

Department of Planning and Environment

# Post-flood water quality and fish kill assessment, Richmond River

February-May 2022



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Cover photo: Dead fish downstream of Bagotville Barrage. Mitchell Call/SCU

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## Executive summary

Major flooding occurred across southeast Queensland and northern NSW in late February-early March 2022 and then again in late March-early April 2022. The February-March flood triggered a large blackwater event which caused a major fish kill that affected the entire lower Richmond River from downstream of Coraki to Ballina.

The term 'blackwater' refers to deoxygenated water draining from flooded low-lying areas of the floodplain after the main flood peak has passed. Blackwater is generated by the die-off and subsequent rotting of inundated vegetation on the floodplain.

The Estuaries and Catchments team and Southern Cross University staff made a series of boat-based and land-based surveys of water quality across the lower Richmond River and Clarence River floodplains from the 12<sup>th</sup> to 18<sup>th</sup> March 2022. These surveys were complemented by data from existing and temporary deployments of *in situ* water quality loggers. This report presents findings from the Richmond River only.

Boat-based surveys on the 12<sup>th</sup> and 13<sup>th</sup> March indicated that the main river was completely anoxic (DO <1% saturation) from just upstream of Swan Bay to the entrance at Ballina, with large volumes of anoxic water still discharging from backswamp drains on the floodplain. In contrast, water in the Wilsons and Richmond River arms upstream of Coraki had much higher dissolved oxygen concentrations (38% and 65% saturation respectively).

Water quality and level logger data indicated that water quality varied in response to a sequence of distinct runoff phases linked to the timing of water level changes across the floodplain, the tributary creeks, and the main river channel during the February-March flood event. Oxygen saturation initially increased during the rising stage of the flood due to localised runoff, which was rapidly replaced by turbid upper catchment flood waters as the flood peak moved downstream. After the flood peak passed, the first stage of floodplain drainage occurred as the hydraulic gradient increased between the floodplain and the main river channel. This water was characterised by depressed dissolved oxygen saturation but was not critically low. The final stage of floodplain drainage involved the discharge of anoxic water from low-lying backswamps coinciding with the re-emergence of a tidal signal at Woodburn on the 10<sup>th</sup> March. It is estimated that this water had been lying on the floodplain for up to 15 days.

Observations of dead fish were first reported on the 10<sup>th</sup> March as the anoxic backswamp water began to overwhelm the main river channel. Large numbers of dead fish observed along the ocean beaches adjacent to the Richmond River entrance suggest that many fish were swept from the system to the ocean making it difficult to ascertain the extent of the initial fish kill.

A second phase of the fish kill occurred as oceanic water started to penetrate the estuary at depth during flood tides as the flood waters receded. Large numbers of dead whiting, luderick, bream and jewfish were observed adjacent to Ballina on the 16<sup>th</sup> and 17<sup>th</sup> March. It is likely that these fish had moved into the lower estuary from the ocean with the incoming tide and become trapped in deeper holes upstream and overwhelmed by anoxic water ebbing from upstream as the tide turned.

Dissolved oxygen saturation began to in the lower estuary recover as flood tide inflows of oceanic water mixed with and diluted anoxic water, and in the upper estuary as better quality upper catchment inflows displaced anoxic water downstream, and atmospheric exchange satisfied residual biochemical oxygen demand (BOD). Logger data showed that this recovery proceeded at a rate of approximately 5km per day.

The second major flood in the Richmond River occurred in late March-early April but did not cause a severe blackwater event or associated fish kill. It is likely that this was due to a

combination of factors including the shorter period of floodplain inundation, lower ambient temperatures, and much lower levels of organic material across the floodplain due to the effects of the first flood.

Measurements of greenhouse gas concentrations (carbon dioxide and methane) in anoxic waters draining from the floodplain and in the main river were extremely high relative to previous measurements in the Richmond River and compared to similar systems around the world. This indicates that flooding of modified floodplains is a significant risk in terms of increased greenhouse gas emissions from coastal environments. This may be due to: 1) the conversion of perennial floodplain swamps to dryland pastures via widespread drainage, thereby increasing the prevalence of vegetation intolerant to inundation; and 2) the accelerated export of waters from backswamps via artificial drainage structures. It is likely that floodplains as a source of greenhouse gasses will increase into the future under current management with the projected increase in severity and frequency of extreme events (i.e. floods and droughts).

This study has provided evidence of: 1) the value of near real-time high-resolution monitoring; 2) key knowledge gaps regarding spatial and temporal processes affecting blackwater generation on the floodplain; 3) clear pathways for the better management of floodplains; and 4) the significant role of flooding in greenhouse gas emissions along the coast. Based on this and in support of previous floodplain management guidelines, we recommend the following:

- Support the recommendations of the 2020 Richmond River Floodplain Prioritisation Study
- Improve the resilience and reliability of existing sentinel water quality monitoring networks to withstand future flood events
- Strategically expand existing monitoring to include water level and quality monitoring of key backswamp and floodplain locations
- Utilise flood and ecosystem response modelling to better understand processes and interpret monitoring data
- Support research aimed at better understanding the spatial / temporal dynamics of blackwater generation across the floodplain and identify opportunities for future management
- Support extension initiatives to improve stakeholder understanding of key processes and landuse activities that contribute to blackwater events
- Work with relevant stakeholders to investigate and implement management options for priority low lying areas of the floodplain.
- Further explore blackwater processes in other NSW estuaries where blackwater-associated fish kills regularly occur by way of implementing routine water quality programs and the above recommendations for the Richmond within these estuaries.

# Background

## Blackwater processes

The term 'blackwater' refers to deoxygenated water draining from flooded low-lying areas of the floodplain after the main flood peak has passed. Blackwater is generated when the floodplain is inundated for extended periods of time during floods, causing terrestrial vegetation (e.g. pastures) to die. Dissolved oxygen in the water is rapidly consumed by bacteria as they decompose the dead plant material and other organic matter on the floodplain<sup>1</sup> (Vithana et al 2019). This can result in water with very little or no dissolved oxygen (termed 'hypoxic' and 'anoxic' respectively). This water is also characterised by large concentrations of dissolved and particulate organic matter which commonly imparts a dark black/brown colouration, hence the term 'blackwater'. This organic matter in anoxic water continues to be decomposed by anaerobic bacteria such as methanogens, causing high concentrations of greenhouse gases (e.g. carbon dioxide and methane).

The degree of deoxygenation of water across the floodplain is dependent on a number of factors including: the depth and time of inundation; ambient temperatures; and the type/quantity of organic matter available for decomposition (Vithana et al 2019; Vithana et al 2017; Johnston et al 2003). Agricultural development and drainage of floodplains has exacerbated the potential for blackwater generation due to the conversion of wetland vegetation (tolerant to inundation) to dryland pasture species and crops (intolerant; Wong et al 2011).

Floodplains usually become inundated during the early stages of floods and are the last areas to drain after the flood peak passes and a hydraulic gradient between the floodplain and the river is re-established (usually once the tidal signal returns). Under natural (pre-European settlement) conditions, backswamps on floodplains were effectively isolated from the main river by levees, and as such remained seasonally inundated for extended periods of time, allowing wetland vegetation to thrive (Tulau 2011). This was changed by construction of drainage networks across floodplains for agriculture, allowing floodwaters to drain more efficiently, thereby providing conduits for the mass drainage of blackwater. The impact of blackwater on receiving waters (and the likelihood of fish kills) depends on the timing and rate of drainage from floodplain compartments and the assimilative capacity of the receiving waters<sup>2</sup> (Wong et al 2010).

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<sup>1</sup> Other sources of organic matter include vegetation trash (e.g. mown grass/hay), detrital organic matter in swamps. Different plant species and detrital matter all have different deoxygenation potentials. There is also oxygen consumption due to the oxidation of reduced iron monosulfides in drains (Eyre et al. 2006)

<sup>2</sup> For further information on blackwater please refer to <https://ballina.nsw.gov.au/files/20-54544--Technical-note---Blackwater-ARC-Project-May-2020pdf---Jointly-developed-by-Rous-and-Ballina-Councils-as-a-community-information-resource.pdf>

## 2022 floods

Major flooding occurred across southeast Queensland and northern NSW in late February 2022 and then again in late March 2022. The February-March 2022 flood in the Richmond River catchment was the highest on record (14.4m AHD at Lismore gauge), exceeding the previous record height set in 1974 by up to 2.3m in Lismore. The March-April 2022 flood was smaller (11.4m AHD), however it was still well above the 'major event' threshold (9.7m AHD at Lismore gauge) and is ranked as the 6th highest flood on record. Both floods caused major inundation of the lower Richmond River floodplain for more than one week. In the case of the February-March flood, this triggered a large blackwater event which affected the entire lower Richmond River from downstream of Coraki to Ballina.

## Current study

The Estuaries and Catchment team<sup>3</sup> responded to the first reports of fish kills at Ballina and Iluka on the 10<sup>th</sup> March 2022 by sending a team to the north coast to provide assistance in monitoring the rapidly changing post-flood water quality in the Richmond and Clarence Rivers. The team was assisted by staff from Southern Cross University, making a series of boat-based and land-based water quality surveys across the Richmond River floodplain between 12<sup>th</sup> and 17<sup>th</sup> March. Existing monitoring stations in the Richmond River damaged during the floods were also replaced with temporary units during this time. This report provides an overview and interpretation of data collected in the Richmond River during this field campaign.

## Study area

The total Richmond River catchment area is approximately 6862 km<sup>2</sup> with a floodplain below 5m AHD of approximately 620km<sup>2</sup> (Harrison et al. 2020). The main freshwater inputs to the Richmond estuary are the Wilson and Richmond Rivers (which merge upstream of Coraki), Bungawalbin Creek which joins the main stem upstream of Woodburn, Tuckean Swamp which joins downstream of Broadwater, and Emigrant Creek which joins upstream of Ballina. The floodplain includes significant areas of backswamp below 1m AHD (Figure 1), many of which are underlain by acid sulfate soils. The natural drainage patterns of the floodplain have been significantly altered by the construction of drains, levees and tidal gates which began in the mid to late 19<sup>th</sup> century (Tulau 2011). These serve to allow backswamps to drain down to the low tide level in the adjacent reach of the main river.

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<sup>3</sup> Within the Water Wetlands and Coastal Science branch, Science Economics and Insights Division, Environment and Heritage Group, NSW Department of Environment and Planning.

