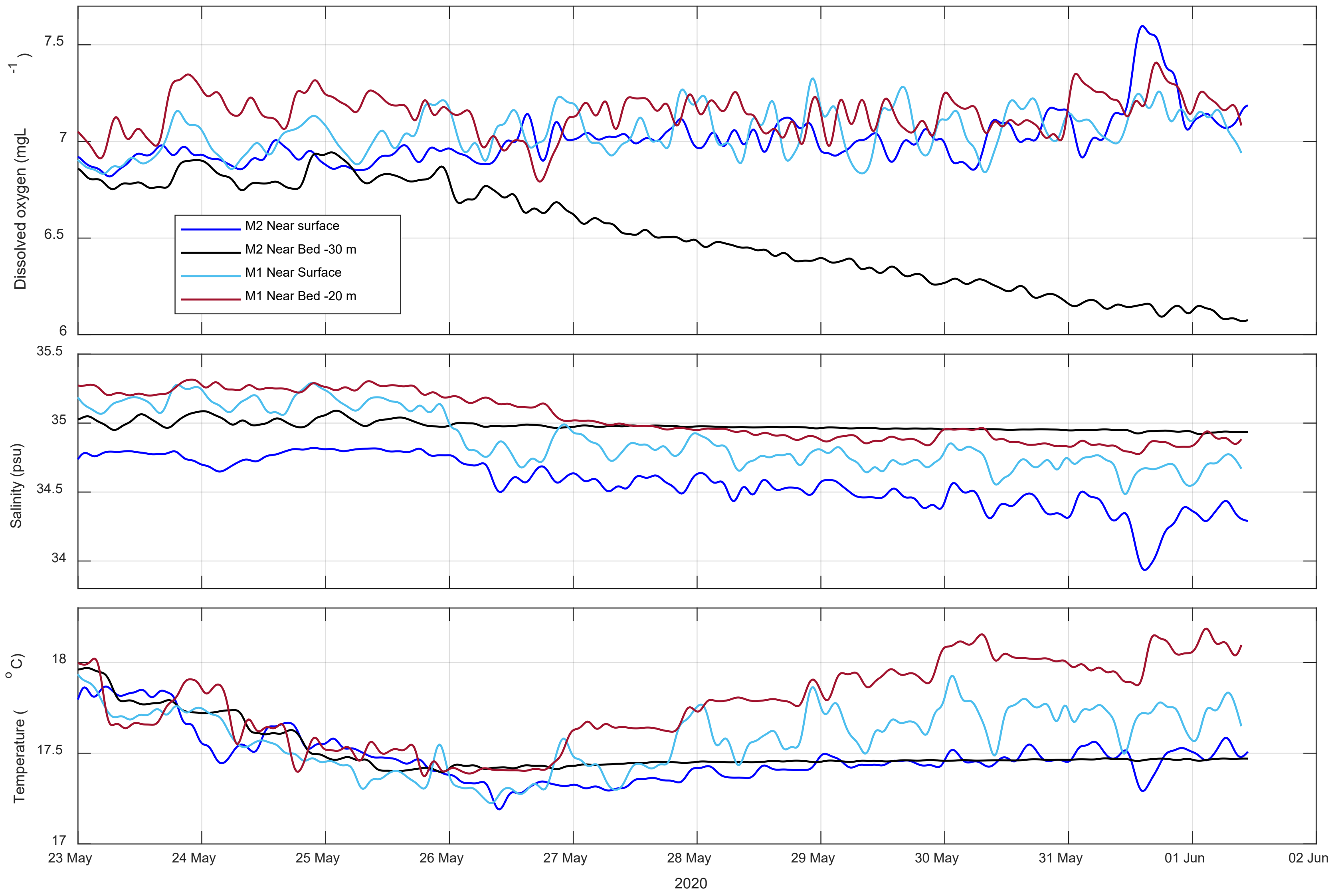

Figure B-10 Dissolved oxygen, salinity and temperature at sites BM1 downstream of the Spit bridge and BM2 (depth -31 metres AHD) upstream of the Spit Bridge near the proposed crossing location

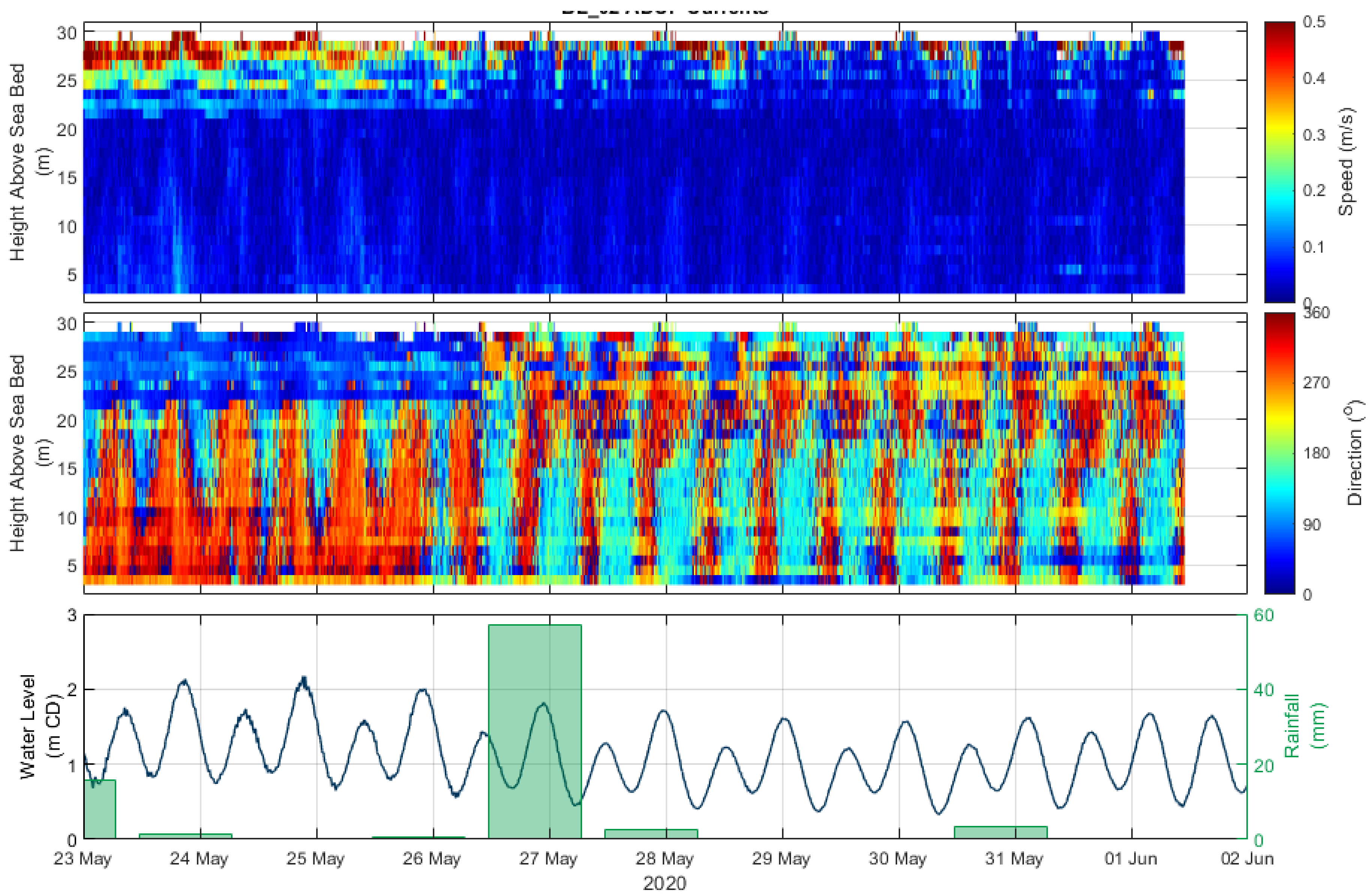

Figure B-11 **B11 ADCP time series at site BM2 at the crossing in water depth -31 metres AHD**

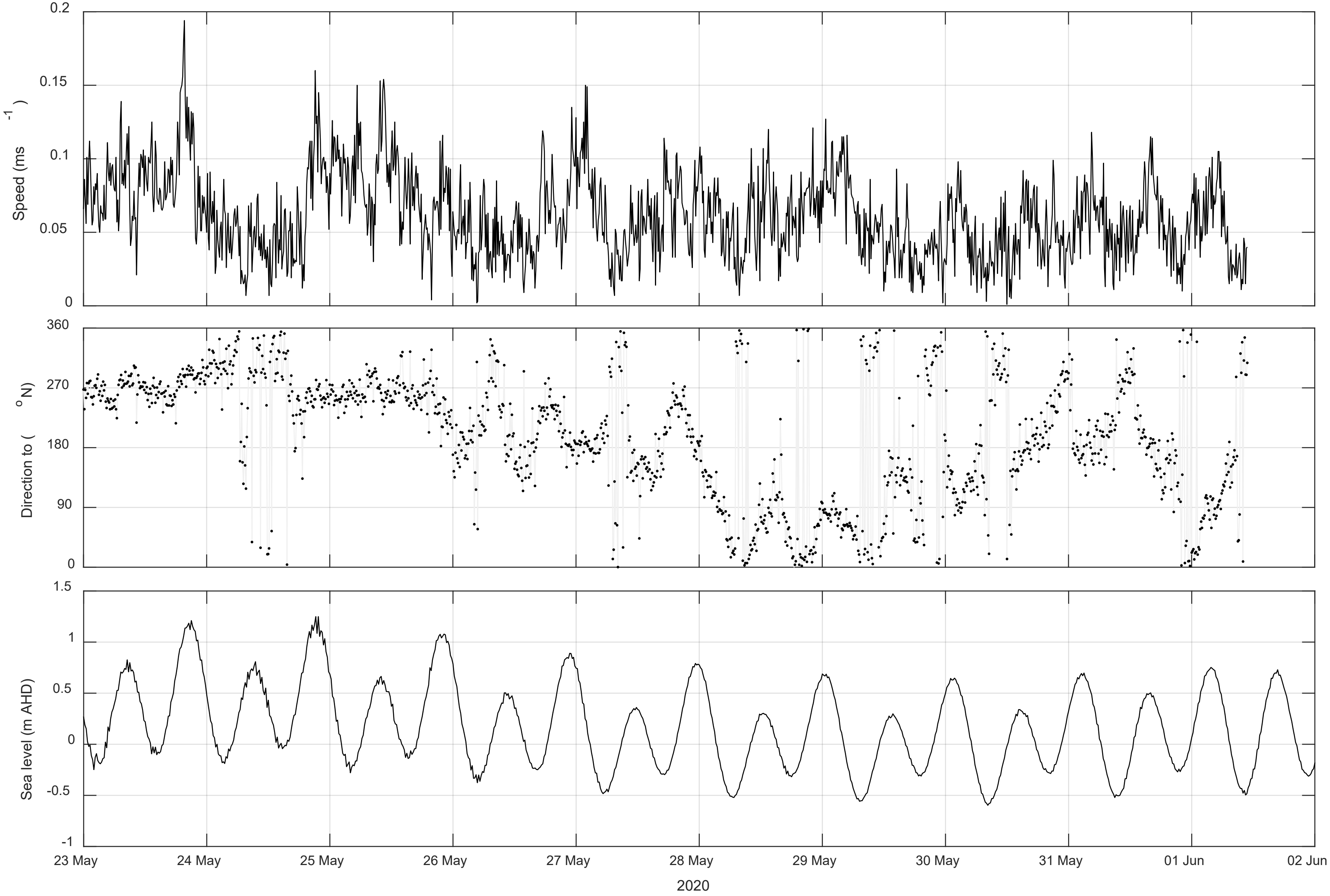

Figure B-12 ADCP near bottom (4.5 metres above bed) currents at site BM2 at the crossing in water depth -31 metres AHD

