Carbon accumulation and transfer modelling (Hattah Lakes)

Report prepared for Mallee Catchment Management Authority

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ENQUIRIES

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Traditional Owner acknowledgement

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EXECUTIVE SUMMARY

The delivery of water to the Hattah Lakes system during August-September 2022 (i.e., planned delivery) resulted in minimal depletion of dissolved oxygen (DO) from most lake sites included in this study. The strongest depletion of DO was observed for the lakes that were most hydrologically distant from the water input point (Messengers regulator). The higher depletion of oxygen from these lake sites was likely due to either: (i) the longer contact time of the delivery water with leachable carbon, and/or (ii) longer hydraulic residence times for water in this more distant lake systems.

The relatively weak depletion of DO during the planned delivery period shows that the Hattah lakes system were at a low risk of oxygen depletion for the lake heights targeted by the planned water delivery. This is supported by hydrological-biogeochemical modelling of the planned delivery period which suggests that the available litter in the inundated dry areas of the lakes system was much lower than that measured in previous surveys, likely due to subsequent water deliveries since that time. The observed DO responses of the sites used in this study were best described by a model that assumed zero oxygen demand from the standing pool of DOC in the lakes prior to delivery and a litter load that was 15% of that measured by field survey in 2019.

The direct connection of the Hattah Lakes system with the River Murray (due to upstream flooding) resulted in extremely strong depletion of DO at all sites over the period December 2022 – January 2023, and occurring during exceptionally high river discharge, in excess of 200 GL/day. This DO depletion was likely due to a number of factors, including: (i) supply of water from the River Murray that was already depleted in DO, (ii) very high lake levels during peak river flow (2m higher than during the planned delivery period), leading to inundation of lake areas that had not been recently flooded, and (iii) higher water temperatures.

The observed responses of the Hattah lakes system to the planned and unplanned delivery of water shows that while smaller managed deliveries of water to this system are effective in reducing the risk of oxygen depletion to similar scale watering events, larger (unplanned) water delivery events are more difficult to manage. However, river discharges of the scale observed over December 2022 – January 2023 are rare, and likely represent an extreme case of connectivity between the River Murray and the Hattah Lakes.

BACKGROUND & CONTEXT

Flooding events can rapidly transfer very large quantities of terrestrial carbon into aquatic ecosystems via leaching of dissolved organic carbon (DOC) from floodplain litter that accumulates on the floodplain between flood events. At high concentrations, DOC can create ‘blackwater events’ which stain the water a dark colour. Under appropriate conditions (e.g. high DOC concentrations and warmer weather), this DOC can be rapidly consumed by microbial organisms (bacteria and fungi), which can deplete oxygen concentrations in the water column leading to hypoxia. While this is a natural process, flow regulation in the River Murray has greatly reduced the frequency of inundation events that episodically remove accumulated organic material. The increased periods of accumulation of carbon between flood events now means that more material is leached when flooding does occur. In turn, this fuels much higher rates of bacterial respiration, increasing the likelihood of respiration rates exceeding rates of oxygen production by photosynthesis or re-supply from the atmosphere. This increases the risk of hypoxic events, which are detrimental to aquatic biota and can lead to mortality of fish and other aquatic fauna.

Understanding the interplay between gas exchange rate, water movement across the floodplain and litter loads through hydrodynamic modelling techniques can help inform management practices around a specific watering. While there are basic steps to manage the risk of hypoxic blackwater (e.g., water outside hot periods, don’t allow water to pool excessively, provide high inflows to allow mixing with ‘fresh’ water), sometimes these are not always practical. Biogeochemical-hydrodynamic water quality models allow managers to assess potential risks to specific areas of the floodplain under different inundation scenarios. Our previous work been directed towards developing these models (Holland 2020; Morales, 2022) however they are yet to be validated during a watering event. This project aimed to validate and refine the coupled Hattah hydrodynamic water quality model by collecting data during the planned spring 2022 watering event. Due to high upstream inflows, very high discharge in the River Murray resulted in an unplanned direct connection with the Hattah lakes immediately after the planned delivery period. As will be shown here, the juxtaposition of these two different connection periods provides important information about the effectiveness and limitations of managed deliveries in controlling the risks of oxygen depletion in the Hattah lakes.