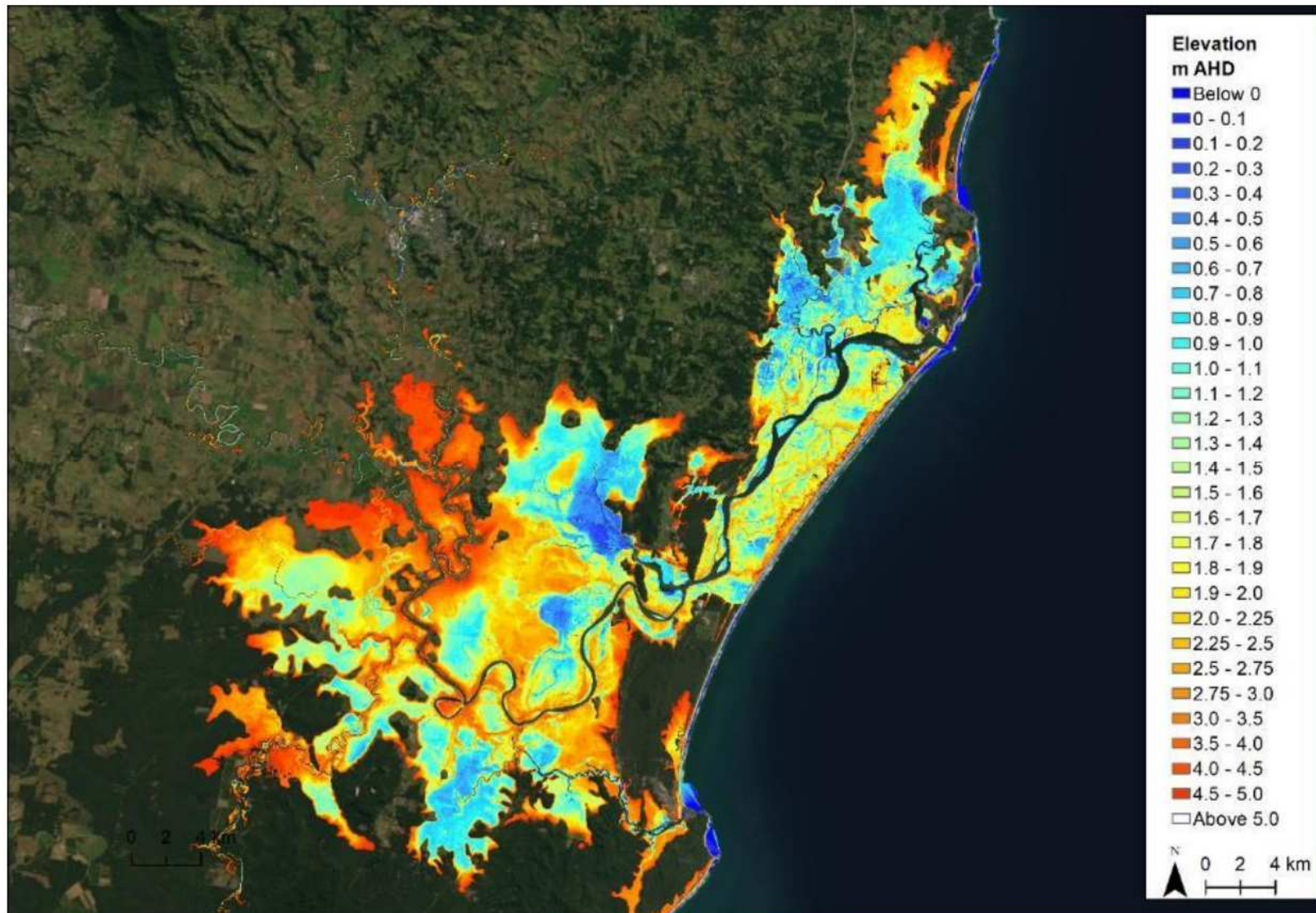


Figure 1 Lidar imagery of the Richmond River floodplain (source Harrison et al. 2020)

# Methods

## Water quality loggers

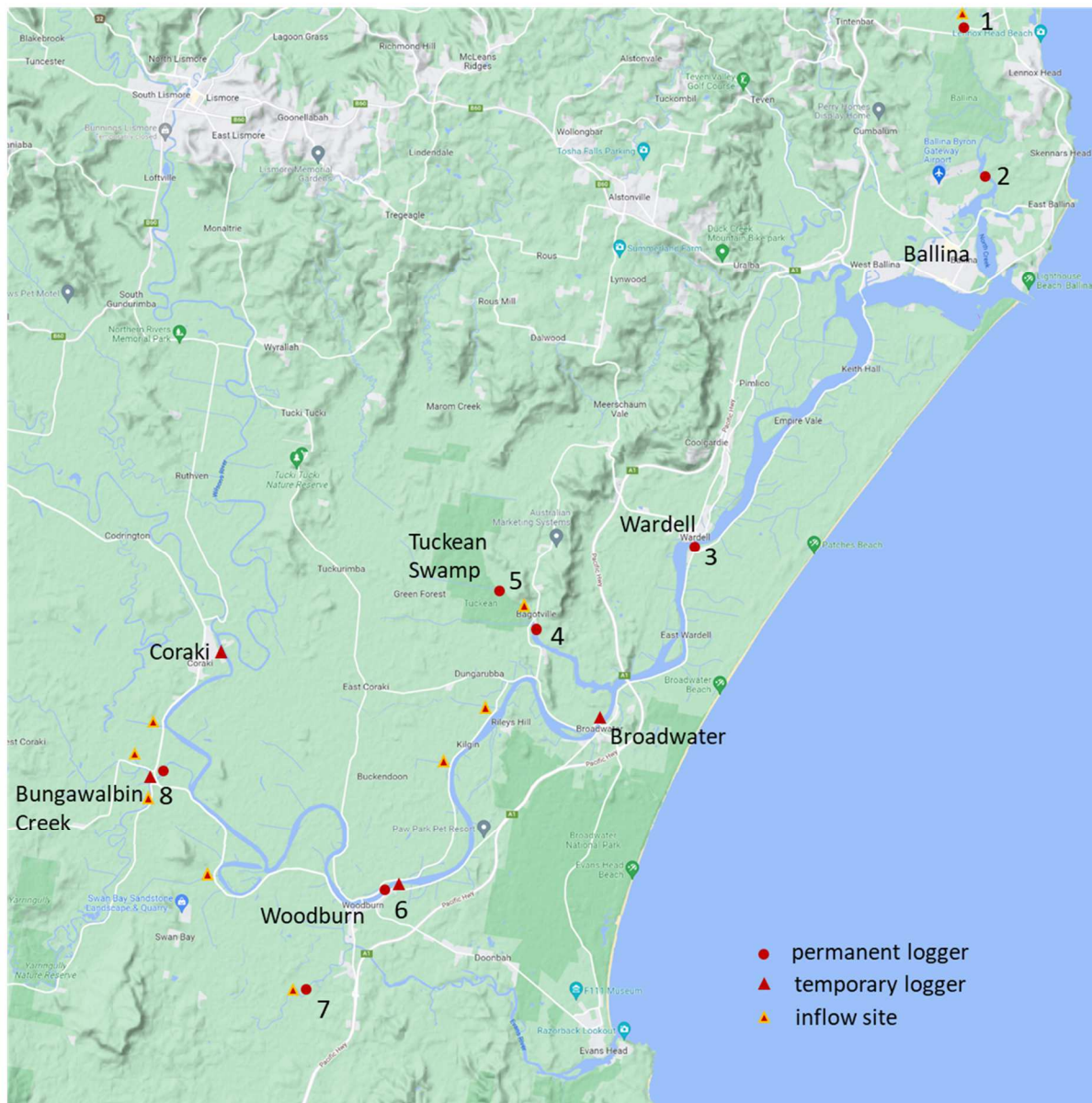
A network of permanent telemetered water quality loggers was established at key sites along the Richmond River floodplain in 2021 (Figure 2; Table 1). The network was developed in collaboration between the Estuaries and Catchments team (NSW DPE) and Southern Cross University, funded by Rous County Council and the NSW government Coastal and Estuary Management grant scheme. The loggers were installed by Rous County Council staff above the 1974 flood level, with samples pumped to a flow-through cell containing the sensor array. The February-March 2022 flood peak destroyed all but the North Creek and Bungawalbin Creek loggers, and temporary loggers were installed at key locations in mid March 2022 to replace missing loggers and track the recovery of water quality throughout the estuary.

## Water quality surveys

The Estuaries and Catchments team and Southern Cross University staff made a series of boat-based and land-based surveys of water quality across the lower Richmond River floodplain from the 12<sup>th</sup> to 18<sup>th</sup> March 2022. Boat-based surveys involved underway sampling of physicochemical / fluorometric parameters using an EXO2 sonde (temperature, conductivity, pH, dissolved oxygen, chlorophyll, fDOM, turbidity) combined with grab samples for total suspended solids, nutrients, BOD<sub>5</sub>, and greenhouse gases (methane and carbon dioxide). Land-based surveys involved sampling major drain outlets for physicochemical / fluorometric parameters using an EXO2 sonde and grab samples for total suspended solids, nutrients, BOD<sub>5</sub>, and greenhouse gases (methane and carbon dioxide). Grab samples were collected from the top 30cm of the water column, avoiding surface scum. Nutrient samples were frozen at -20°C until analysis. Greenhouse gas samples were killed using 20µL of saturated HgCl<sub>2</sub>, with care taken to ensure no head space was retained.

**Table 1 Details of Rous County Council water quality logger stations in the Richmond River**

Site	Map ID	Parameters	Multi-depth	Web link
North Creek upper	1	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	no	<a href="https://admin.tago.io/public/dashboard/6079113343223c0018d5f4f6/1735c686-d35d-4e3d-a717-fb1f5c174db">https://admin.tago.io/public/dashboard/6079113343223c0018d5f4f6/1735c686-d35d-4e3d-a717-fb1f5c174db</a>
North Creek lower	2	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	no	<a href="https://admin.tago.io/public/dashboard/60791190d8dd70001859c87d/2acbee17-7c29-4c52-9788-729657e682ec">https://admin.tago.io/public/dashboard/60791190d8dd70001859c87d/2acbee17-7c29-4c52-9788-729657e682ec</a>
Wardell	3	Temperature, conductivity, dissolved oxygen, pH, chlorophyll, turbidity, CDOM, cyanobacteria	yes	<a href="https://admin.tago.io/public/dashboard/5fe10078cb2fb80027aab002/852be6d1-3029-4623-baff-11a53ca83945">https://admin.tago.io/public/dashboard/5fe10078cb2fb80027aab002/852be6d1-3029-4623-baff-11a53ca83945</a>
Tuckean Swamp	4	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	no	<a href="https://admin.tago.io/public/dashboard/60239222a5e2c70012e5020/29ec54bd-4d5d-4d9f-b32f-d98b8d2068c2">https://admin.tago.io/public/dashboard/60239222a5e2c70012e5020/29ec54bd-4d5d-4d9f-b32f-d98b8d2068c2</a>
Tuckean Broadwater	5	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	no	<a href="https://admin.tago.io/public/dashboard/5fc04650f3bce001c3d0626/31170c76-79d5-4104-b8fa-2c20234ae879">https://admin.tago.io/public/dashboard/5fc04650f3bce001c3d0626/31170c76-79d5-4104-b8fa-2c20234ae879</a>
Woodburn	6	Temperature, conductivity, dissolved oxygen, pH, chlorophyll, turbidity, CDOM, cyanobacteria	yes	<a href="https://admin.tago.io/public/dashboard/60de1436152a9c001194196b/5d8aee30-222a-424d-b8bc-8d177117729f">https://admin.tago.io/public/dashboard/60de1436152a9c001194196b/5d8aee30-222a-424d-b8bc-8d177117729f</a>
Rocky Mouth Creek	7	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	no	<a href="https://admin.tago.io/public/dashboard/5fc7052b39445800261e66bb/bb1fb984-783b-4c37-9661-8e1b82e2288a">https://admin.tago.io/public/dashboard/5fc7052b39445800261e66bb/bb1fb984-783b-4c37-9661-8e1b82e2288a</a>
Bungawalbin Creek	8	Temp, conductivity, dissolved oxygen, pH, chlorophyll, turbidity	yes	<a href="https://admin.tago.io/public/dashboard/6079113343223c0018d5f4f6/1735c686-d35d-4e3d-a717-fb1f5c174db">https://admin.tago.io/public/dashboard/6079113343223c0018d5f4f6/1735c686-d35d-4e3d-a717-fb1f5c174db</a>



**Figure 2** Location of long term and temporary telemetered loggers and inflow sample sites

## Flood levels and floodplain inundation

The February-March flood was characterised by two flood peaks in close succession: a smaller peak (~8m AHD at Lismore) on the 25<sup>th</sup> Feb, followed by a second larger peak (14.4m AHD) on the 28<sup>th</sup> Feb (Figure 3). This resulted in an extended period of time when the low-lying parts of the floodplain were inundated (e.g. Table 2). This flood was also characterised by relatively similar levels between Coraki and Woodburn during the flood peak (Figure 3). The March-April flood also had a two-staged peak, however the first peak was much smaller and levels only exceed 2m AHD at Coraki during this time. In contrast to the February-March event, the second was characterised by a large gradient in water levels between Coraki and Woodburn (Figure 3). Accordingly, estimated floodplain inundation times were approximately 5-7 days less for this event (Table 2). Mean air temperatures were slightly higher during the February-March flood (averaged over the period water levels at Woodburn exceed 2m AHD during each event; Table 2).