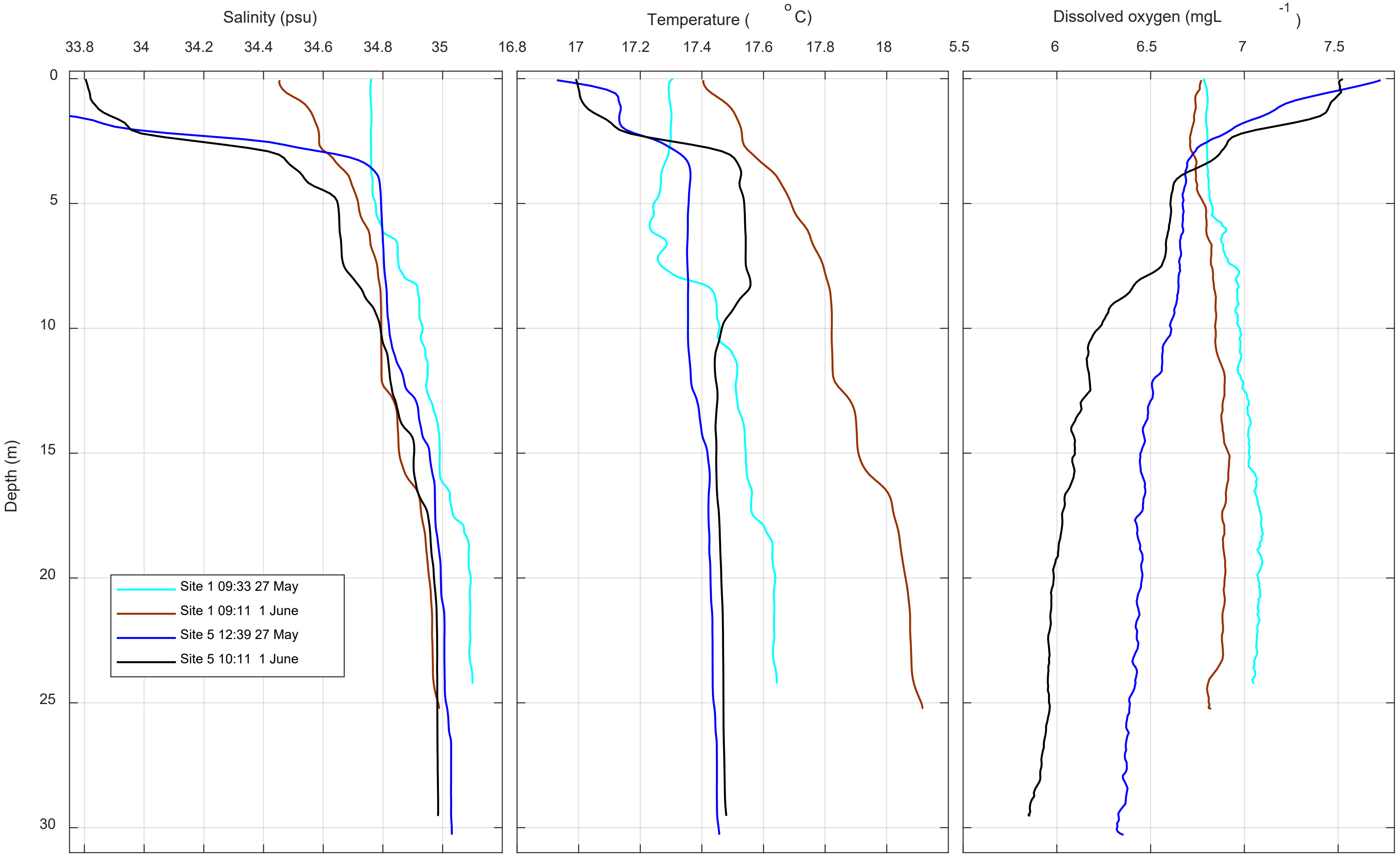

Figure B-13 Vertical profiles at on 27 May and 1 June at sites BM1 and BM2

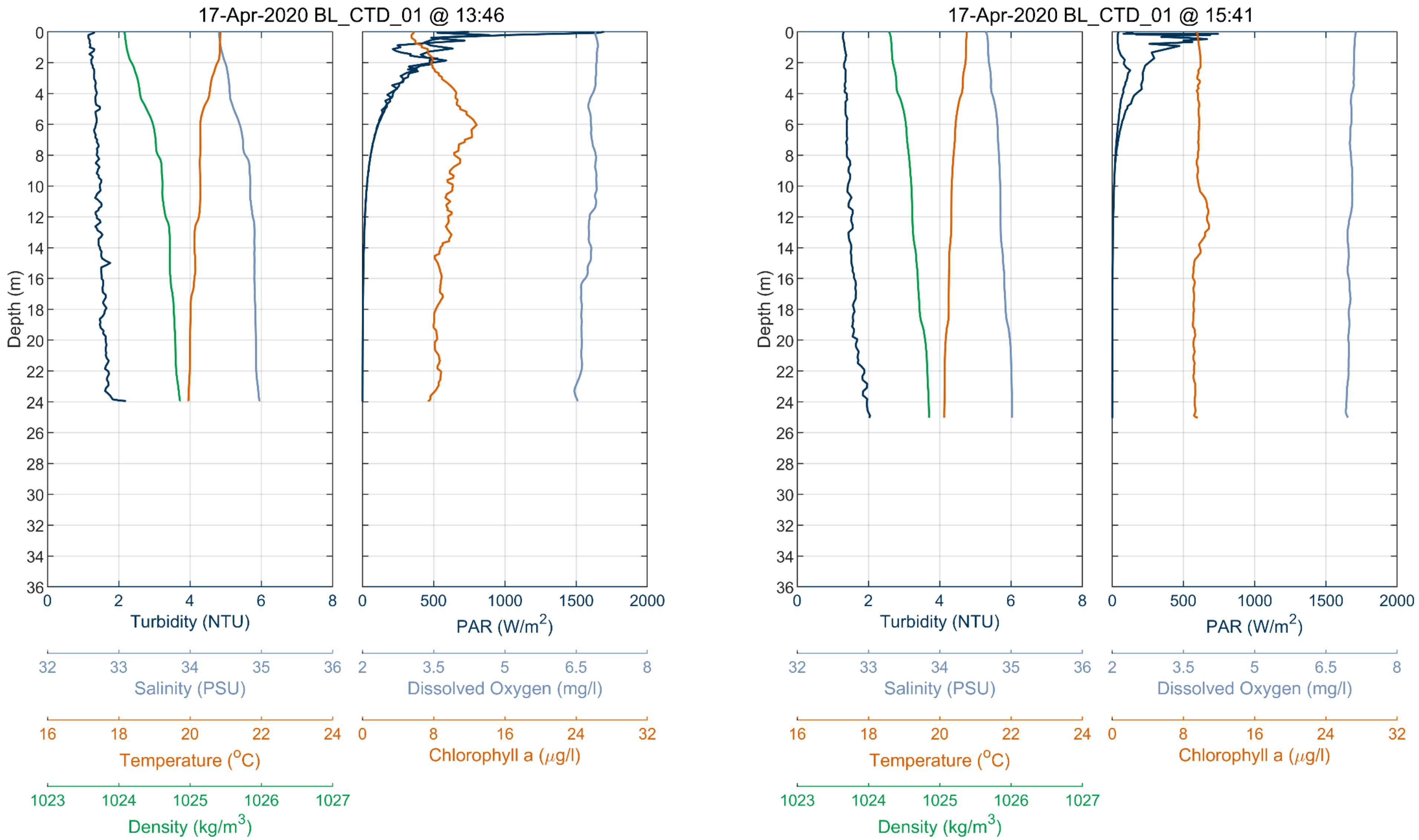

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Figure B-14 Vertical profiles at B1 on 17 April 2020

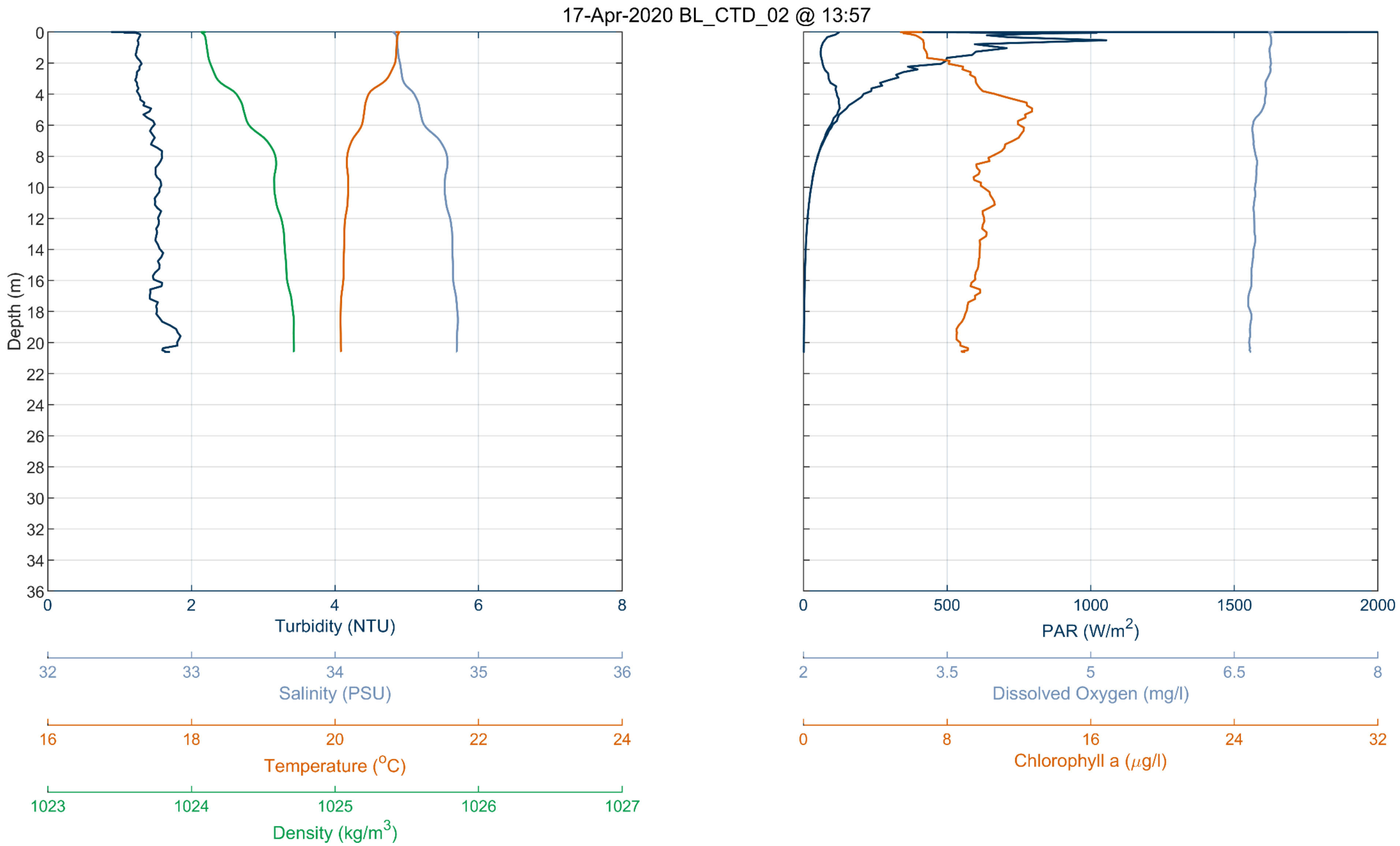

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Figure B-15 Vertical profiles at B2 on 17 April 2020