The areas of potential inundation on the floodplain at different water levels are presented in Figure 4, based on outputs from an online flood risk tool<sup>4</sup>. This tool does not account for variation in water level along the estuary, however it does serve to illustrate the relative areas of inundation at different stages of the flood. For example, the vast bulk of the floodplain above 4m AHD was inundated for less than 6 days, while backswamp areas (e.g. west Coraki, Dungarubba, Tuckean) were likely inundated for up to 15 days.

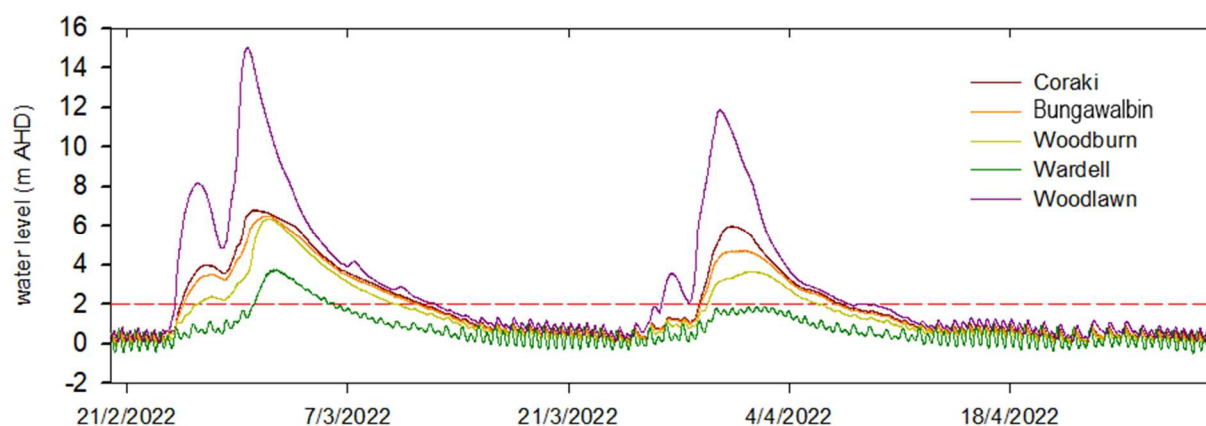
## Blackwater generation potential

Patterns of floodplain inundation are key drivers of blackwater events in the Richmond River. The deoxygenation potential for waters overlying the floodplain depends on factors including: 1) inundation depth; 2) inundation time; 3) ambient temperature; and 4) vegetation type (Vithana et al. 2019). Factors 1 and 2 imply there is likely be spatial variability in blackwater potential across the floodplain, although there are no data to test this. Furthermore, it is likely that oxygen stratification may develop in more sheltered backswamp areas (i.e. bottom waters will be lower in oxygen due to consumption at the sediment-water interface). The implication of this is that the first stage of floodplain drainage will likely comprise better oxygenated surface waters from multiple drains along the system, while the deeper waters in backswamps is likely to be more depleted in oxygen and be the last to drain.

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<sup>4</sup> <https://www.floodmap.net/Elevation/ElevationMap/?qi=2177069>

# Post-flood water quality and fish kill assessment, Richmond River

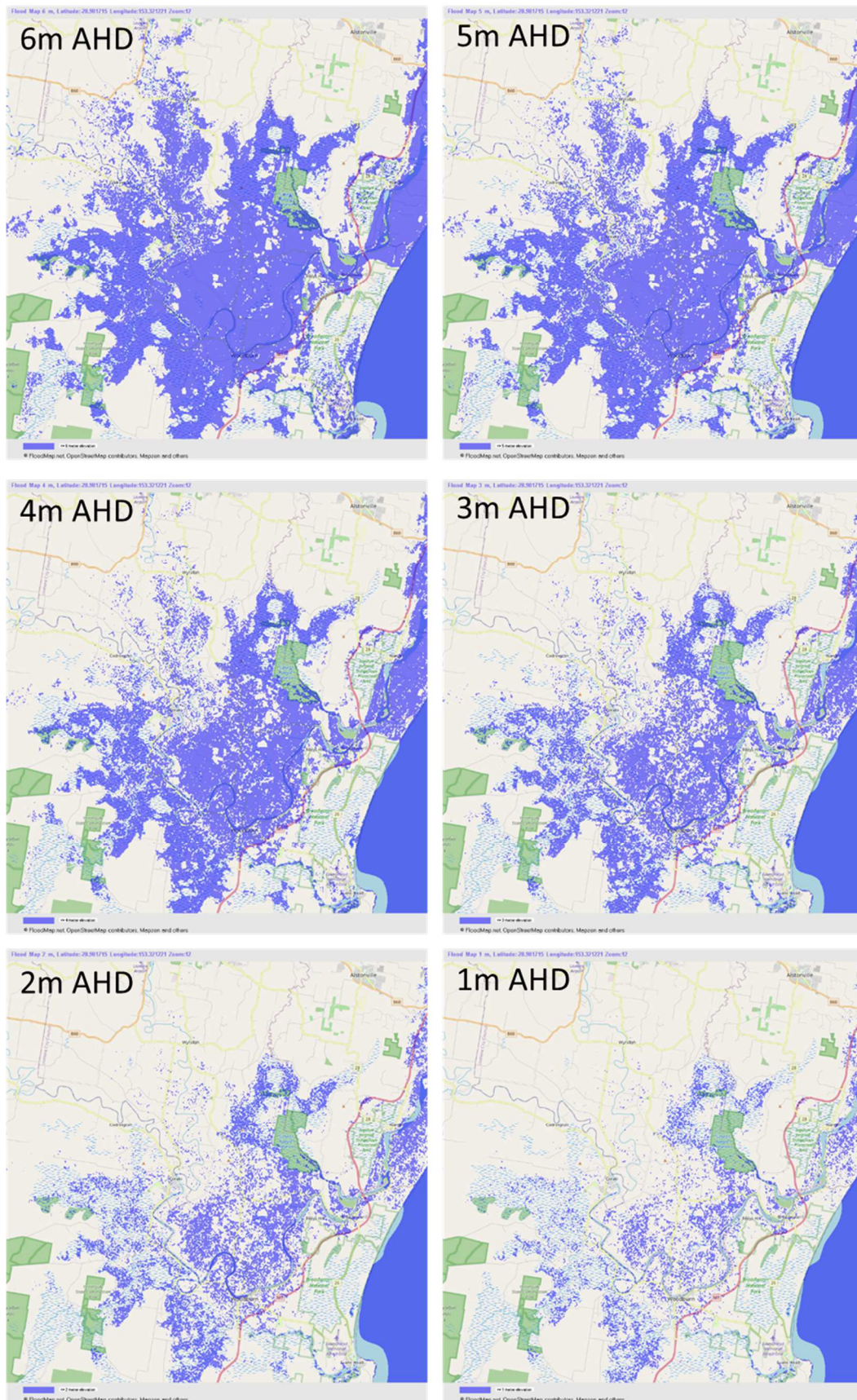


**Figure 3** Water levels at different stations in the Richmond River (source MHL)

**Table 2** Duration of floodplain inundation (days) at different elevations for the 2022 floods.

Note: Also shown is mean air temperature over the period when water level was greater than 2m at the Woodburn gauge.

	m AHD	Coraki	Bungawalbin	Woodburn	Wardell
<b>February-March flood</b>	>6	3.2	2.1	1.4	n/a
mean temp. 27.1°C	>5	4.7	4.0	3.0	n/a
	>4	6.6	6.1	4.6	n/a
	>3	11.8	11.1	7.3	2.4
	>2	15.3	14.9	12.6	5.1
<b>March-April flood</b>	>6	n/a	n/a	n/a	n/a
mean temp. 25.4°C	>5	2.6	n/a	n/a	n/a
	>4	4.1	3.6	0.0	n/a
	>3	5.8	5.4	4.3	n/a
	>2	9.0	8.7	7.0	n/a



**Figure 4 Estimated areas of inundation for different river levels at Woodburn**

## Fish kill observations

The earliest available reports of fish kills in the Richmond River following the February flood were of thousands of dead fish (mainly bream) observed on the 10<sup>th</sup> March around the Richmond oyster shed in North Creek (Figure 5), and large numbers of dead fish between Emigrant Creek and the river mouth and extending to Lighthouse Beach (DPI Fisheries and John Larsson pers. comm.). DPI Fisheries carried out a water quality survey on the 9<sup>th</sup> March, and observed hundreds of eels and thousands of juvenile carp dead at Bagotville Barrage (Figure 6). Surveys undertaken by DPE staff between 12<sup>th</sup>-14<sup>th</sup> March revealed sparse numbers of dead fish along the entire lower Richmond River (Coraki to Ballina). Species included eels, mullet, bream, garfish, carp, and bass. Numerous small fish and eels were observed gasping at the surface around the margins of the upper reaches of the river during this time. It is likely that observations significantly underestimated the actual number of dead fish during this phase as river discharges were still high and many dead fish would have been washed out to sea.

On the evening of 16<sup>th</sup> March, hundreds of fresh, recently dead fish (bream, whiting, luderick, jewfish) were observed along the shoreline of Ballina. Similar observations were made the following morning throughout the lower estuary (Emigrant Creek to the entrance; Figure 7). It is likely that these fish had moved into the lower estuary from the ocean with the incoming tide and become trapped in deeper holes upstream and overwhelmed by anoxic water from upstream as the tide turned. This mechanism is explored more fully in the Post-flood recovery section below.