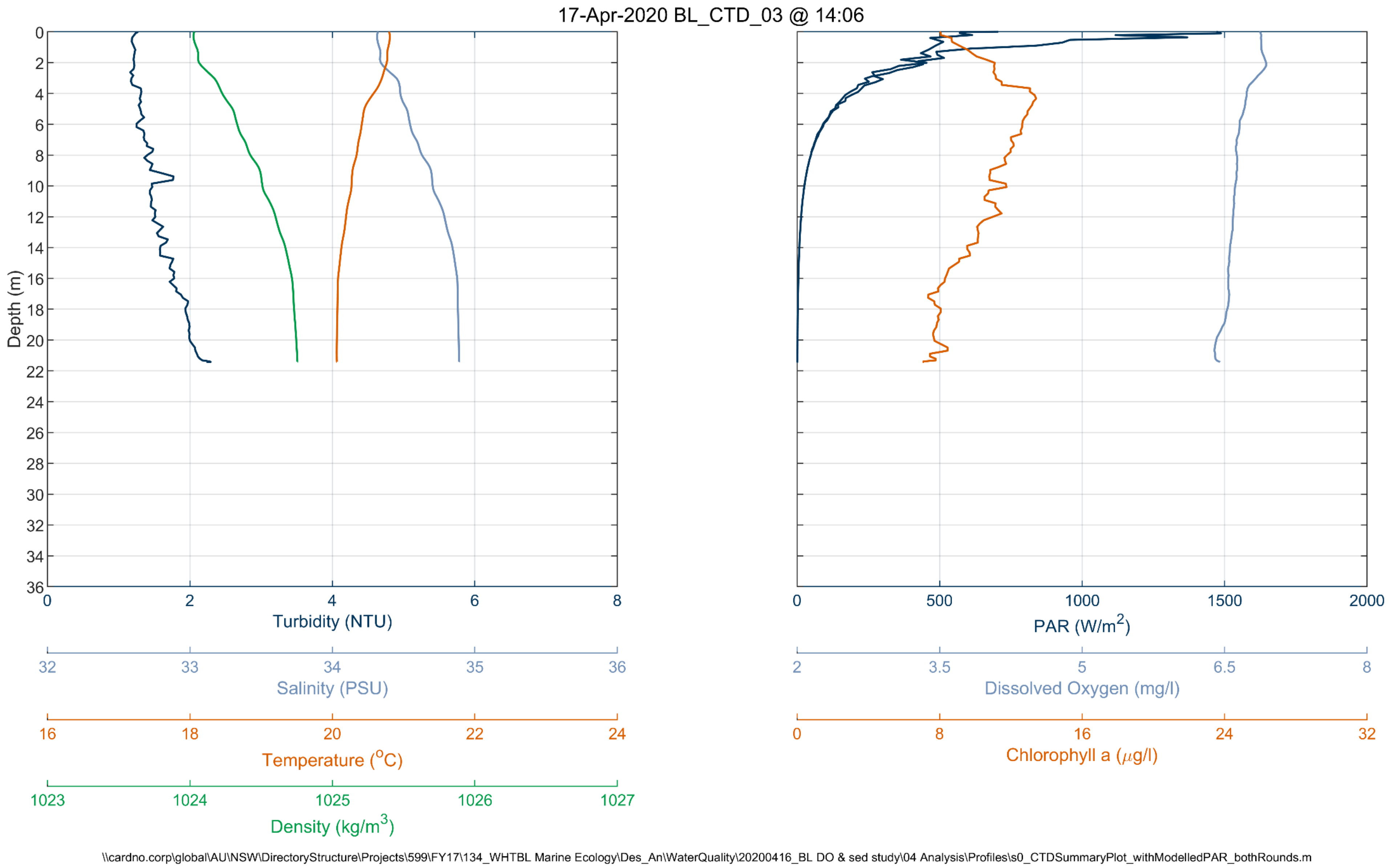

Figure B-16 Vertical profiles at B3 on 17 April 2020

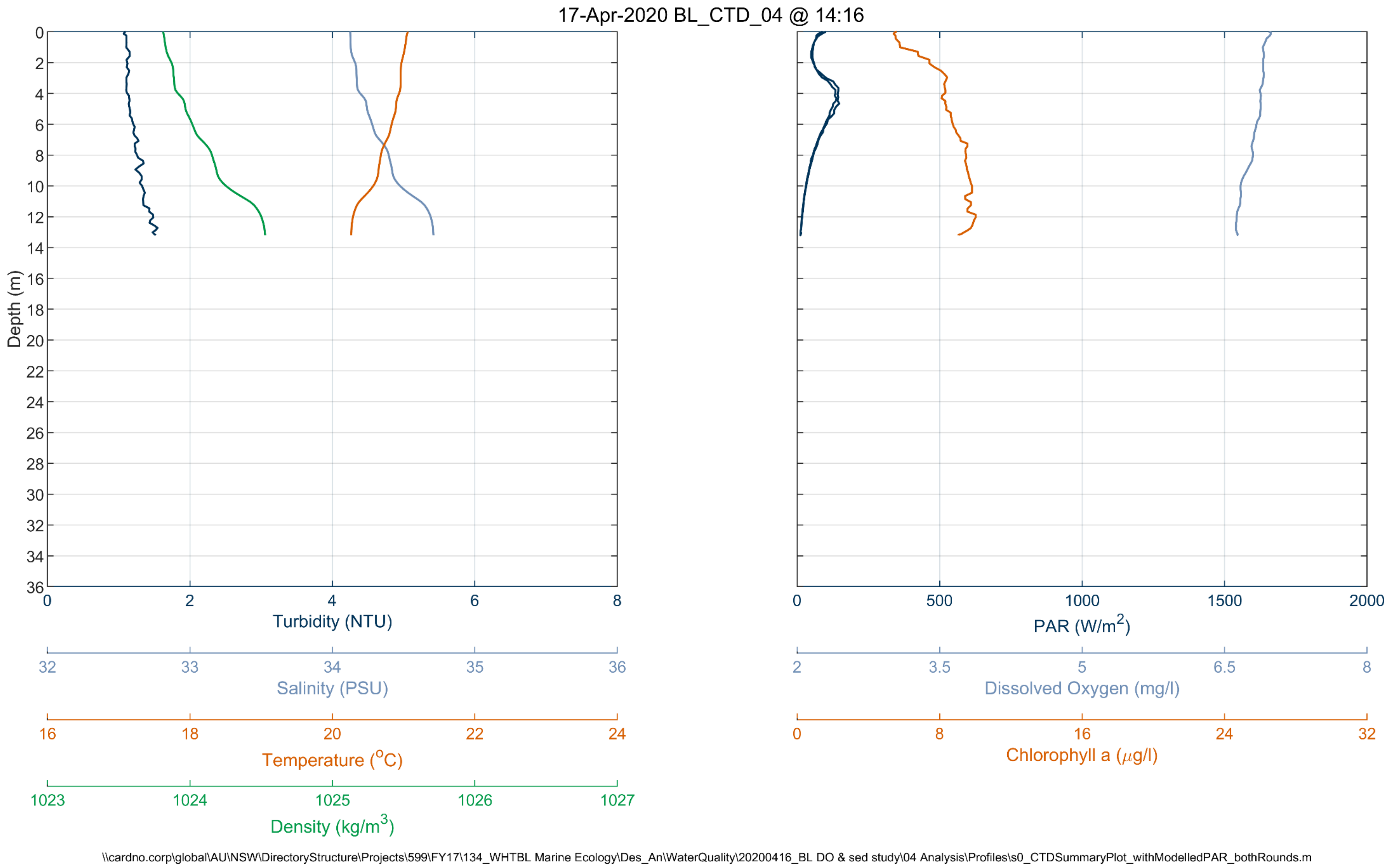

Figure B-17 Vertical profiles at B4 on 17 April 2020

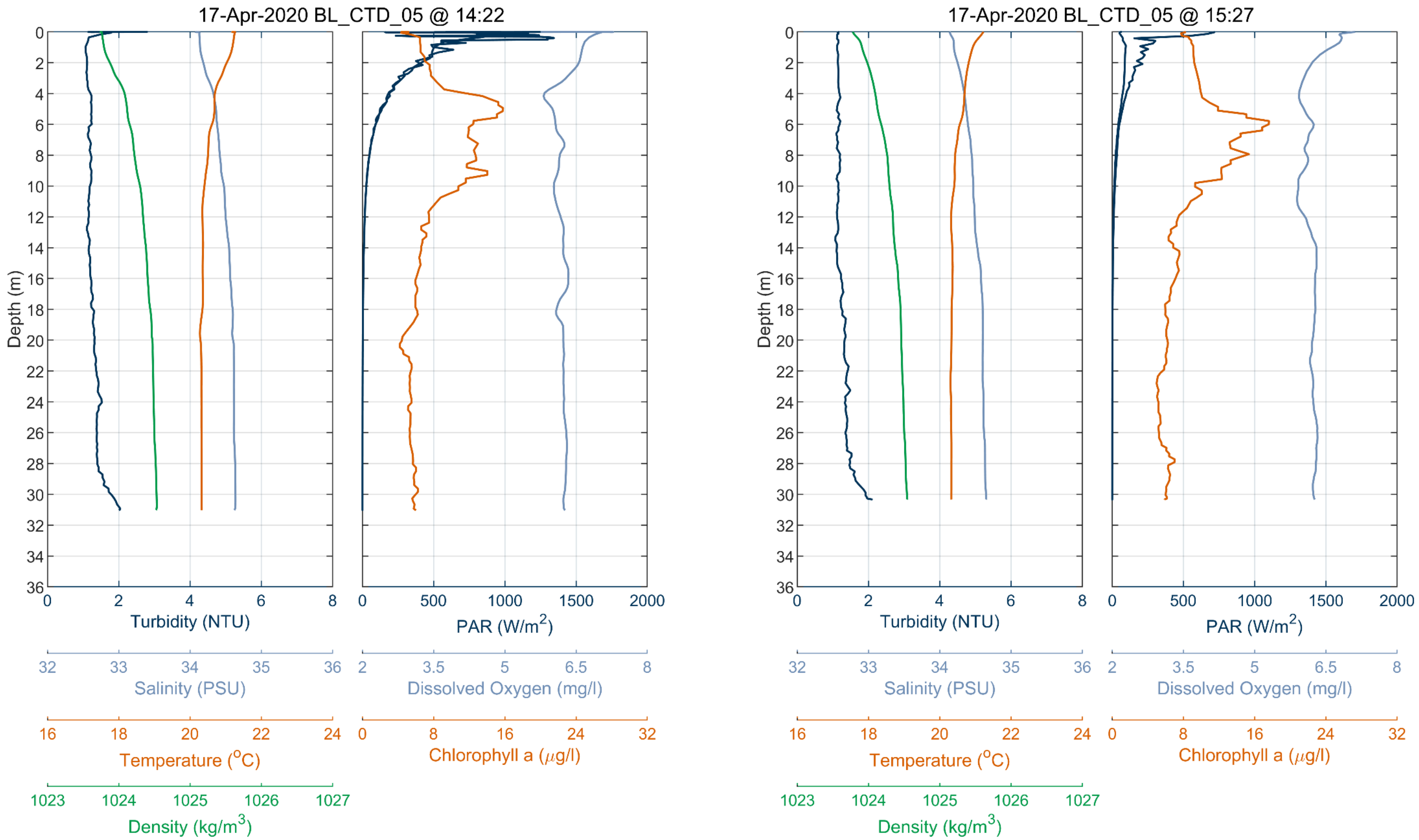

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Figure B-18 Vertical profiles at B5 on 17 April 2020

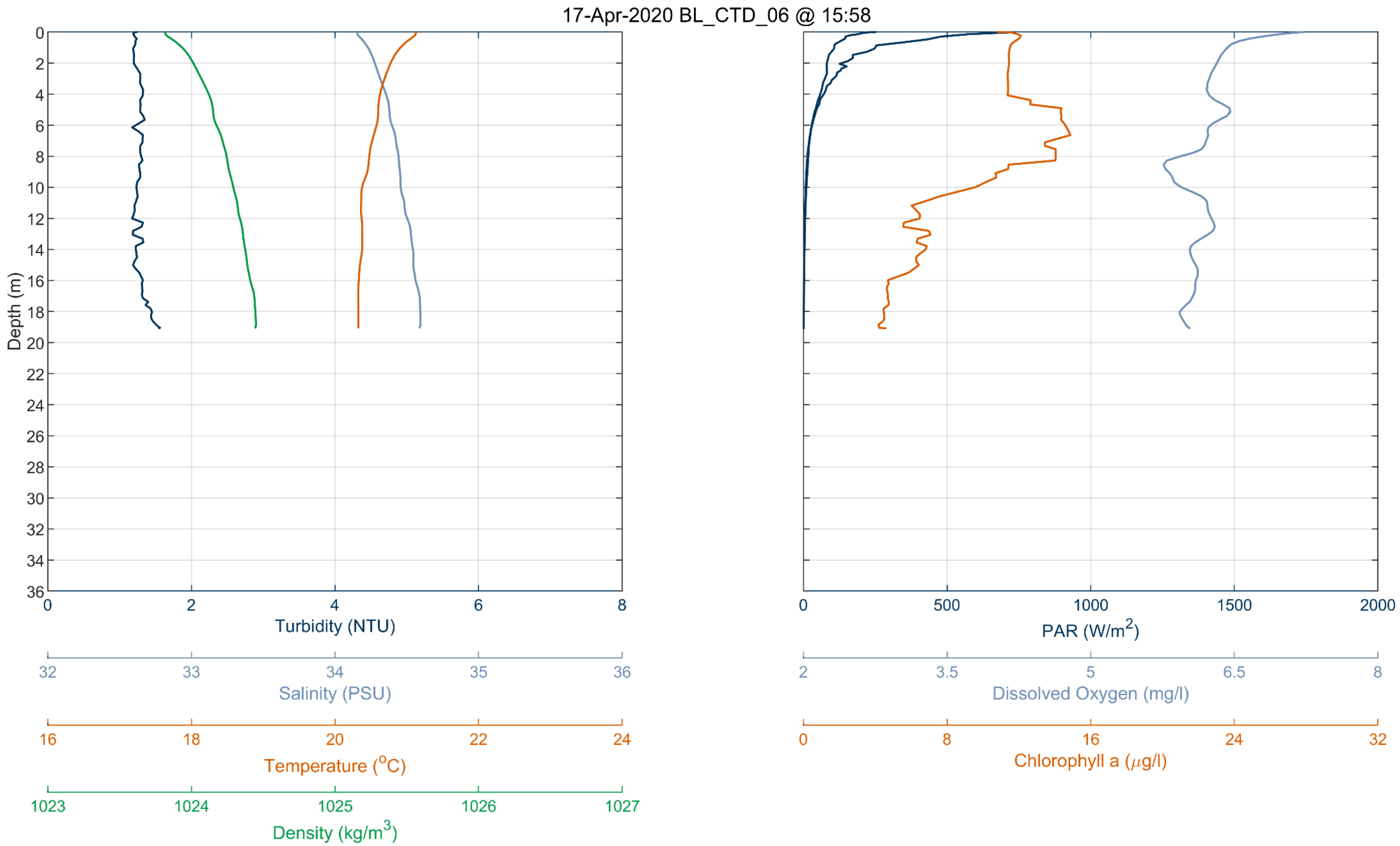

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Figure B-19 Vertical profiles at B6 on 17 April 2020

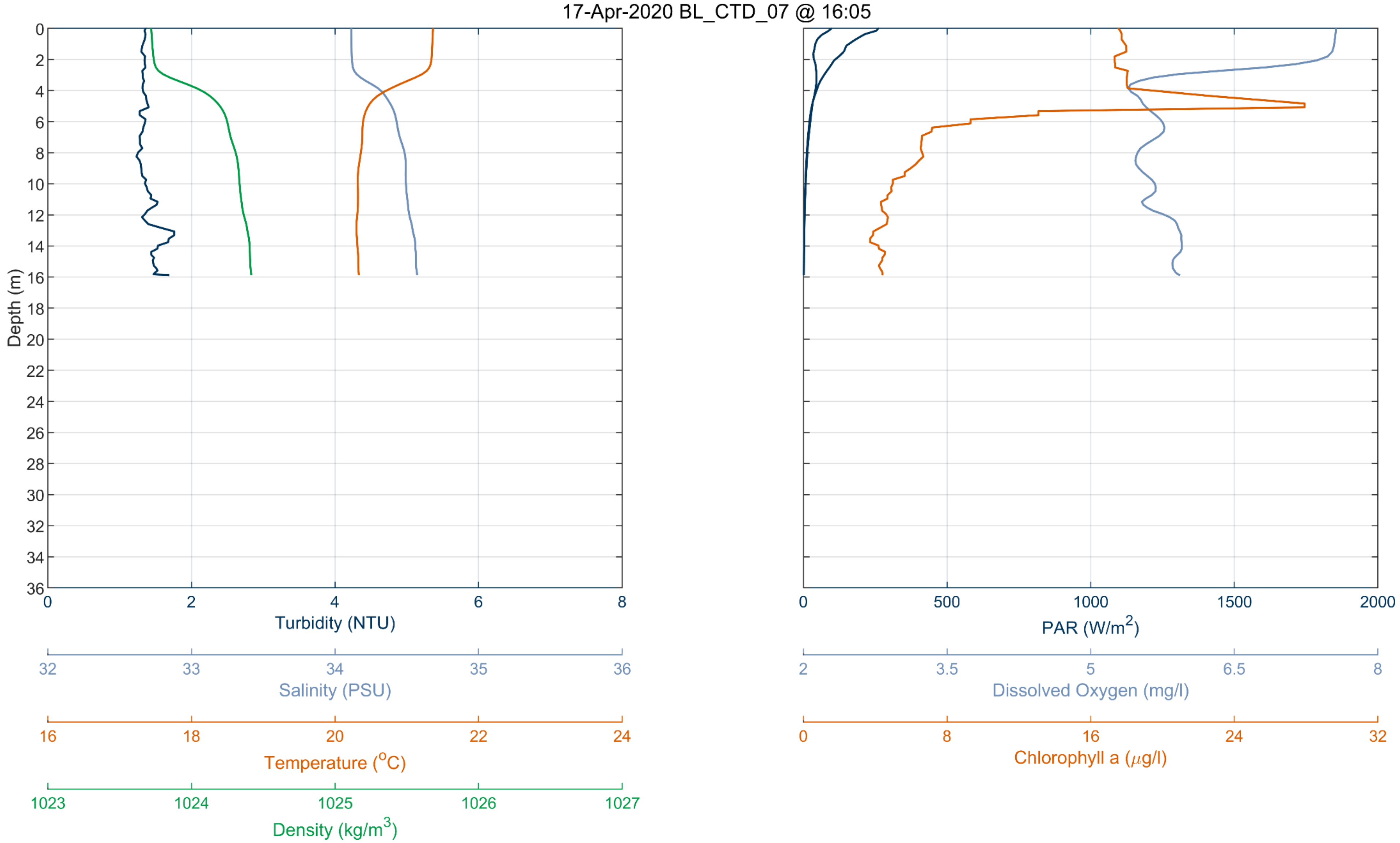

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Figure B-20 Vertical profiles at B7 on 17 April 2020

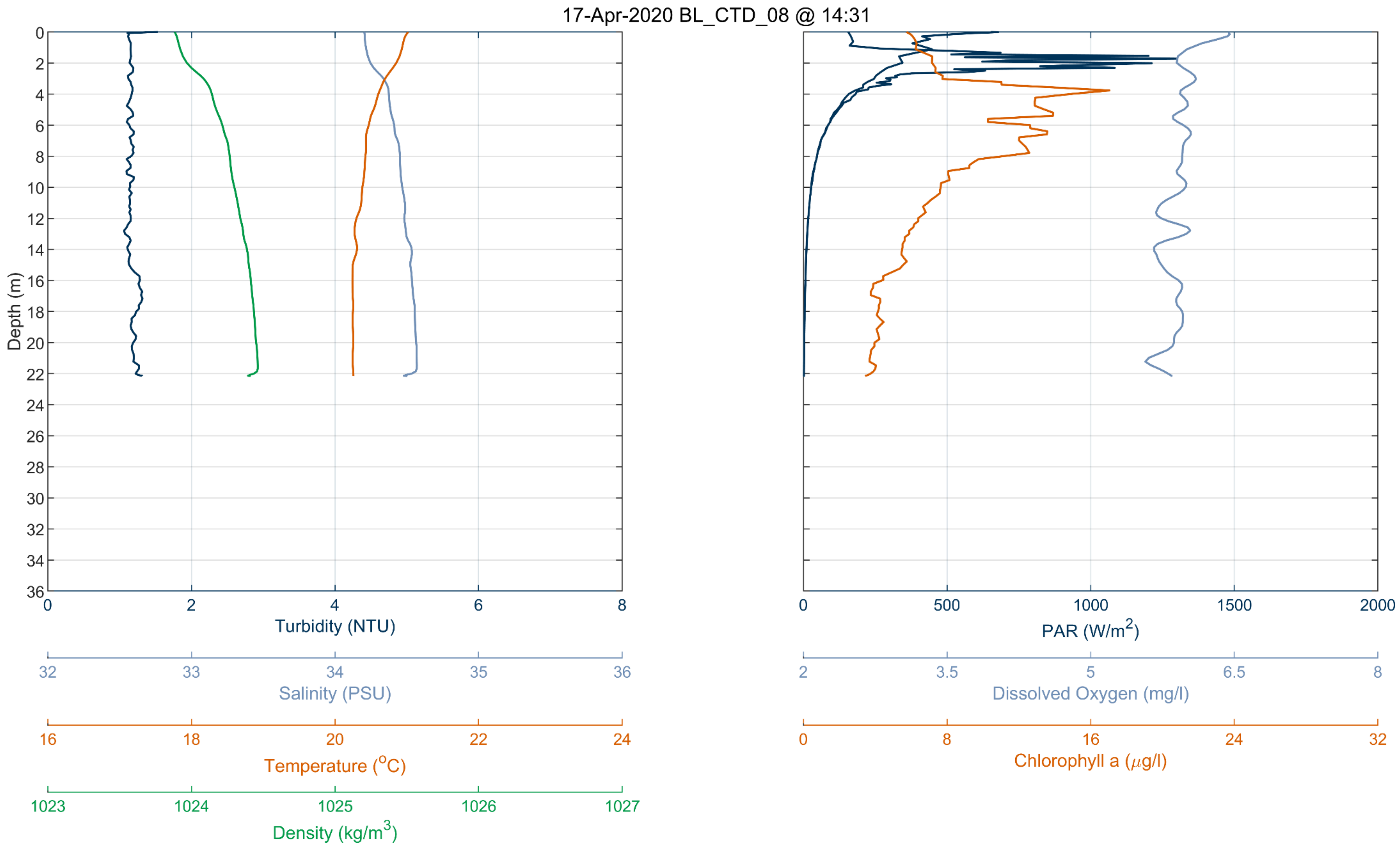

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Figure B-21 Vertical profiles at B8 on 17 April 2020