**Figure 5 Large numbers of dead bream observed in North Creek on the 10<sup>th</sup> March 2022**



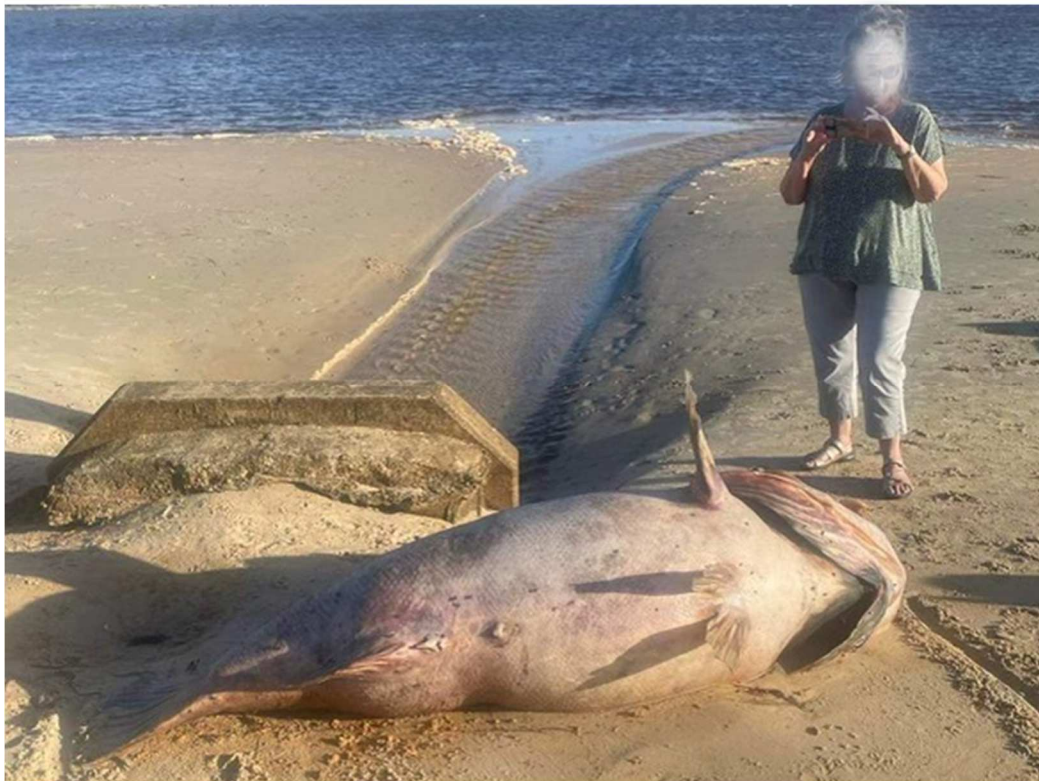
**Figure 6 Dead fish along Lighthouse Beach, 10<sup>th</sup> March 2022**



**Figure 7 Dead fish just downstream of Bagotville Barrage observed on the 13<sup>th</sup> March 2022**



**Figure 8 Recently dead jewfish and whiting observed on ebb tide plumes adjacent to Ballina on the 16<sup>th</sup> to 18<sup>th</sup> March 2022**



**Figure 9 Large Queensland Grouper washed up in Ballina after the February-March 2022 flood**

# Water quality analysis

## Conceptual framework

The following analysis is based on a generalised conceptual model taking account of the quality and origin of the different water bodies moving through the Richmond River estuary during the rising and falling stages of floods (Table 3).

**Table 3 Conceptual framework guiding the interpretation of water quality data**

<b>Flood stage</b>	<b>Hydraulic processes</b>	<b>Water quality processes</b>
<b>Pre flood</b>	Heavy rainfall across the floodplain causes localised flooding and a rapid increase in discharge from drains and tributaries	Tributaries and the main river are primarily influenced by localised runoff until the main flood peak from the upper catchments moves downstream.
<b>Rising stage</b>	Upper catchment flood peak moves into the floodplain. Rapid water level rise in the main river causes water to back up onto the floodplain. Water residence times reduce dramatically (~hours) as the entire system is flushed fresh to the entrance.	A rapid transition in water quality as upper catchment floodwater flushes the main river channel and backs up into the tributaries. Floodwater from the upper catchment is commonly characterised by variable quality during the rising and falling stages (refs).
<b>Flood peak</b>	Floodwater spills onto the floodplain.	Water quality in the main channel progressively dominated by upper catchment floodwaters delivered during the falling stage of the upper catchment flood.
<b>Floodplain drainage stage 1</b>	Water starts to drain from the floodplain once the main flood peak passes and water levels in the main channel reduce enough to create hydraulic gradients to the river.	Small hydraulic gradients at first cause the 'decanting' of better-quality surface water from the floodplain. This floodplain water mixes with the receiving waters causing a transition in water quality in the main river
<b>Floodplain drainage stage 2</b>	The relative volume of floodplain drainage increases as river levels drop and hydraulic gradients increase	Floodplain water begins to dominate water quality in the main river channel
<b>Backswamps drain</b>	The final stage of floodplain drainage occurs as water levels in the river continue drop sufficiently to allow the backswamps drain. This stage coincides with a significant reduction in overall river discharge and the re-emergence of tidal influence, both of which serve to increase water residence times along the estuary	Water quality in the river becomes increasingly dominated by backswamp water until it is advected downstream by residual upper catchment river flows

## February-March flood and blackwater event

All available dissolved oxygen data spanning the two floods is compiled and presented in Figure 11. The assessment below for the February-March flood is based on data from the Bungawalbin and North Creek logger which were the only Rous County Council sites to survive and continue operating throughout the flood. Temporary loggers installed immediately after the flood provide further evidence of recovery processes and track the changes in water quality associated with the second flood in late March. These data provide an opportunity to qualitatively test the general conceptual model presented in Table 3, however it is recognised that there was likely significant variation in processes across the floodplain which may differ from the model presented here. For this analysis we have also used the difference between water levels in Bungawalbin Creek at the confluence with the Richmond River (station 203450) and Woodburn as a proxy for the hydraulic gradient between the floodplain and the main river (e.g. Figure 12).

### Spatial trends

Boat-based surveys on the 12<sup>th</sup> and 13<sup>th</sup> March indicated that the main river was completely anoxic (DO <1% saturation) from just upstream of Swan Bay to the entrance at Ballina (Figure 10). Dissolved oxygen improved upstream to Coraki reflecting the mixing of inflows from the Wilsons River (DO ~38% saturation) and Richmond River reaches (DO ~65% saturation; Figure 8). There were large discharges of anoxic water emanating from West Coraki drain, Bungawalbin Creek, Rocky Mouth Creek, Dungarubba Drain, and the Bagotville Barrage at the base of Tuckean Swamp at this time. Anoxia persisted along the entire river from Swan Bay to Ballina until 15<sup>th</sup> March. By the 17<sup>th</sup> March dissolved oxygen improved substantially in the Richmond and Wilsons River immediately upstream of Coraki (74% and 68% saturation respectively), and along the entrance reach adjacent to Ballina where ocean water had begun to penetrate during flood tides.

### Temporal trends

The Bungawalbin Creek data demonstrate a sequence of distinct runoff phases linked to the timing of water level changes across the floodplain, the tributary creeks, and the main river channel during the February-March flood event. The timing and magnitude of water level differences between floodplain drains and the main channel occur in response to interactions between localised flooding and the downstream migration of the flood peak from the upper catchments (Figure 12; Tables 3 and 4). These factors determine the duration and depth of floodplain inundation, and the hydraulic gradients that control the timing and rate of floodplain drainage. The data show that anoxia in the Richmond River estuary developed in response to the final phase of post-flood runoff when water levels in the main river allowed the backswamps to drain. At this point, floodplain land at <2m AHD had been inundated for up to 15 days, with mean air temperatures of 27.1°C (Table 2).

### Post-flood recovery, March 2022

The final boat-based surveys made on the 17<sup>th</sup> and 18<sup>th</sup> March showed that the lower estuary was recovering progressively as flood tide inflows of oceanic water mixed with and diluted anoxic water (Figure 10). Profiles made along the lower estuary showed that the estuary was sharply stratified on the flood tide, with ocean water penetrating along the bottom as far upstream as Pimlico Island at high tide (Figure 16). Logger data showed that the salt wedge had reached as far as Wardell by the 24<sup>th</sup> March, however the brackish gradient recovery was rapidly reversed by the onset of the second major flood in late March.

Echo sounder readings on the 17<sup>th</sup> March showed evidence of large fish moving upstream in this bottom layer of oxygenated oceanic water with the incoming tide. Towards the bottom of

the outgoing tide there was evidence of oxygenated ocean water trapped in deeper holes upstream of Byrnes Point, surrounded by ebbing anoxic water. It is likely therefore that fish venturing upstream with the incoming tide may have become cut off and trapped in these deeper holes when the tide turned, eventually becoming overwhelmed when their refuge was broken down by turbulent mixing with ebbing anoxic water.

The upper estuary recovery proceeded as better quality upper catchment inflows displaced anoxic water downstream, and atmospheric exchange satisfied residual biochemical oxygen demand (BOD). The downstream advection of anoxic water is illustrated by the sequential improvement in dissolved oxygen saturation over time moving down the estuary (Figure 14). The rate of downstream advection of anoxic water can be estimated by the time taken for the same water (based on oxygen saturation) to travel from Woodburn to Wardell. Based on this calculation the upper estuary recovered downstream at a rate of 5km day<sup>-1</sup>. All sites in the main river from Woodburn and Wardell had recovered to approximately 50% saturation by the time the second flood hit in late March. In contrast, the floodplain tributaries (Tuckean Swamp, Bungawalbin Creek and Rockymouth Creek) took longer to recover, only reaching 50% saturation on the 27<sup>th</sup> March on the eve of the second major flood. This most likely reflects the ongoing inputs of hypoxic groundwater in these systems.

**Table 4 Description of the distinct runoff stages during the February-March 2022 flood**

Note: based on interpretation of Bungawalbin Creek logger data (Figure 12)

<b>Flood stage</b>	<b>Processes</b>
<b>Early flood</b>	Floodplains experience flooding from local subcatchments due to ~200mm of rain over 3 days from the 23 <sup>rd</sup> Feb
<b>Rising stage</b>	Water quality dominated by local overland runoff – moderate DO and low turbidity
<b>Flood peak</b>	Turbid water from upper catchment dominates as flood peak moves downstream and hydraulic gradient between Bungawalbin Creek and Woodburn approaches zero. Floodplain becomes flooded with upper catchment water as levees overtop. Dissolved oxygen concentrations start to decline due to internal consumption (i.e. breakdown of suspended organic matter in the water column)
<b>Floodplain drainage Stage 1</b>	The hydraulic gradient between the floodplain and main channel increases as the system drains and the tidal signal appears at Wardell. Upper catchment water drains from the system and water in the estuary becomes rapidly dominated by the first stage of floodplain drainage, as indicated by the drops in turbidity, pH and conductivity.
<b>Floodplain drainage Stage 2</b>	The hydraulic gradient between the floodplain and main channel further increases, thereby increasing the rate of discharge to the estuary. Drainage is also likely to have been influenced by tidal effects.
<b>Backswamps drain</b>	Low lying backswamps drain as the water level in the main channel dropped below 2.5m AHD (Woodburn gauge) and tidal influence became increasingly apparent at Woodburn. This phase saw the influx and increasing dominance of anoxic water, coinciding with the first reports of dead fish throughout the system.

## March-April flood event

The follow up major flood starting on 30<sup>th</sup> March displayed distinct stages and trends in water quality over time that are consistent with the generalised conceptual model presented in Table 3. These trends are illustrated using the data from Wardell as an example (Figure 13), which shows distinct water quality signatures for the different flood stages. It is notable that there was no overwhelming blackwater event associated with this flood, with dissolved oxygen in the main river only falling to around 50% saturation in the floodplain drainage phases. This may be due to a number of factors:

1. Floodplain inundation times and depths were significantly less for the second event
2. Ambient air temperatures were lower
3. Floodplain vegetation had not recovered since the previous flood and there was less fresh material to breakdown and consume oxygen
4. The overall volumes of floodplain drainage were relatively less compared to upper catchment floodwater

Given previous floods of this scale have resulted in blackwater and corresponding fish kills in the Richmond, it is more likely that factor 3 above was the main contributing factor for the March-April flood event not resulting in an overwhelming blackwater event.