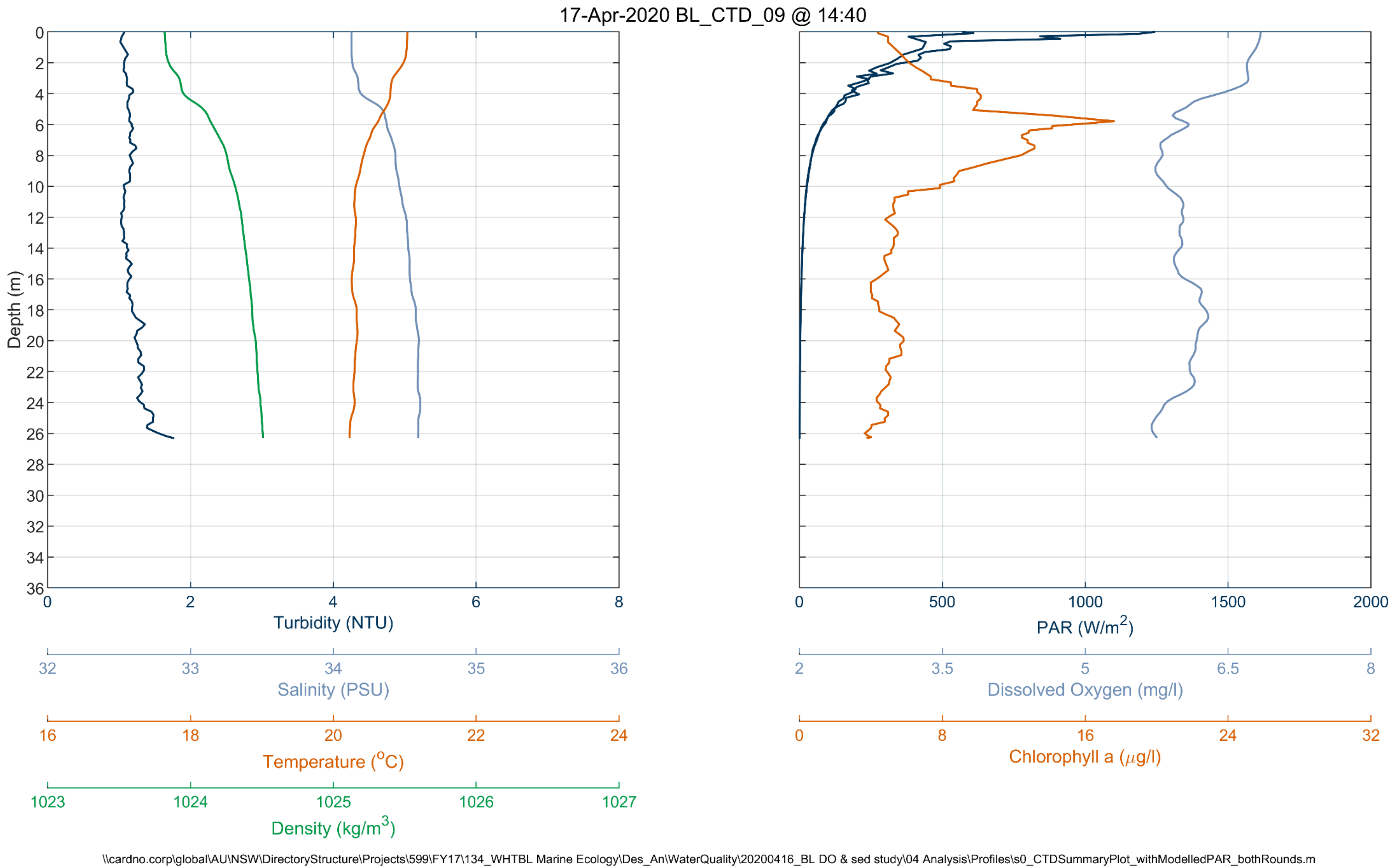

Figure B-22 Vertical profiles at B9 on 17 April 2020

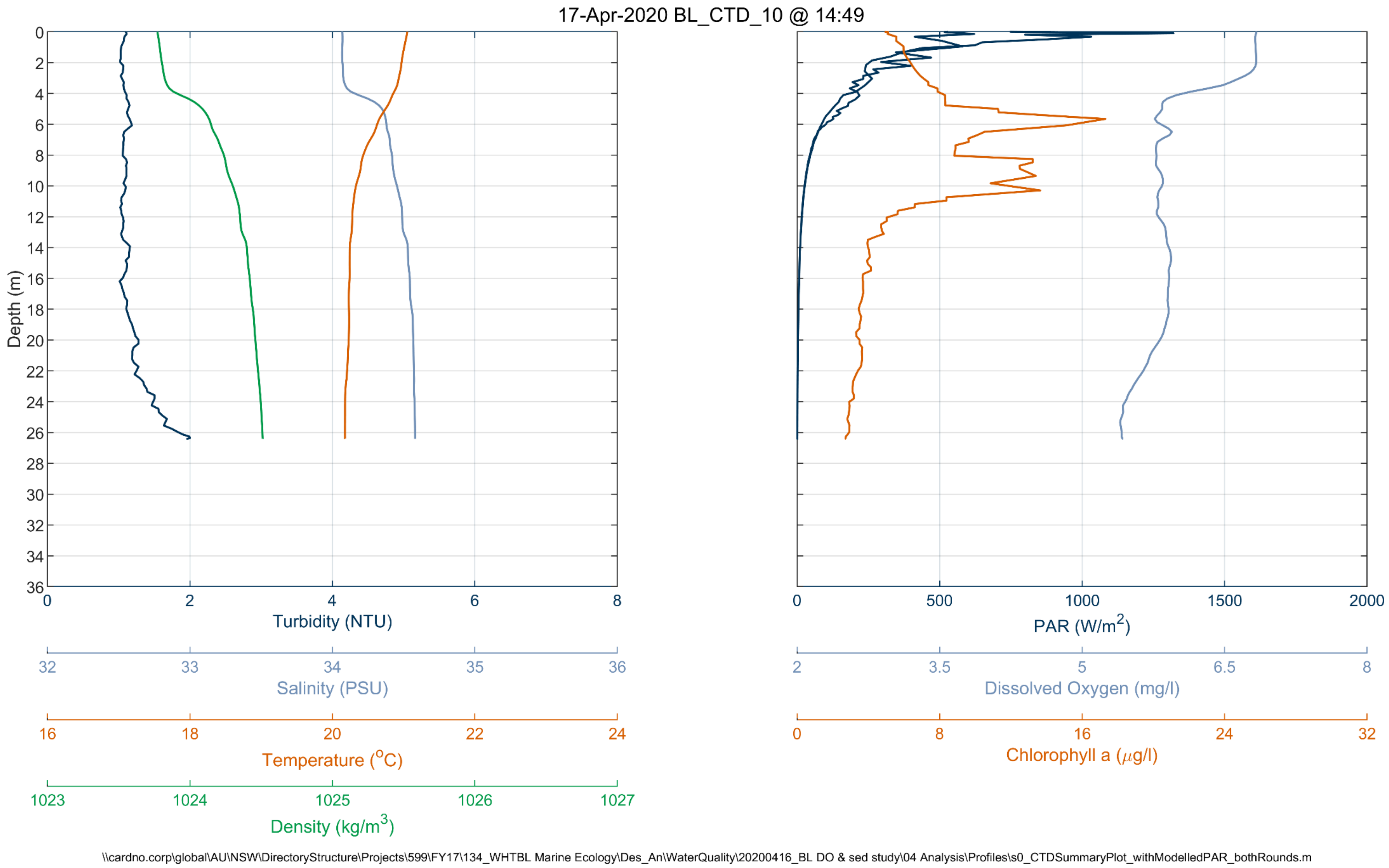

Figure B-23 Vertical profiles at B10 on 17 April 2020

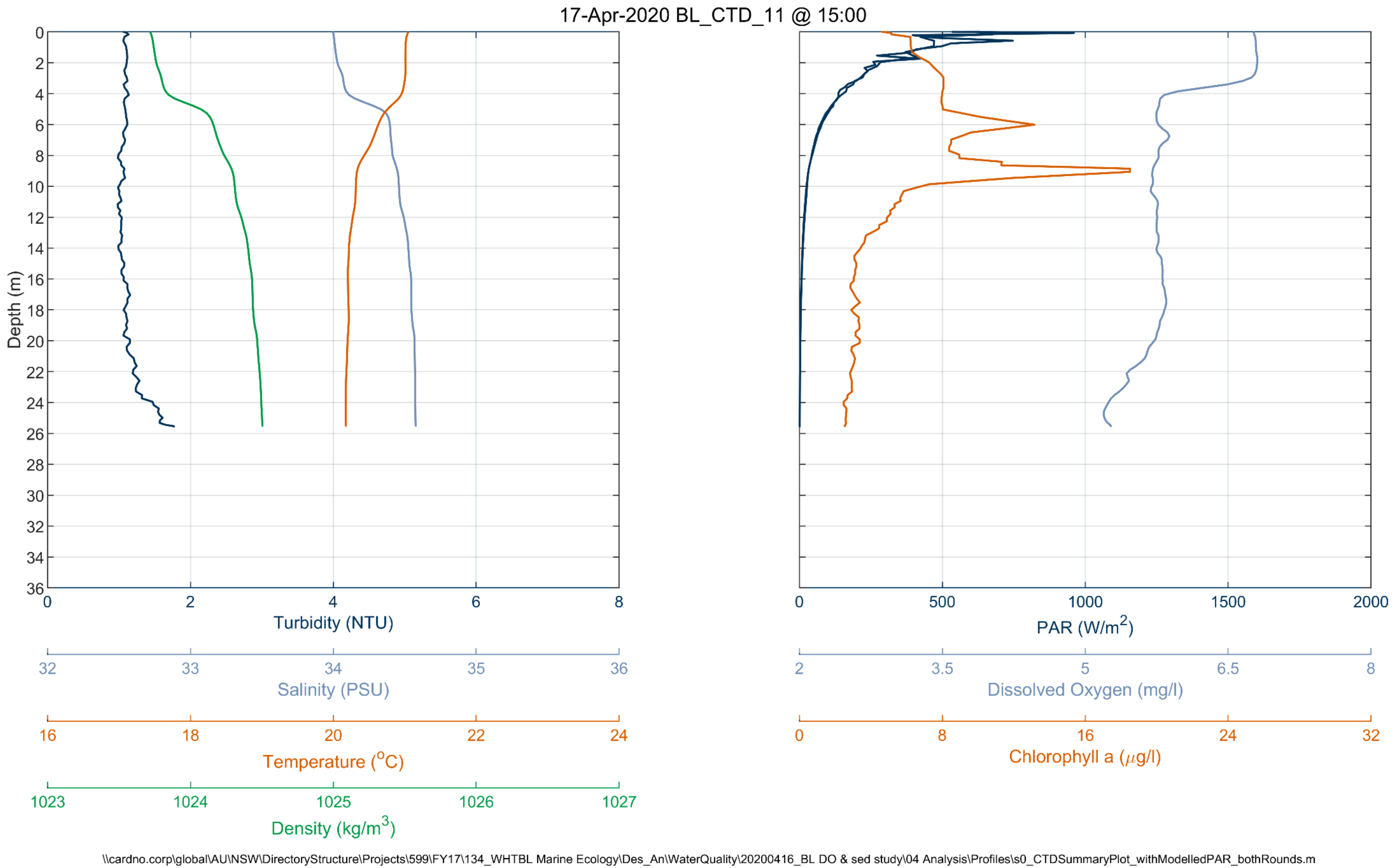

Figure B-24 Vertical profiles at B11 on 17 April 2020

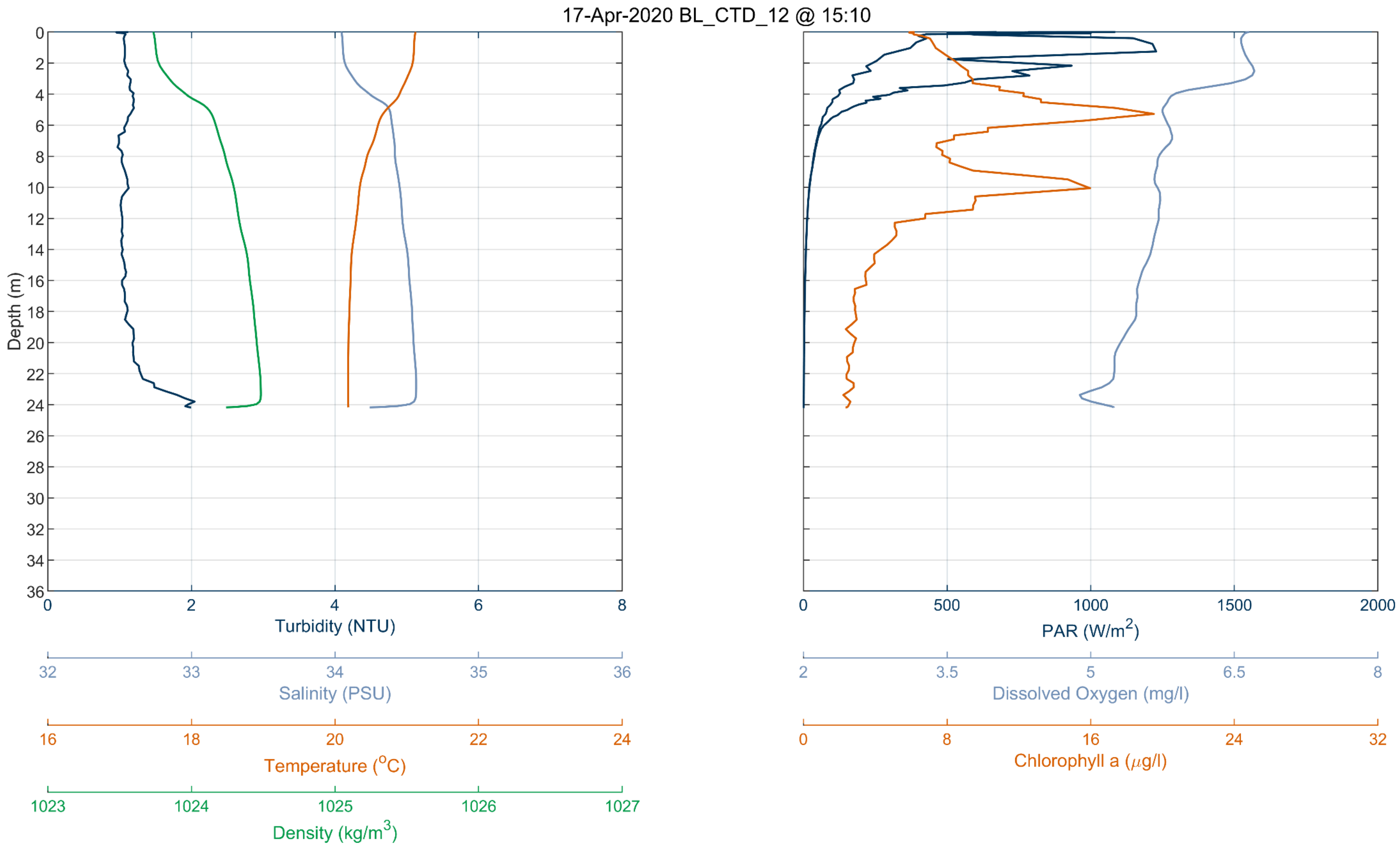

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Figure B-25 Vertical profiles at B12 on 17 April 2020

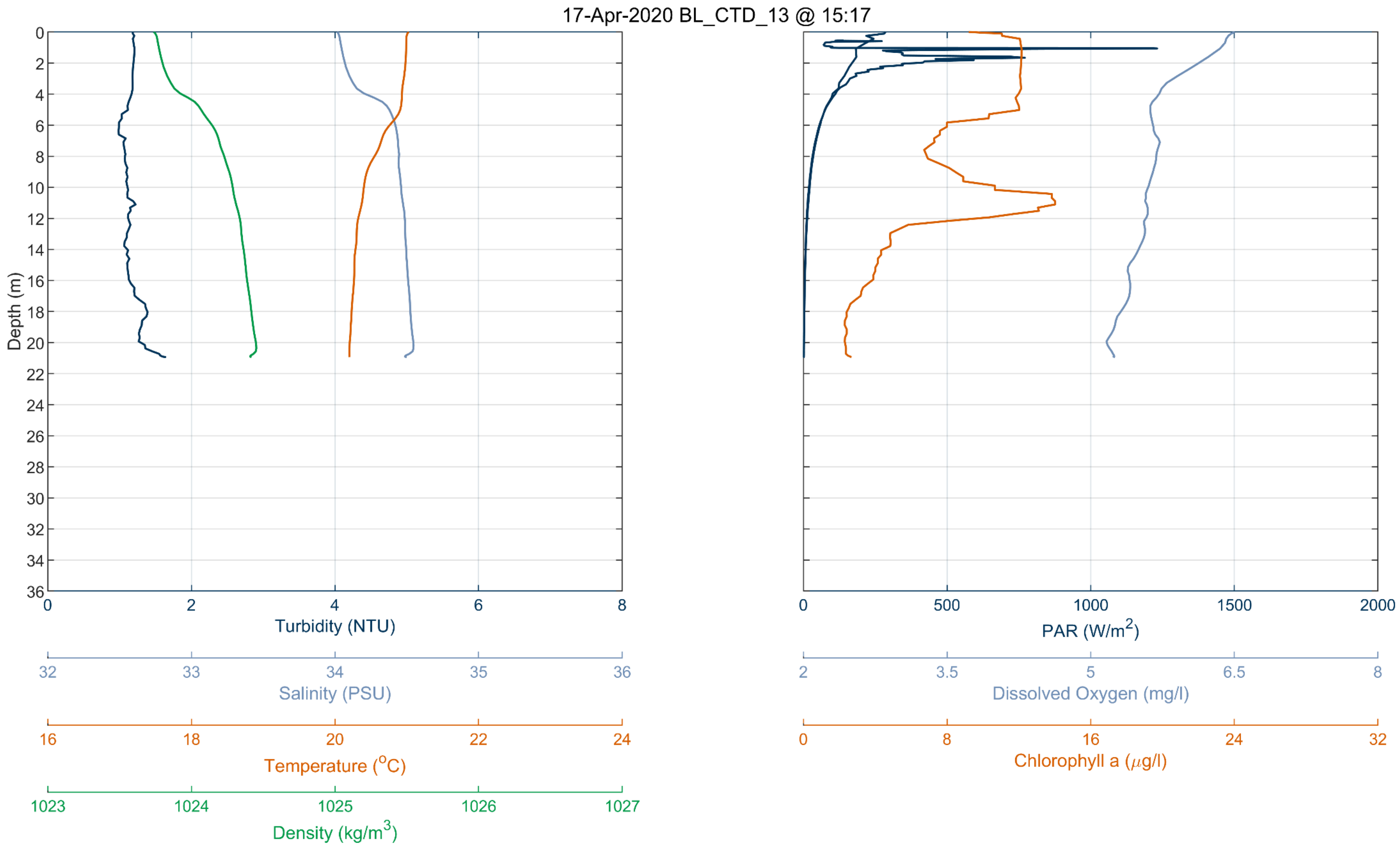

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Figure B-26 Vertical profiles at B13 on 17 April 2020

ANNEXURE

C

MIDDLE HARBOUR FLUVIAL LOADS, SEDIMENTATION AND OXYGEN

C Middle Harbour fluvial loads, sedimentation and dissolved oxygen

C.1 Introduction

This annexure provides a detailed assessment of the effects of sill that would be created by the crossing of Middle Harbour (Figure C-1) on the distribution of sedimentation in Middle Harbour and on the dissolved oxygen concentrations in the deeper waters upstream of the sill.

This assessment is in response to inclusion of Item no. 6.10 in the Secretary's environmental assessment requirements:

6. 10 Identify and assess the impact of tidal flushing on the crossing of Middle Harbour. This assessment should also include details of any potential sediment accumulation and the impact this may have on marine populations that dwell on the harbour floor.

At the deepest point in the crossing alignment, the top of the immersed tube tunnel is projected to be at a level of 22 metres below mean sea level (~AHD) and about 9.2 metres above the existing bed of the harbour of about -32 metres AHD (Figure C-1).

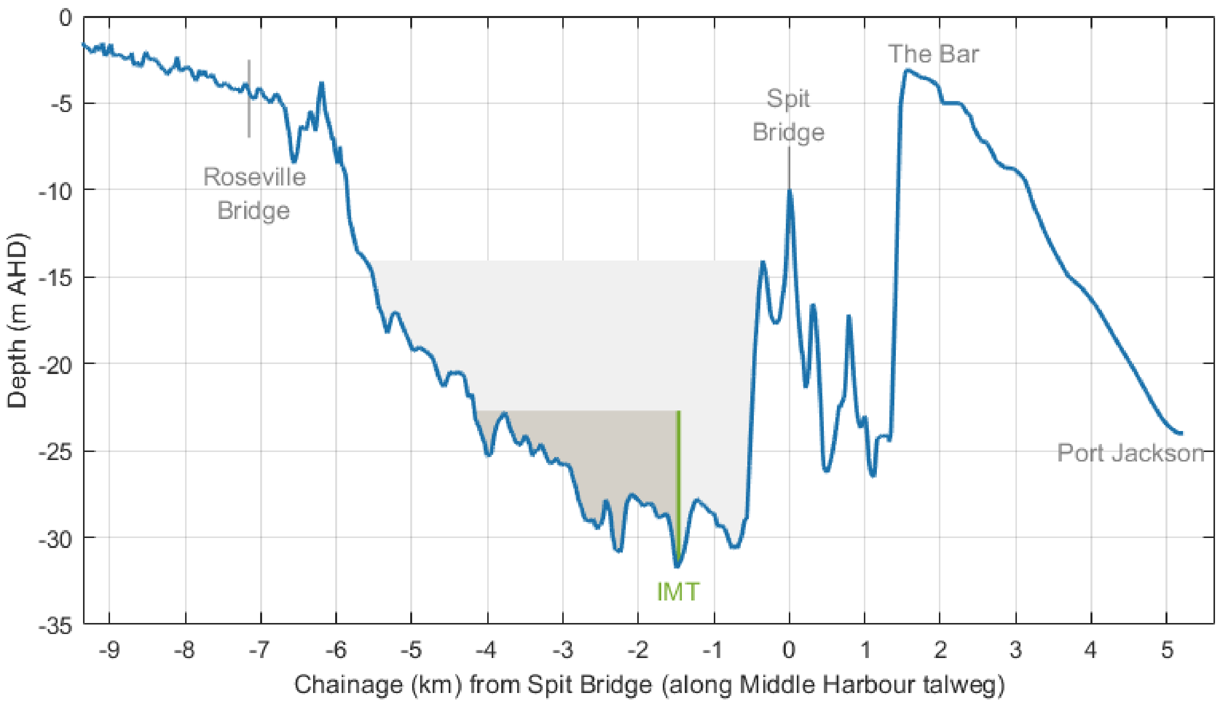

Figure C-1 Long section of Middle Harbour indicating the existing system sills and the immersed tube tunnel crossing (IMT)

Sedimentation and the rate of estuarine infill due to fluvial runoff and sediment load entering Middle Harbour was assessed using catchments inflow information from the Sydney Harbour Ecological Response Model (Cardno, 2016). The catchment rainfall-runoff model applied during that study provides estimates of stream flow, total suspended solids (TSS), total phosphorus, total nitrogen, dissolved organic carbon and biological oxygen demand derived on the basis of a 13 years rainfall sequence from 2000 to 2013.

Other data collection (Section 2.3 and Annexure A), and the estimated change in tidal flushing due to the presence of the immersed tube tunnel crossing sill (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)) have informed the assessment of effects during the construction phase. The potential effects during the ongoing operation were informed by field-based data collection to investigate the dissolved oxygen characteristics of the existing deep water system upstream of the Spit Bridge (Annexure B).

C.1.2 Scope of work

A desktop study of information was combined with Cardno's existing catchment model (SHERM) to determine potential changes to sedimentation load from the catchment and sedimentation rate upstream of the sill created by the Middle Harbour crossing. This included the following tasks:

> Estimate total sediment inputs from the Middle Harbour catchment streams (estimated from 13 years 2000 to 2013)

> Utilise Cardno's (2016) existing catchment model (SHERM) stream inputs to provide an estimate of sediment load (over the model duration about 10 years) to Middle Harbour in the following two basins: upstream of Spit Bridge and upstream of the proposed crossing

> Extrapolate 10 year estimates to design life of crossing, taking account of the runoff events captured in the modelling period

> Derive hypsographic curves (surface area and volume versus water depth) for the two basins from existing SHERM bathymetry

> Estimate sedimentation rate in the existing Spit basin and compare with available estimates from literature

> Estimate sedimentation rates in the future for the basin upstream of the crossing and compare with estimates for the existing Spit basin

> Compare the pre- and post -crossing sedimentation estimates and assess the impact of the crossing.

Investigations of the effect of the crossing on dissolved oxygen included combining profiling and fixed probe data and selected periods were plotted to determine flushing processes and dissolved oxygen responses to tidal flushing and fresh water inflows.

C.2 Overview: marine ecology, dissolved oxygen and sedimentation

The condition of biota in estuarine environments is linked to the concentrations of dissolved oxygen. The significance of dissolved oxygen concentrations in aquatic systems is summarised on the OzCoasts website (https://ozcoasts.org.au/indicators/biophysical-indicators/dissolved_oxygen/):

Measures of dissolved oxygen refer to the amount of oxygen contained in water, and define the living conditions for oxygen-requiring (aerobic) aquatic organisms. Oxygen has limited solubility in water, usually ranging from six to 14 milligrams per litre (mg/L). Dissolved oxygen concentrations reflect an equilibrium between oxygen-producing processes (e.g. photosynthesis), and oxygen-consuming processes (e.g. aerobic respiration, nitrification, chemical oxidation), and the rates at which dissolved oxygen is added to and removed from the system by atmospheric exchange (aeration and degassing), and hydrodynamic processes (e.g. accrual/addition from rivers and tides versus export to ocean).

C.2.1 Sydney Harbour Ecological Response Model (SHERM)

The SHERM system incorporates results of catchment – runoff modelling that have been used to estimate sediment and nutrient loads to Middle Harbour. In addition, the SHERM water quality model uses the organic loads to calculate a range of water quality responses in the harbour. There is a strong connection between the catchment loads, water quality and marine ecology - the basic interactions these and dissolved oxygen response are described below.

The complex interactions between the hydrodynamics, water mixing and bio-geochemical processes that lead to changes in dissolved oxygen concentrations have been simulated in the SHERM (see Section 2.2.2). Figure C-2 shows the various pathways linking sediment inputs, biochemical transformations in the sediment and water and the sediment-water fluxes that can all affect dissolved oxygen concentrations in estuarine waters. The fluxes of nutrients to and from estuarine sediments are mediated by and influence dissolved oxygen concentrations in the water and particularly near the bed of the harbour.