## North Creek

Hypoxic water began to progressively dominate the Newrybar drain and upper North Creek in the days immediately following the first flood peak, with anoxic conditions developing by the 6<sup>th</sup> March (Figure 15). There was a brief improvement in dissolved oxygen to ~25% saturation over the next day, most likely reflecting the transient influence of a discrete water body / component of the post-flood runoff. This water body was rapidly replaced by anoxic water from the evening of the 7<sup>th</sup> March, with complete anoxia prevailing from midday 8<sup>th</sup> March until the 11<sup>th</sup> March. This coincided with the reported fish kill in North Creek, and suggests that fish were overwhelmed by the influx of anoxic water, with escape to the ocean blocked by worsening water quality in the main river. Dissolved oxygen concentrations in North Creek began to recover from the 11<sup>th</sup> March, although there were pulses of hypoxic water pushing downstream on ebb tides.

By the onset of the second flood in late March, dissolved oxygen in North Creek had recovered to ~50% saturation due to a combination of tidal flushing and diminishing hypoxic water inputs (Figure 15). The flood peak raised dissolved oxygen to ~80% saturation, with the falling stage of the peak seeing a rapid transition to a dominance of hypoxic water, with dissolved oxygen saturation falling to ~10% on the 6<sup>th</sup> April. Following this, dissolved oxygen saturation recovered steadily over the following two weeks to ~60%. No fish kills were reported following the second flood event.

## Tributaries and major drains

Relative to the upstream riverine inputs (i.e. Wilsons and Richmond Rivers upstream of Coraki) and the estuary (Woodburn to Ballina), the floodplain tributaries and drains displayed the worst water quality during the post-flood surveys (Figure 19). During boat-based sampling on the 12<sup>th</sup> and 13<sup>th</sup> March all floodplain drains were discharging large volumes of anoxic water to the main river. At the time of land-based sampling (15<sup>th</sup> March) the main river level at Woodburn was ~1m AHD and the majority of the floodplain had drained, leaving isolated areas of inundated land within low lying backswamps (e.g. Figure 4). Despite this, there were still large volumes of water still discharging from the main backswamp outlets (West Coraki, Rocky Mouth Creek, Dungarubba, and Tuckean Swamp). All water draining

from backswamp drains at this time was anoxic and had high BOD<sub>5</sub> and concentrations of greenhouse gases (CO<sub>2</sub>, methane; Figures 17, 18 and 19).

Despite the relative quick recovery of dissolved oxygen saturation along the main river following the floods, it is notable that the floodplain tributaries (e.g. Bungawalbin Creek and Tuckean Broadwater) were much slower to recover. In particular, Tuckean Broadwater remained hypoxic following the second flood.

There was no evidence of acidic groundwater discharges from known acid sulfate soil areas during the post-flood surveys, with pH >6 at all sites (Figure 19). This is to be expected as river levels were still relatively high and hydraulic gradients between groundwater and drains were minimal.

## **Biochemical oxygen demand and greenhouse gases in post-flood waters**

The highest BOD<sub>5</sub> values and greenhouse gas concentrations were recorded in drain waters discharging to the river (Figures 17, 18 and 19), further implicating the last stage of floodplain runoff as a major factor in the March 2022 blackwater event. In particular, BOD<sub>5</sub> values for Dungarubba canal and Tuckean main drain were an order of magnitude higher than all other values recorded. In contrast, BOD<sub>5</sub> values and greenhouse gas concentrations were low in the Richmond and Wilsons Rivers reaches above Coraki. There was a relatively high residual BOD<sub>5</sub> along the river which suggested that in the absence of mixing with upper catchment water anoxia could persist in the main river for some time.

It is likely that methane and carbon dioxide concentrations were the result of three main sources: the anaerobic breakdown of inundated vegetation on the floodplain; the ongoing breakdown of dissolved organic matter in anoxic waters; and inputs of groundwater at the tail end of the post-flood runoff. Methane and carbon dioxide were closely correlated suggesting their production is coupled and associated with acetotrophic methanogenesis which may be expected to dominate in freshwater under anoxic conditions (Whiticar et al. 1986). These results suggest that methanogenesis is a major pathway of organic matter breakdown in floods, in addition to other pathways previously suggested as important for blackwater generation in the Richmond River (e.g. iron reduction; (Eyre et al. 2006).

The greenhouse gas concentrations measured during this study were extremely high relative to previous measurements in the Richmond River (Maher et al. 2015) and compared to similar systems around the world (Borges and Abril 2011; Stanley et al. 2015). This highlights the importance of floods and blackwater events as sources of greenhouse gas which may increase with the predicted increase in the frequency and severity of flooding due to climate change.

# Conclusions and recommendations

## Flooding and the evolution of blackwater events

This study has identified clear signatures of the different flood runoff stages that impact water quality in the Richmond River estuary. The data support and add to the existing paradigm of understanding about the evolution of blackwater events in the Richmond River and similar systems. The general sequence of events for floods is summarised as:

- Floodplains are inundated initially by localised flooding, followed by the overtopping of natural and constructed levees along the floodplain by upper catchment floodwaters
- Blackwater is generated on parts of the floodplain as a function of inundation time and inundation depth, and the amount of fresh non-flood tolerant vegetation available for microbial decay
- Floodplain waters are held back until the water level in the main river drops enough to create a hydraulic gradient
- Floodplain runoff then comprises a number of stages including the initial 'decanting' of better-quality surface waters, ending in the drainage of anoxic waters from low lying backswamps
- Artificial drainage structures in backswamps have greatly enhanced the rate and extent of backswamp drainage at a time when water residence times in the receiving waters are increasing due to diminishing flows from the upper catchment and tidal influence
- This results in the receiving waters being overwhelmed by anoxic water which is the primary cause of fish kills
- Spatial and temporal variation in the evolution of blackwater events result in a dynamically cryptic and dangerous environment for fish, whereby apparent refugia from poor water quality are rapidly overwhelmed by lethal water quality as conditions (e.g. tide) change
- The recovery of dissolved oxygen concentrations in the river proceeds via the gradual advection of anoxic water downstream driven by residual upper catchment inflows, and tidal mixing with ocean water in the lower estuary.

## Climate change implications

The study has identified flooding of modified floodplains as a significant risk in terms of increased greenhouse gas emissions from coastal environments. This may be due to: 1) the conversion of perennial floodplain swamps to dryland pastures via widespread drainage, thereby increasing the prevalence of vegetation intolerant to inundation; and 2) the accelerated export of waters from backswamps via artificial drainage structures. It is likely that floodplains as a source of greenhouse gasses will increase into the future under current management with the projected increase in severity and frequency of extreme events (i.e. floods and droughts).<sup>5</sup>

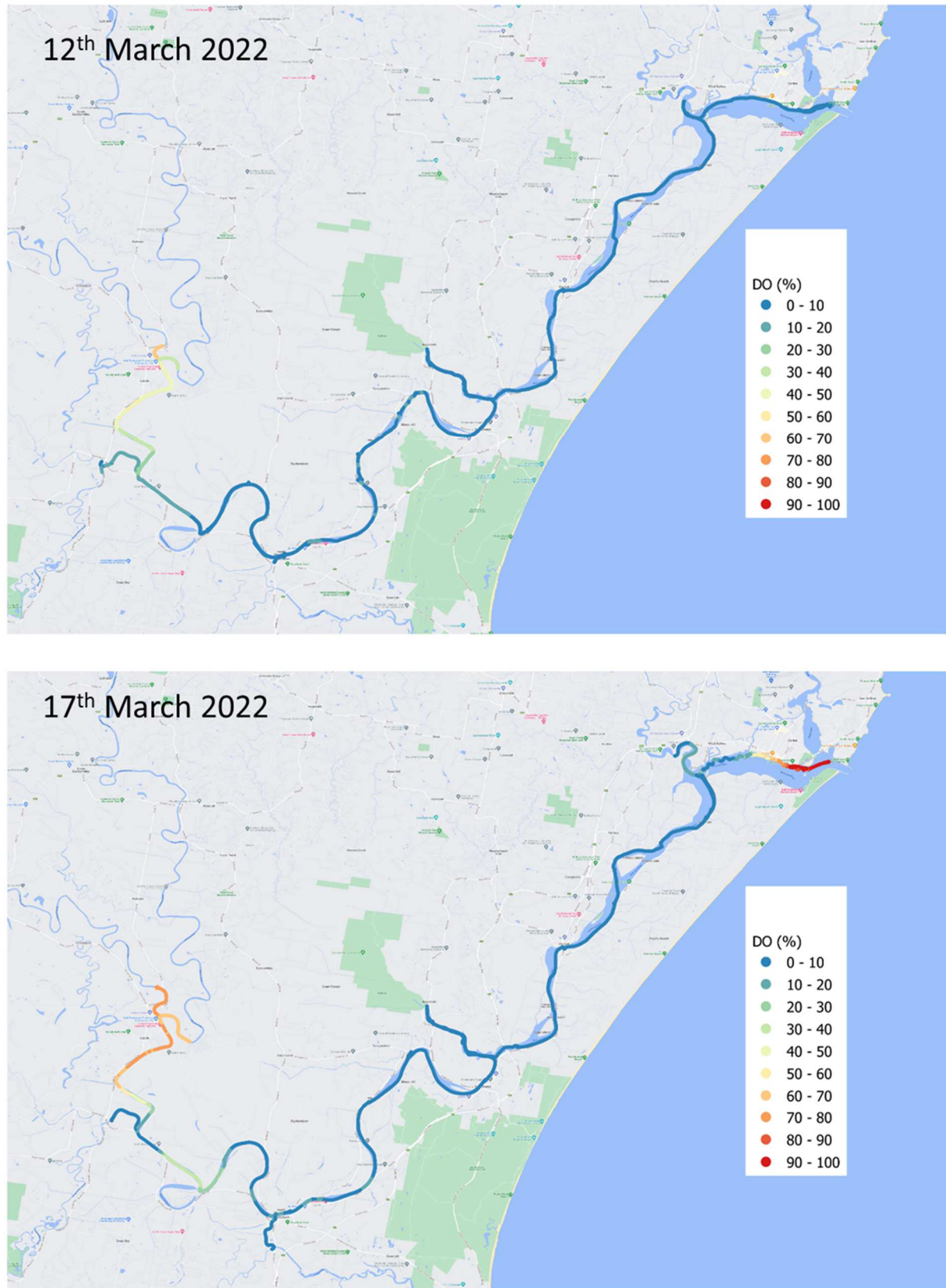
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<sup>5</sup> Note: the dynamics of greenhouse gas emissions from undisturbed and rehabilitated backswamps is not well known.

## Recommendations

This study has provided evidence of: 1) the value of near real-time high-resolution monitoring; 2) key knowledge gaps regarding spatial and temporal processes affecting blackwater generation on the floodplain; 3) clear pathways for the better management of floodplains; and 4) the significant role of flooding in greenhouse gas emissions along the coast. Based on this and in support of previous floodplain management guidelines (Johnston et al. 2003), we recommend the following:

- Support the recommendations of the 2020 Richmond River Floodplain Prioritisation Study (Harrison et al. 2020)
- Improve the resilience and reliability of existing sentinel water quality monitoring networks to withstand future flood events
- Strategically expand existing monitoring to include water level and quality monitoring of key backswamp and floodplain locations
- Utilise flood and ecosystem response modelling to better understand processes and interpret monitoring data
- Support research aimed at better understanding the spatial / temporal dynamics of blackwater generation across the floodplain and identify opportunities for future management
- Support extension initiatives to improve stakeholder understanding of key processes and landuse activities that contribute to blackwater events
- Work with relevant stakeholders to investigate and implement management options for priority low lying areas of the floodplain.
- Further explore blackwater processes in other NSW estuaries where blackwater-associated fish kills regularly occur by way of implementing routine water quality programs and the above recommendations for the Richmond within these estuaries.