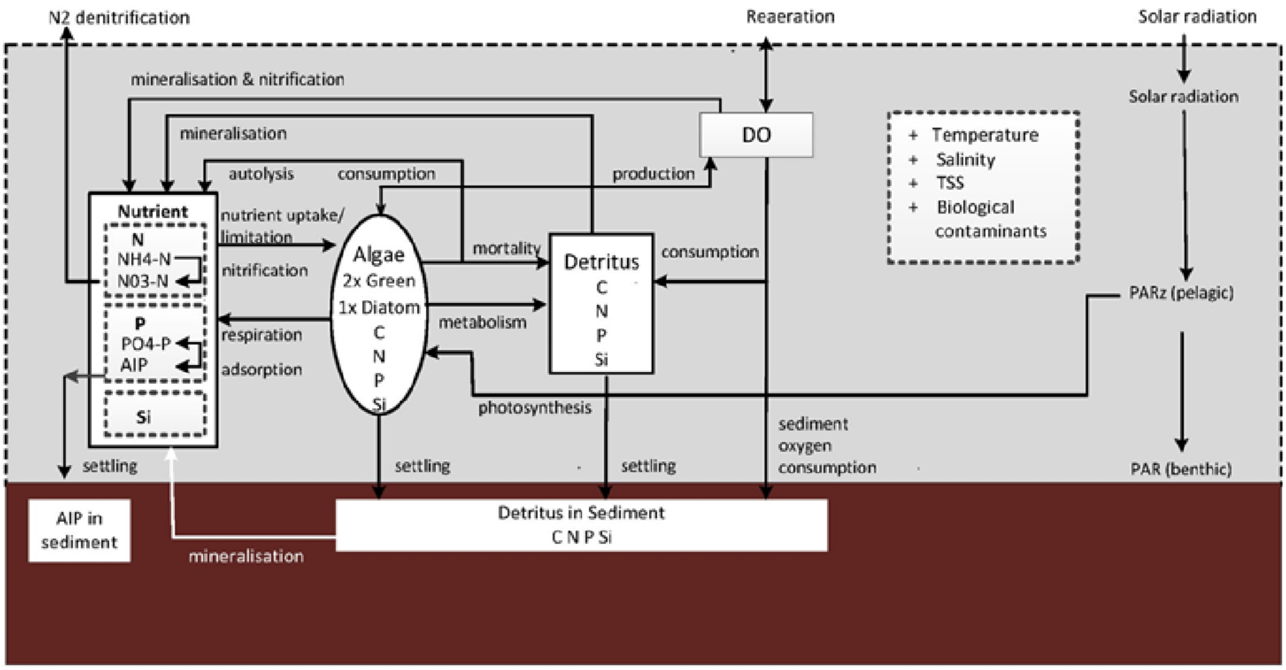

Figure C-2 Water quality processes in the SHERM (WAQ) module (after Deltares, 2011)

The organic load, its sedimentation within the estuary, its subsequent decay at the sediment-water interface, effect on sediment biochemical oxygen demand and consequently water column dissolved oxygen, is a key component of the dissolved oxygen signature. Replenishment of dissolved oxygen transferred through the water surface from the atmosphere and physical flushing processes also play a key role in determining the dissolved oxygen signature. In general, the time rate of change of the dissolved oxygen concentration at a location in the water column is governed by the balance between sources and sinks of dissolved oxygen expressed by the equation (Deltares, 2014):

$$\frac{dO_2}{dt} = \text{loads} + \text{transport} + \text{reaeration} + \text{net primary production} + \text{denitrification} - \text{mineralization} - \text{nitrification}$$

The rates of change of the different sources and sinks depends upon a number of factors including nutrient concentrations and microphytobenthos community density, as well as mixing and transport of dissolved oxygen by physical processes. Hence to inform the assessment of potential effects of the sill on marine ecology requires information on the likely changes in a range of variables affecting dissolved oxygen, including organic loads, settling and retention within the deep basin, sediment oxygen demand and rates of oxygen replenishment through vertical mixing that are in turn dependent upon the hydrodynamics - namely tides, freshwater inflow and stratification in the system.

The catchment loads derived from the SHERM inputs (Section 2.2.2) are summarised in section C3.4 and used to inform the discussion of potential impacts on dissolved oxygen. Loads are derived for the tributary inflows upstream of the Spit and upstream of the proposed immersed tube tunnel crossing location.

C.3 Review of Middle Harbour siltation characteristics

The harbour infill rate in the basin upstream of the immersed tube tunnel crossing sill has been estimated via two methods. First, assessment of historical information derived from sediment cores and discussions with Professor Gavin Birch (Sydney University) and second, using the SHERM catchment model inputs to derive the loads to Middle Harbour, from which sedimentation in harbour basins is assessed.

C.3.1 Historical/bed sediment basis

Taylor et al. (2004) describe analyses of seabed sediment cores taken at twelve locations within Port Jackson. Pertinent to this investigation is their core from the Sugarloaf Bay fluvial delta near the mouth of Scotts Creek in upper Middle Harbour. This core penetrated through muddy sediments to a depth 1.37 metres below the bed surface. Radio-isotope based analyses using lead (210Pb), radium (226Ra) and caesium (137Cs) determined an average annual siltation rate of about 15 millimetres per year. Noting that Martin and Whitfield (1983) estimated that greater than 90 per cent of particulate material transported by rivers accumulates in estuaries or coastal waters, this core depth of 1.37 metres represents about 90 years of siltation. This site is near the mouth of Scotts Creek in the fluvial delta and likely to represent higher rates of sedimentation than the wider estuary average. Taylor et al. (2004) do not report investigation of change of siltation rate with time – top to bottom of the 1.37 metre core from Sugarloaf Bay, but radio-isotope dating are consistent. This rate may have increased since European settlement in the Chatswood to Middle Harbour catchment region as the associated land clearing, introduction of deciduous terrestrial vegetation, impervious surfaces and stormwater channels has likely led to increases in the sediment and organic loads to the estuary. The Sugarloaf Bay sediments are muddy, with variable sand content. Minor shell fragments were identified.

Scotts Creek discharges into the northern arm of Sugarloaf Bay. Contaminant profiles were consistent with the history of urbanisation and industrialisation of the catchment; noting that the main focus of Taylor et al. (2004) was the temporal change in sediment contamination concentrations.

Sediment sampling carried out for the project found many contaminants common to the harbour bed of Sydney Harbour (Douglas Partners and Golder Associates, 2017). Within the dredge footprint, selected contaminant concentrations were above guideline criteria (where available). These contaminants were found within the top one metre of sediments, with minor detections of selected contaminants above guideline criteria from deeper sections. This observed one metre of contaminated sediments represents about 65 years of sedimentation from catchment industrialisation – the primary source of these contaminants.

C.3.2 Discussions with Professor Gavin Birch – Sydney University

Professor Gavin Birch has been investigating the sediments of Sydney Harbour for over 30 years and has published widely in peer reviewed journals. Cardno sought his advice on historic patterns of sedimentation in Sydney and Middle Harbours through conversation with Dr Doug Treloar. Based on this conversation, Cardno understands that during the last glacial period between approximately 120,000 and 20,000 years before present, the ‘Sydney Estuary’ was scoured to bedrock by fluvial flows eroding the escarpment. Following this glacial period, climate began to warm with melting ice and thermal expansion leading to a rise in sea levels of 100 to 120 metres before stabilising at the present levels at 7500 years ago.

During the post-glacial Holocene period (about 9000 to 5000 years before present), rising sea levels caused offshore sand deposited during the glacial period to gradually migrate back onshore and into estuaries; a process essentially halted by the current relatively steady sea levels. Onshore transport moved marine sands into Middle Harbour to a distance of about 0.5 kilometres upstream of The Spit Bridge, with a very steep slope on the inward propagating face – forming a mid-channel sill at The Spit of about 20 metres height above the present day bed of the harbour of -30 metres AHD. Fluvial and tidal flows of water into and out of Middle Harbour are constrained by this sill and material delivered from the fluvial inputs may settle and be trapped in the deep basins upstream of the sill (Figure C-1). Upstream of the sand sill, the bed of the harbour is comprised of about 20 to 25 metres of mud carried into the estuary by catchment flows (predominantly from Middle Harbour Creek and Scotts Creek) over the past 7500 years, consolidating within the basin and overlying the scoured rock base. Some of the catchment flow sediments, particularly lighter organic material and finer particulates that settle very slowly, will have moved further downstream and out to sea during the floods and occasional higher wave action causing re-suspension. Previous physical parameter investigations carried out by Cardno in Port Jackson have demonstrated that fresh water riverine flows form a distinct surface layer of lower density catchment runoff water that can transport the finest catchment sediments to sea.

It may be assumed that the natural sill at The Spit has essentially trapped about 90 per cent of the past 7500 years of catchment sediment inputs within the estuarine basin upstream of The Spit leading to the roughly 25 metres of vertical accumulation.

The actual proportions of the muddy sediments shape are unknown, but an estimate of areal average siltation rate may be made from the vertical accumulation of 25 metres over 7500 years of 3.3 millimetres per year. This rate will have varied from Epoch to Epoch with low rates during droughts and high rates during very wet periods. Note that siltation rates are expected to be significantly higher in areas of alluvial fans near creek mouths where rapid settling of the larger sized fluvial particles occurs. The higher siltation rates described by Taylor et al. (2004) near the mouth of Sugarloaf Bay relate to these areas.

C.3.3 Sedimentation estimate based on sediment core

The top of the immersed tube tunnel crossing would form a sill about 9.2 metres high above the bed of the harbour in the deepest part of the Middle Harbour crossing, reducing in height closer to the northern and southern ends where the immersed tube tunnel crossing connects to the subterranean tunnels. Although the immersed tube tunnel crossing sill would not be as high as the natural sill closer to The Spit (Figure C-1), it would likely be equally effective in trapping catchment sediments upstream. The immersed tube tunnel crossing sill is located about 1.5 kilometres upstream of The Spit in a total estuarine extent of about seven kilometres. Hence the rate of siltation upstream of the tunnel crossing will likely increase by a maximum factor of 6.5/5.5 = 1.18, or to about 3.9 millimetres per year rather than the current estimate of 3.3 millimetres per year. There is likely to be some leakage of sediment over the tunnel sill leading to a smaller rate of sedimentation upstream. There would be a related decrease in siltation rate downstream of the tunnel sill. Moreover, the height of the immersed tube tunnel crossing sill above the bed of the harbour reduces from about 9.2 metres at the deepest point in the bed of the harbour to zero as it disappears into the north and south tunnel entrances. Assuming a parabolic seabed cross-section profile, it is expected that the increased siltation rate upstream of the sill would be to around 3.7 millimetres per year, or an increase of about 0.4 millimetres per year (4 millimetres per decade) higher than the existing rate. Practically, present day seabed depth sounding instruments have an accuracy typically of about 20 millimetres; hence a change in sedimentation due the immersed tube tunnel crossing would be difficult to resolve within about 50 years.

C.3.4 Catchment loads entering Middle Harbour (SHERM estimates)

As part of the SHERM program undertaken by Cardno for Greater Sydney Local Land Services, Cardno (2015, 2016b), a Sydney Harbour Catchment Model (SHCM) was developed to provide estimates of the discharge and quality of runoff entering Sydney Harbour estuarine arms. This model includes time-series of catchment inputs into Sydney Harbour for the 13 years period from January 2001 to 25 July 2013, in 30 minute increments.

To estimate sediment and pollutant loads entering Middle Harbour, the catchment data was extracted from this model for all of the contributing inflows upstream of the Spit Bridge (Table C-1), as well as for the catchments upstream of the proposed immersed tube tunnel crossing sill (Table C-2). These data are summarised in terms of the total load over the simulation period, the average annual load and the maximum daily load (taken as the maximum load in any given 24 hour period).

Table C-1 Total catchment loads entering Middle Harbour upstream of the Spit Bridge

Parameter	Total load (over 13.7 years)	Mean annual load	Maximum daily load
Flow (Mm^3)	591	43.6	7.4
Total suspended solids (tonnes)	77,938	5742	915
Total nitrogen (tonnes)	1249	92.0	15.0
Total phosphorus (tonnes)	134	9.9	1.6
Total organic carbon (tonnes)	8969	661	106
Biological oxygen demand (tonnes)	3985	294	49.4

Table C-2 Total Catchment loads entering Middle Harbour upstream of the immersed tube tunnel crossing

Parameter	Total load (over 13.7 years)	Mean annual load	Maximum daily load
Flow (Mm^3)	486	35.8	6.3
Total suspended solids (tonnes)	61,529	4533	740
Total nitrogen (tonnes)	1001	73.8	12.3
Total phosphorus (tonnes)	107	7.9	1.3
Total organic carbon (tonnes)	7060	520	85.7
Biological oxygen demand (tonnes)	3231	238	41.1

C.3.4.1 Fluvial sedimentation estimate

The sill that would be created due to the Middle Harbour crossing would be about 9.2 metres above the bed of the harbour in the centre of the Middle Harbour estuarine waterway, reducing in height closer to the northern and southern shorelines. As discussed above, although this sill would not be as high as the natural sill closer to The Spit, it would likely be equally effective in trapping catchment sediments upstream of itself.

A second estimate of sedimentation rate within Middle Harbour has been made by assuming all of the catchment derived total suspended solids contributes to sedimentation upstream of the natural sill located about 0.5 kilometres upstream of the Spit Bridge. Assuming that the sedimentation is equally distributed over the waterway area below one metre AHD, a dry bed density of 600 kg/m^3, then the current sedimentation upstream of the Spit Bridge is estimated to be about 1.9 millimetres per year, on average.

A similar analysis using the waterway area and catchment inputs upstream of the proposed immersed tube tunnel crossing sill gives a slightly higher sedimentation rate of 2.2 millimetres per year, on average. This equates to an extra 3 millimetres of sedimentation over a 10 year period.