**Figure 10** Heatmaps of dissolved oxygen saturation in the Richmond River following the February-March flood

Post-flood water quality and fish kill assessment, Richmond River

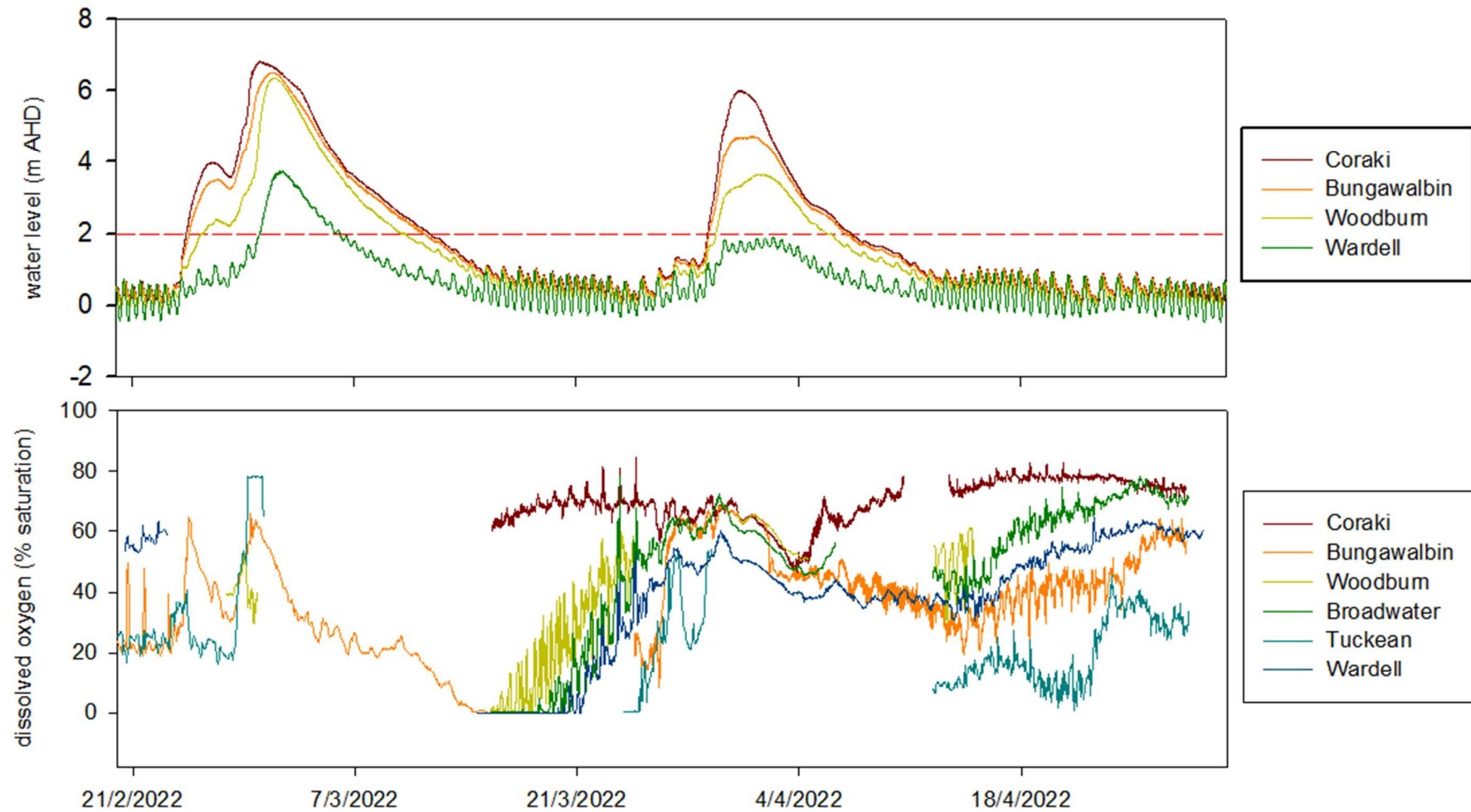


Figure 11 Water levels and dissolved oxygen saturation throughout the Richmond River estuary during the 2022 floods

Post-flood water quality and fish kill assessment, Richmond River

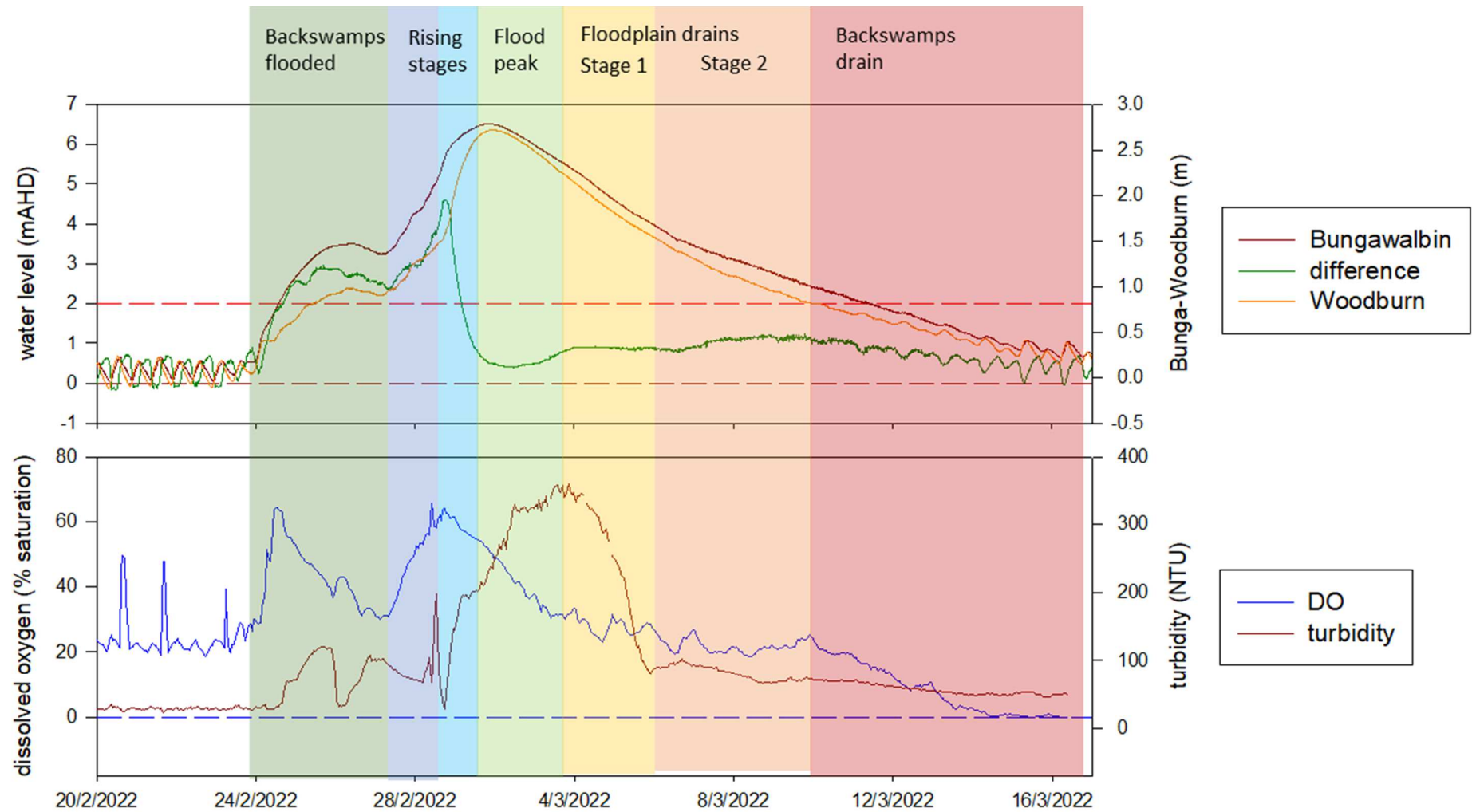


Figure 12 Bungawalbin Creek and Woodburn water levels, and turbidity and dissolved oxygen variation during the February-March flood event

Post-flood water quality and fish kill assessment, Richmond River

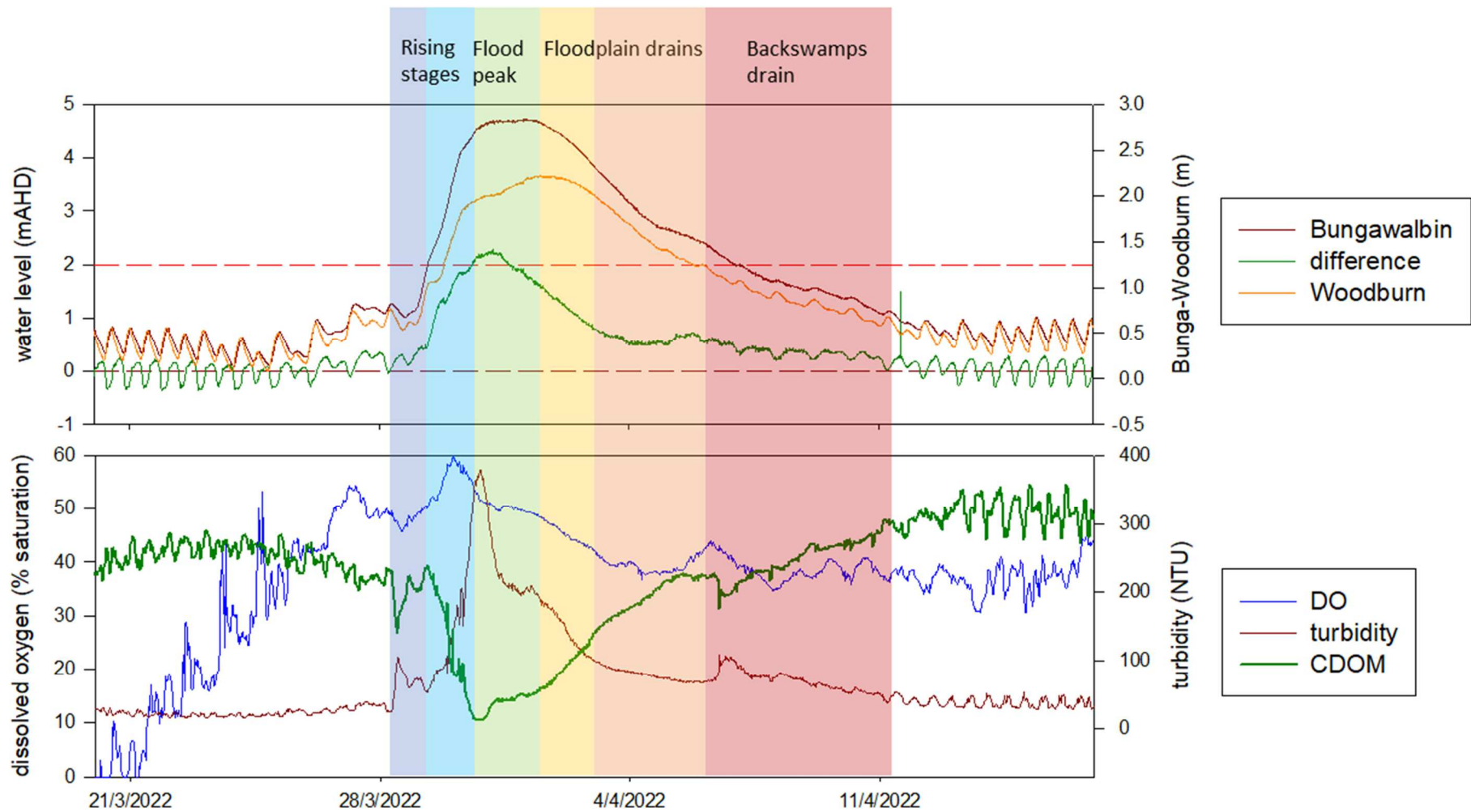


Figure 13 Bungawalbin and Woodburn water levels, and water quality variation at Wardell during the March-April flood event