These values are area averaged, and are likely to be slightly higher in the deeper portions of the harbour, and lower in the shallower reaches. It is also likely that a portion of the sediments will leak over the sill, leading to lower siltation rates.

C.3.5 Summary of sedimentation upstream of The Bar and upstream of the proposed crossing

Both estimates of sedimentation derived from the sediment core observations and from catchment inflow estimates provide similar order-of-magnitude outcomes. The creation sill by the tunnel crossing would likely increase the rate of mud siltation upstream of the crossing by three to four millimetres per decade. This rate is within the range of sedimentation rates within Middle Harbour and forms a negligible contribution to overall sedimentation.

C.4 Discussion

C.4.1 Physical effects and flushing events

Birch et al. (2009) categorise rainfall and the implied stream inflow conditions according to the effects on harbour stratification as follows:

- Baseflow: less than five millimetres per day - minimal effects on stratification
- Moderate rainfall: five to 50 millimetres per day - majority of nutrient load delivered to the estuary
- High rainfall: greater than 50 millimetres per day - estuary stratifies and nutrients transported to ocean.

It is assumed that under baseflow conditions any freshwater inputs are rapidly mixed in the Sydney Harbour estuary waters with minimal effect on the general tidal flushing. Tidal flushing times generally increase with increasing distance upstream in the estuary. As Middle Harbour is located close to the ocean, tidal flushing is more dominant within this arm than the Sydney Harbour arm of Port Jackson, most of which is located further upstream.

While Birch et al. (2009) suggest that under moderate conditions most of the nutrient load to the wider estuary is retained within the estuarine system, they also acknowledge that the proximity of Middle Harbour to the ocean likely leads to a significant proportion of the moderate flow nutrient loads to Middle Harbour being flushed to the ocean. Under the strongly stratified high flow events it is suggested that most (say 90 per cent) of the Middle Harbour nutrient load is flushed to the ocean.

In terms of the deeper basin waters upstream of the sills present within the harbour, flushing times are more variable due to the interaction of stratification, that inhibits vertical mixing and transport, and the tidal currents. During the freshwater inflows the lighter (less dense) freshwater input from the catchment initially forms a thin surface layer near the input stream that mixes with the estuarine waters as it propagates downstream and gradually becomes mixing indistinguishable from the wider estuarine water. In larger volume inflow events the freshwater plume can extend well down the estuary and hence during these events most of the organic and lighter particulate material input from the catchment is transported out of Middle Harbour to the ocean.

Computer modelling of the flushing times of the waters upstream of the sill (refer to Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)) indicated that the flushing times in the deep basin upstream of the crossing sill would increase by around 30 percent from 1.6 to 2.4 days (see box T1 in Figure C-3).

The recovery of the pre-event water conditions in the deeper basins is prolonged due to the stratification that inhibits tidal mixing as the salt wedge propagates upstream. Hence, the trapping of waters within the deeper basins following wet weather events leads to longer water retention times than estimated by the tidal flushing alone. Under these conditions the concentration of dissolved oxygen is depleted by the sediment oxygen demand that in turn depends upon the organic load and oxygen consumption characteristics of the microbial populations in the sediment and water.

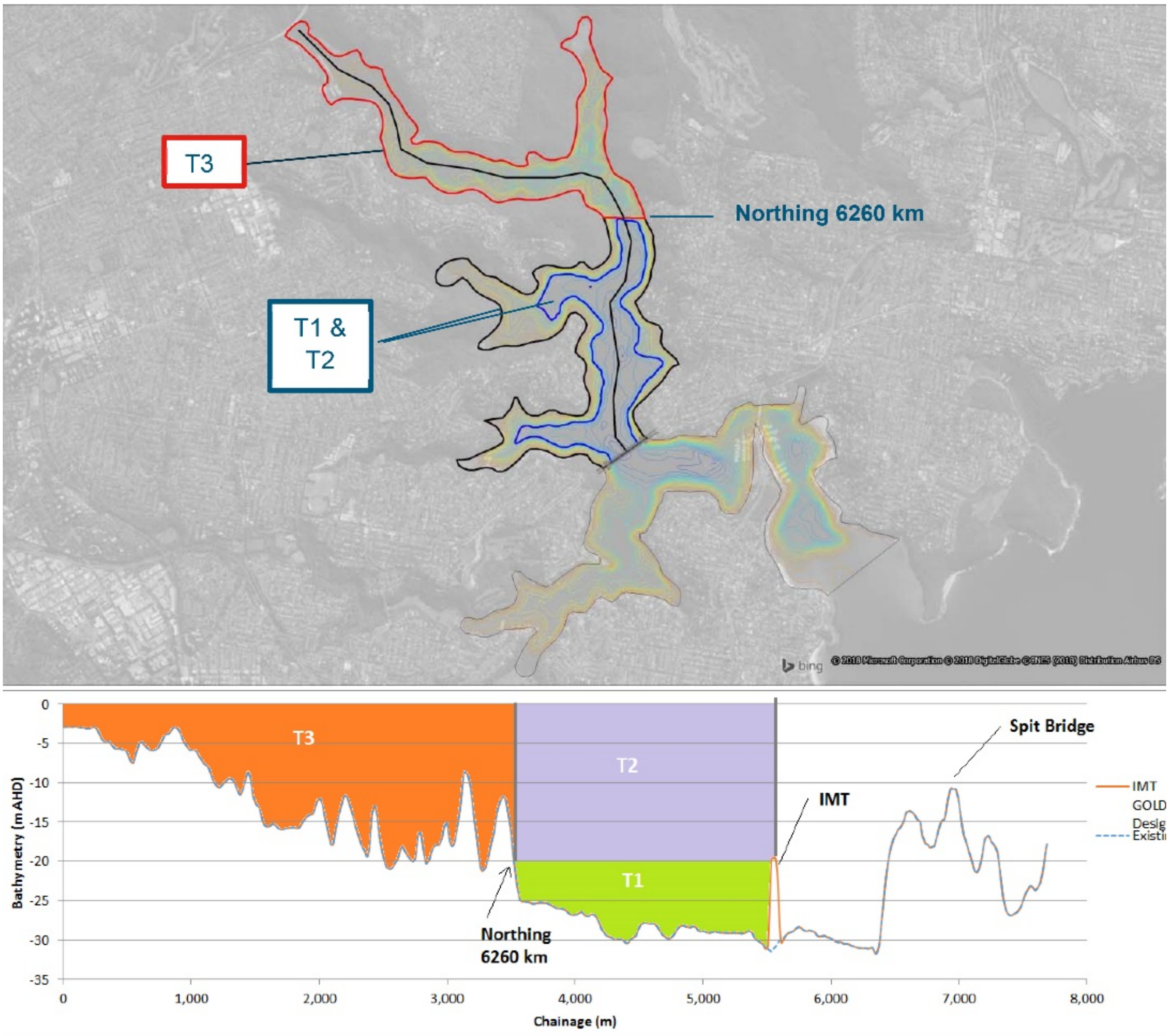

Figure C-3 Waterbodies upstream of the crossing (above) and long section of Middle Harbour (below) (Source: Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling))

C.4.2 Catchment derived organic load and its retention in Middle Harbour

The organic portion of seabed sediments may be derived from external sources, primarily catchment inflows, and internal loads from collapsing algal blooms. Birch et al. (2009) suggest that algal blooms, when Chlorophyll-*a* concentrations exceed the ANZECC (2000) water quality guidelines occur on average two to six times per year. Although the duration of these exceedance events is not discussed it is likely that these algal blooms last for a few days to a week, similar to those observed in Berowra Creek (Coad et al., 2014) in the Hawkesbury River system.

In the deep basin upstream of the crossing, the tidal flushing time increases retention of organic sediment from settling of fluvial inputs during inflow events and longer term migration of organic sediments from upper bays by downslope turbidity currents induced during resuspension events.

Birch et al. (2009) estimated average annual loads to Middle Harbour (derived from the MUSIC model applied 1990 to 2002) 93.2 tonnes total nitrogen, 3.69 tonnes total phosphorous and 6,310 tonnes TSS. These estimates are in close agreement with those derived here (Table C-1) using similar methods. Birch et al. (2009) suggest up to 30 per cent of the nutrient input to the whole of Port Jackson may be flushed to the mouth, primarily during the larger high rainfall events. Due to its proximity to the ocean the Middle Harbour nutrient and organic loads are likely to be flushed to ocean with little contribution to the wider Port Jackson. Given the tidal influence is stronger in Middle Harbour than other parts of Port Jackson it is suggested that more than 50 per cent of the nutrient and organic load to Middle Harbour would be flushed directly to the ocean during inflow events.

It is assumed that about 20 per cent of the total nitrogen, total phosphorous, total organic carbon loads is retained within the Middle Harbour, the remaining 80 per cent passing through to the ocean. As this material has low settling velocity it is dispersed widely by the tidal and wind-driven currents and hence settles across the wider Middle Harbour. After its initial settling this lighter material is subject to resuspension events and formation of slightly heavier near-bed turbidity layers that progressively flow downslope with the particles resettling in slightly deeper water. This ongoing process leads to the accumulation of the muds within the deepest parts of the system. On this basis the sill created by the crossing is likely to lead to a small increase in organic material loading to the deep water basin upstream of the sill.

C.4.3 Dissolved oxygen summary

The vertical profiles collected on 18 and 30 January 2018 demonstrated the conditions of a minor summer inflow event. Following the event, the temperature and salinity characteristics indicated that a deep water layer roughly four metres above the bottom persisted for some time with minimal mixing and exchange of the deep water with waters above this bottom layer. Within this bottom boundary, layer dissolved oxygen declined from about 90 to 50 per cent saturation over 12 days in late January 2018.

The field measurements carried in late autumn 2020 captured a significant (greater than 50 millimetre rainfall in 24 hours) inflow and showed a similar decline in dissolved oxygen within the deep basin upstream of the Spit Bridge. The temperature and salinity structure showed a much deeper mixing layer, about 15 metre thick above the bed of the harbour and the lower salinity inflow waters flowing in the surface layer some 10 metres deep. Within the bottom layer the dissolved oxygen declined at a rate of around one per cent dissolved oxygen per day. This rate reflects the difference between the rate of depletion at the bed due to the sediment oxygen demand and the rate of replenishment into the bottom layer through the surface waters and atmosphere.

The autumn sediment oxygen demand is likely to have been lower than the January period due to the cooler water temperature (reduces microbial metabolism and oxygen demand), and relatively low amount of fresh organic material due to the low runoff under the dry antecedent conditions. Further, the large volume of the relatively deep bottom layer in late autumn results in more effective replenishment of dissolved oxygen from the surface thereby maintaining dissolved oxygen concentrations at reasonably high levels within the deep water.

Seasonal variability in the temperature and salinity characteristics and salt wedge/fjord-like behaviour leads to considerable variations in the flushing characteristics of the deep water. Flushing times were estimated at about 1.5 days, although under stratified conditions water in the bottom boundary layer upstream of the sill may reside for longer periods and thereby promote conditions more favourable to the depletion of dissolved oxygen in the bottom layer.

Based on average annual rainfall patterns (greater than 50 millimetre rainfall in 24 hours occurs about three to four times per year, refer Table 3-2), the conditions leading to the dissolved oxygen depletion to about 50 per cent saturation concentrations are likely to naturally occur a few times per year and particularly during the warmer late summer and autumn period. Conditions where dissolved oxygen concentrations reduce to lower than 50 per cent saturation are also likely to occur a few times per summer/autumn season.

The presence of an extra sill in Middle Harbour has the potential to increase residence times of the deeper waters immediately upstream of the sill by about 30 per cent from about 1.6 days to 2.1 days and thereby promote conditions more favourable to the depletion of dissolved oxygen in the bottom boundary layer; albeit in a relatively small volume of water affected by the immersed tube tunnel crossing sill.

The volume of water below the immersed tube tunnel crossing sill level of -22 metres AHD and the bed of the harbour at -32 metres AHD extends about one kilometre upstream of the proposed tunnel crossing location. This volume represents only five per cent of the total water volume upstream of the tunnel sill and nine per cent of the volume (surface to the bed of the harbour) two kilometres upstream of the tunnel sill. As with the existing conditions, any depletion of dissolved oxygen in the deeper water would be rapidly mixed vertically resulting in negligible effects on dissolved oxygen in the surface waters as a consequence of the project. In the deeper waters the low dissolved oxygen events of the present natural system are likely to last a slightly longer period and potentially attain slightly lower concentrations of dissolved oxygen than in the present system.

The potential impacts of the likely slightly prolonged periods of low deep water dissolved oxygen concentrations to the marine environment are discussed further in Appendix T (Technical working paper: Marine ecology).