Post-flood water quality and fish kill assessment, Richmond River

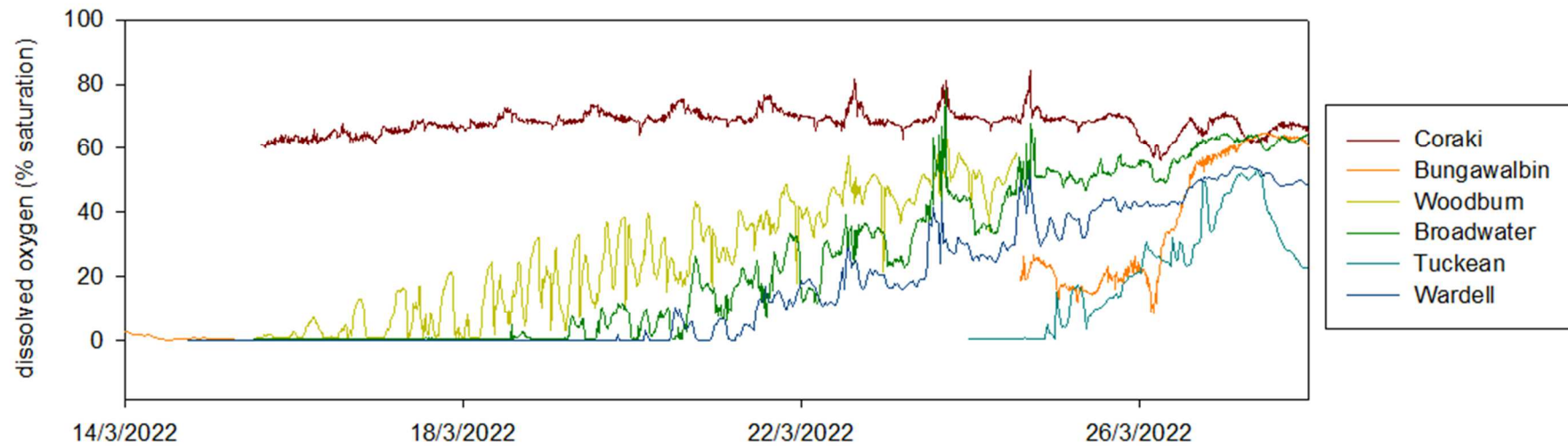


Figure 14 Post-flood recovery of dissolved oxygen saturation after the February-March flood event

Post-flood water quality and fish kill assessment, Richmond River

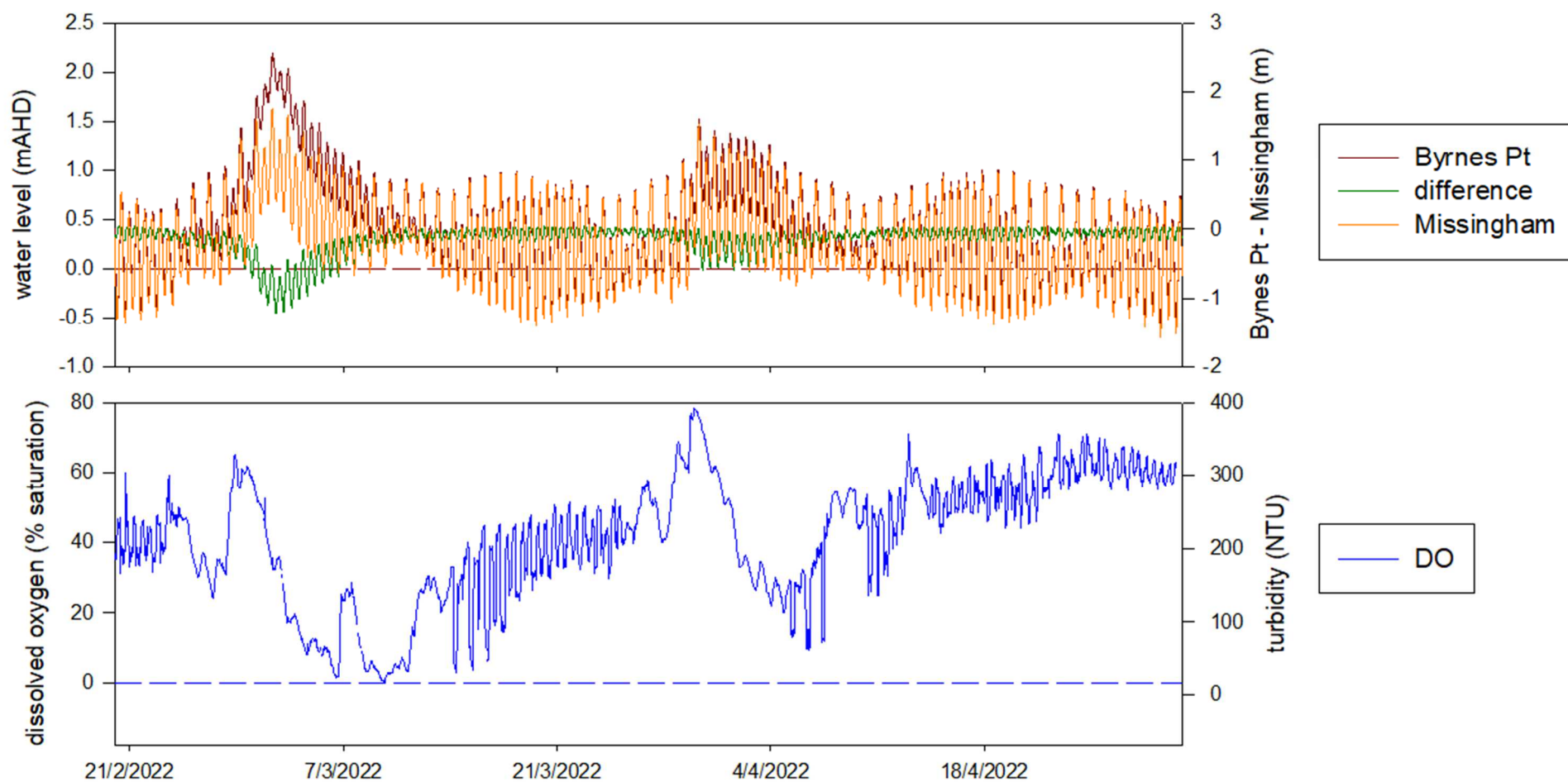


Figure 15 Lower estuary water levels and dissolved oxygen saturation in upper North Creek (station 1; Figure 3)

Post-flood water quality and fish kill assessment, Richmond River

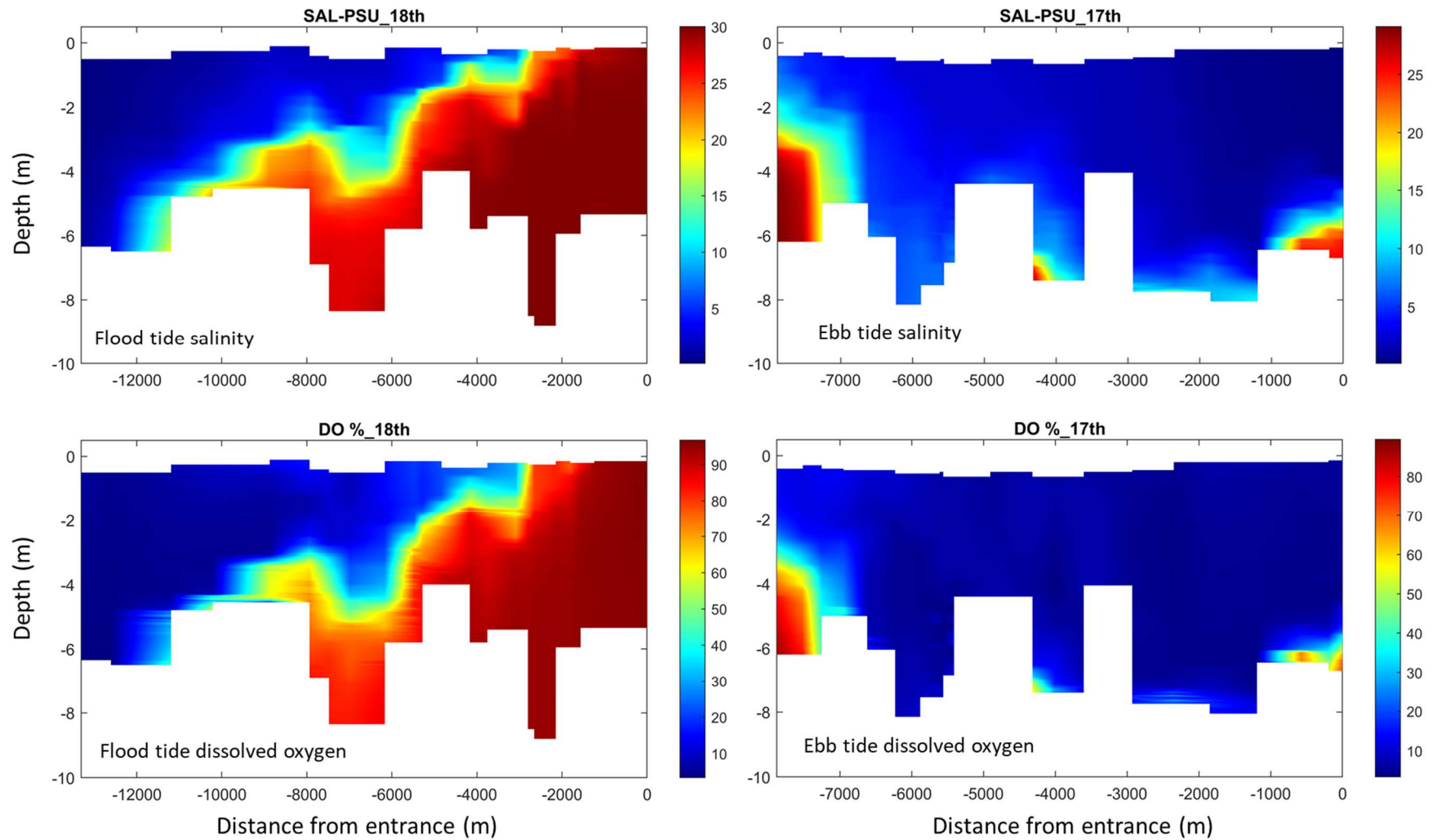


Figure 16 Salinity and dissolved oxygen profiles in the lower Richmond River estuary during flood and ebb tides

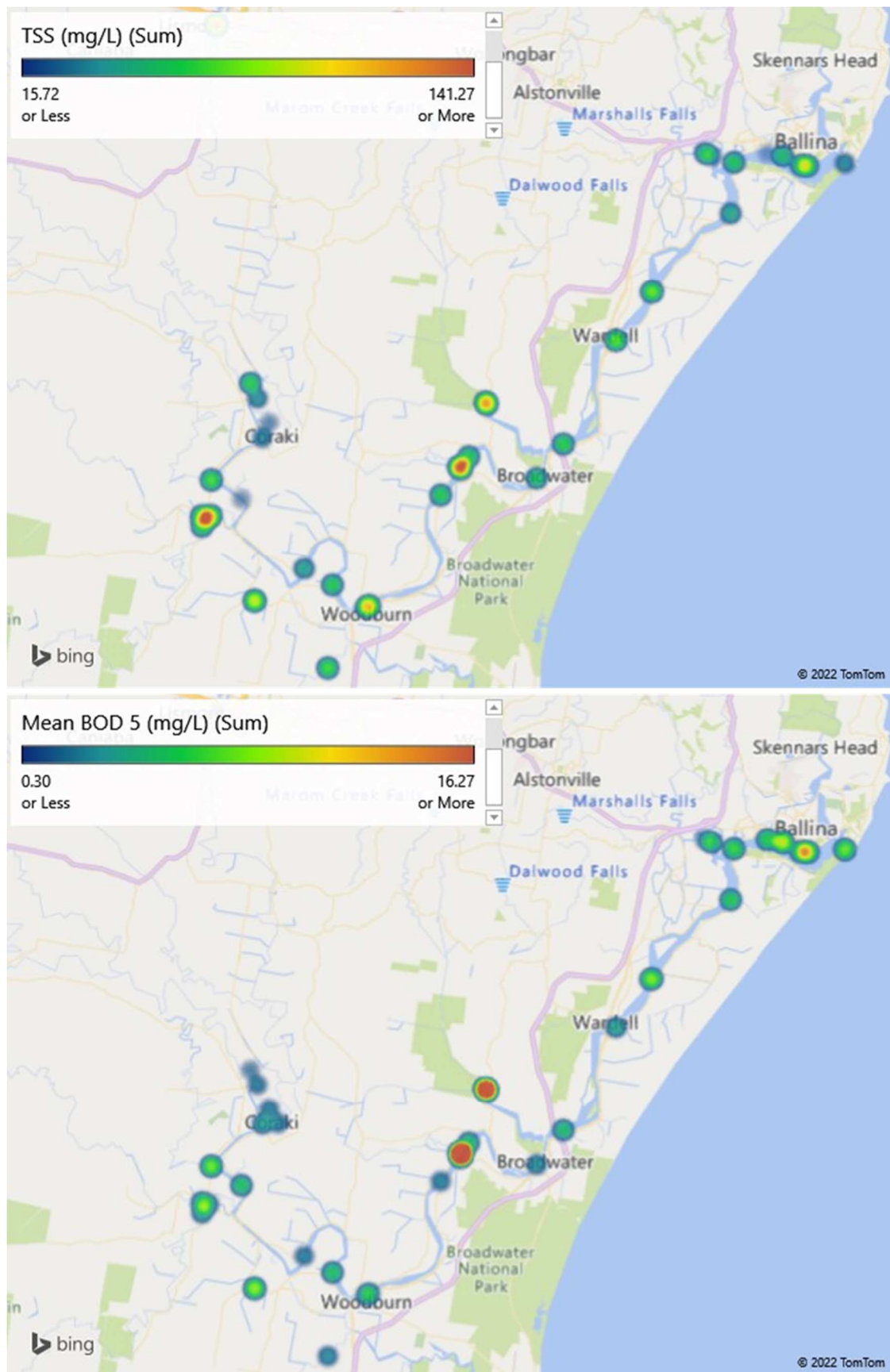


Figure 17 Heatmaps of total suspended solids and BOD<sub>5</sub> following the February-March flood

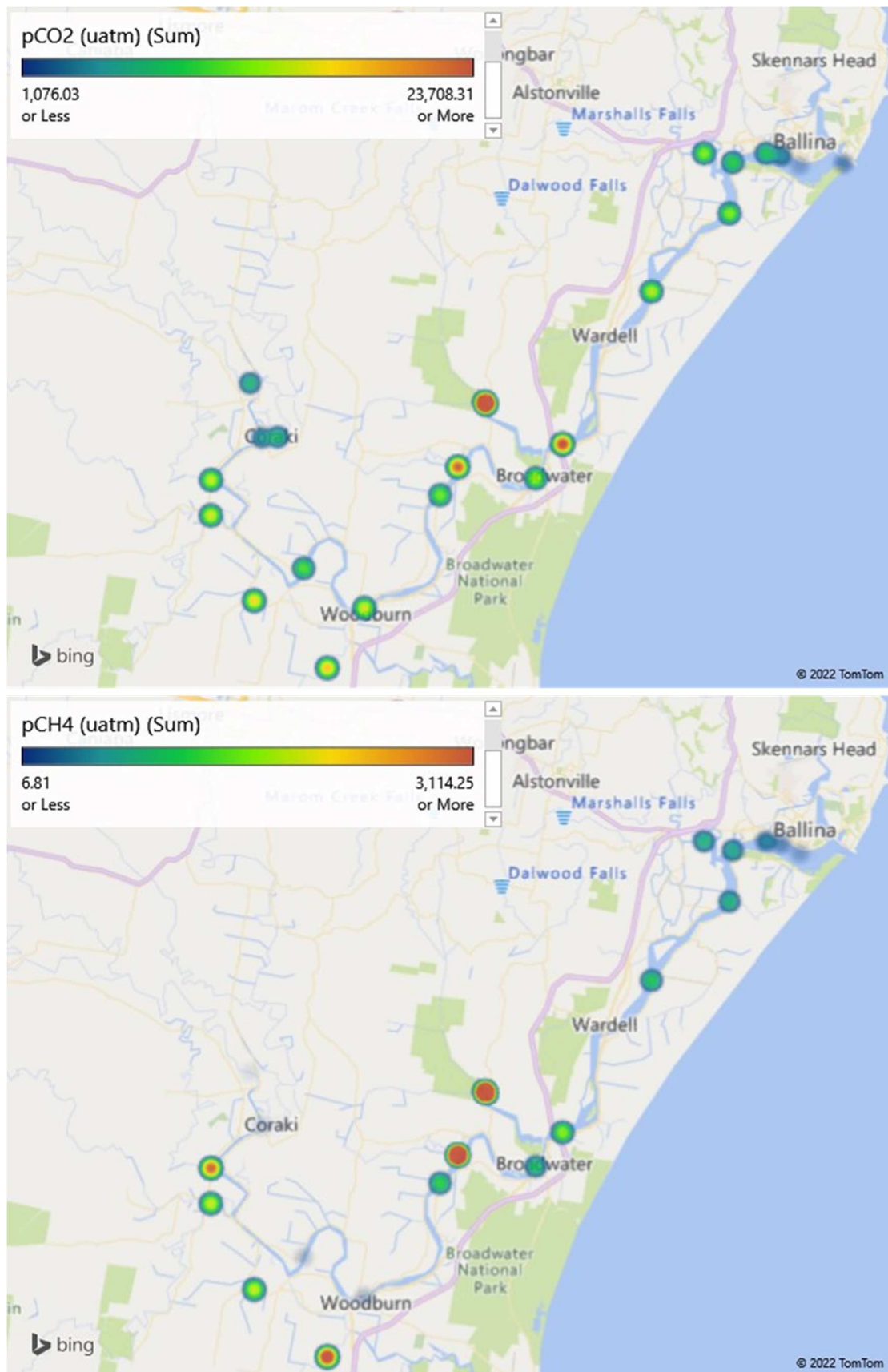
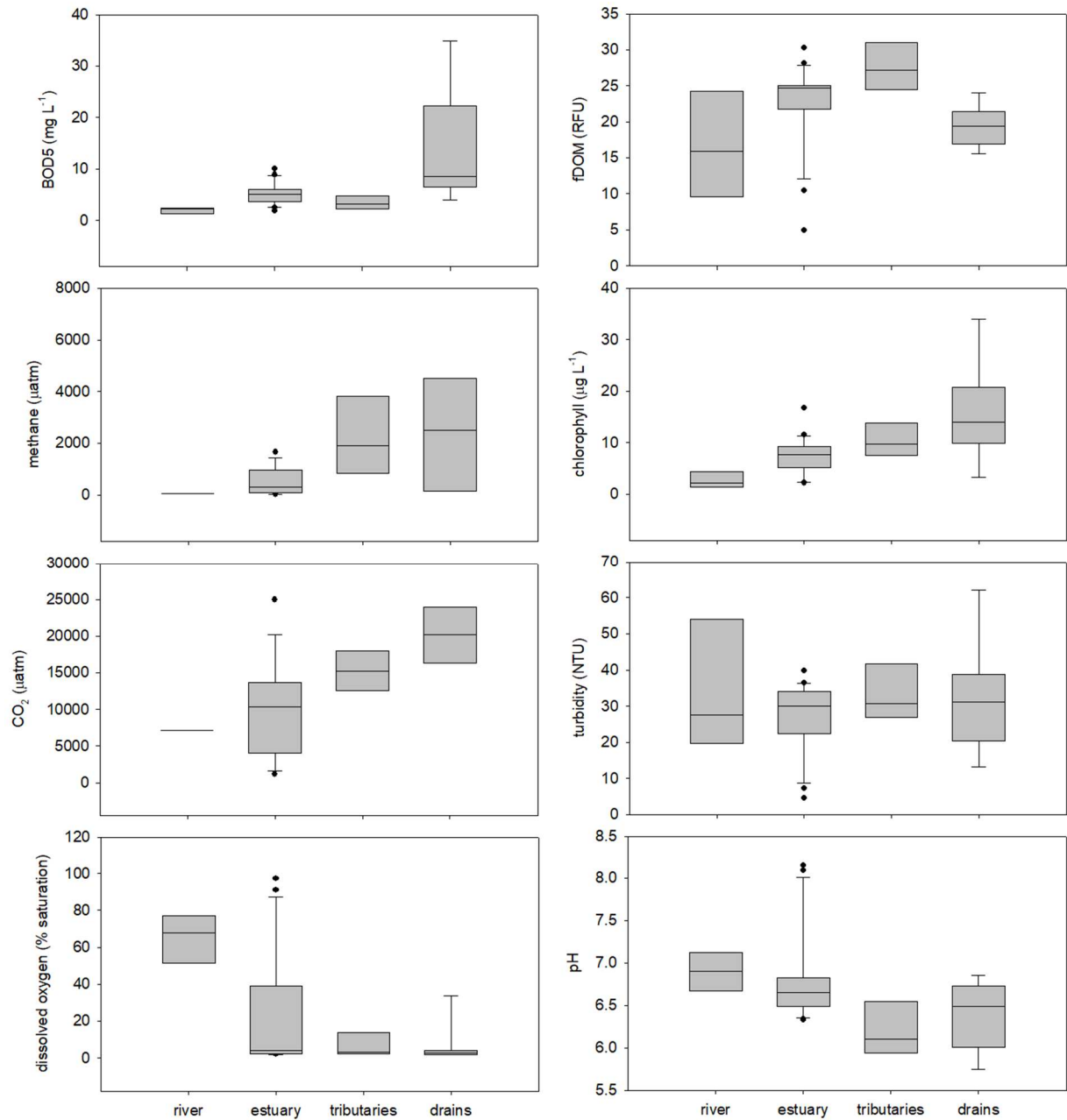


Figure 18 Heatmaps of carbon dioxide and methane following the February-March flood

Post-flood water quality and fish kill assessment, Richmond River



**Figure 19 Summary of water quality properties for different waterbodies following the February-March flood**

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