EXPERIMENTAL METHODS

FIELD DEPLOYMENT OF LOGGERS

The purpose of this study was to validate existing coupled biogeochemical-hydrodynamic models for dissolved organic carbon (DOC) leaching and dissolved oxygen (DO) depletion, developed previously for the Hattah Lakes system (Morales, 2022). Site selection was based on a number of factors, including: (i) selection of high and low risk sites for DO depletion (based on previous hydrodynamic modelling), (ii) proximity to existing lake telemetry sites, and (iii) site access considerations. All sites used in this work are listed in Table 1 and shown in Figure 1; loggers at site 2 (Chalka Creek-2) were lost during deployment.

Two (2) D-OPTO loggers (ENVCO, Auckland, New Zealand) were deployed at each of the fourteen (14) sites for the continuous measurement of water temperature and dissolved oxygen (DO). The sensor windows of the two D-OPTO loggers were placed at heights of 0.4 m and 0.8 m above the base of the support stand (Figure 1). The purpose of this configuration was to determine whether any significant variations in DO occurred with water depth, keeping in mind that the hydrodynamic model outputs are two dimensional (i.e., are averaged through depth). Very little difference was observed between the two loggers at any site, so all logger data (Temperature, DO and DO saturation) were averaged for each logger pair; after trimming for any periods of time when the loggers were not submerged (as determined from air temperature variations). At most sites an additional Trutrack water level logger (WT-HR 2000; TruTrack Ltd, Christchurch, New Zealand) was also deployed, providing information on lake height, water temperature and air temperature. Water height data from Trutrack loggers were calibrated against manual readings of lake heights. All loggers (both D-OPTO and Trutrack) were configured to collect data at 30-minute intervals.

Loggers at sites 1 – 13 were deployed during the period 16 – 18 August 2022; site 14 (Oateys Regulator) was deployed on 31-August-2022. The original intention was to retrieve the loggers later in 2022 (December), approximately two (2) months after completion of the planned delivery. The unplanned direct connection with the River Murray due to upstream flooding resulted in sites being inaccessible until early 2023. All loggers (except sites 12 and 13) were retrieved on 3-March-2023; sites 12 and 13 were retrieved one month later.

Figure 1. Photo of logger station with two D-OPTO loggers (0.4 m and 0.8 m above base) and Trutrack water level logger, prior to deployment.

Table 1. Location of field logger sites (site numbers correspond to locations marked on map; Figure 1).

Site name	Site number	South	East	Water depth (m) ¥
River Murray@Chalka	1	-34.73685	142.50007	NA
Chalka Creek-1	2	-34.72238	142.4592	NA
Chalka Creek-2 *	3	-34.72066	142.451	NA
Chalka Creek-3	4	-34.71458	142.414	NA
Lake Hattah	5	-34.75962	142.3409	0.77
Lake Lockie	6	-34.7319	142.3607	0.82
Lake Mournpall	7	-34.70481	142.3377	1.08
Lake Konardin	8	-34.69398	142.3432	1.01
Lake Yelwell	9	-34.69994	142.3729	0.80
Lake Woterap South	10	-34.67147	142.3503	0.80
Lake Woterap North	11	-34.66785	142.3521	0.83
Lake Bitterang North	12	-34.66357	142.3818	0.83
Lake Bitterang South	13	-34.66905	142.3752	0.87
Oateys Regulator	14	-34.63858	142.427	NA

* Chalka Creek-2 loggers not recovered; ¥ water depth at logger deployment position prior to water delivery.

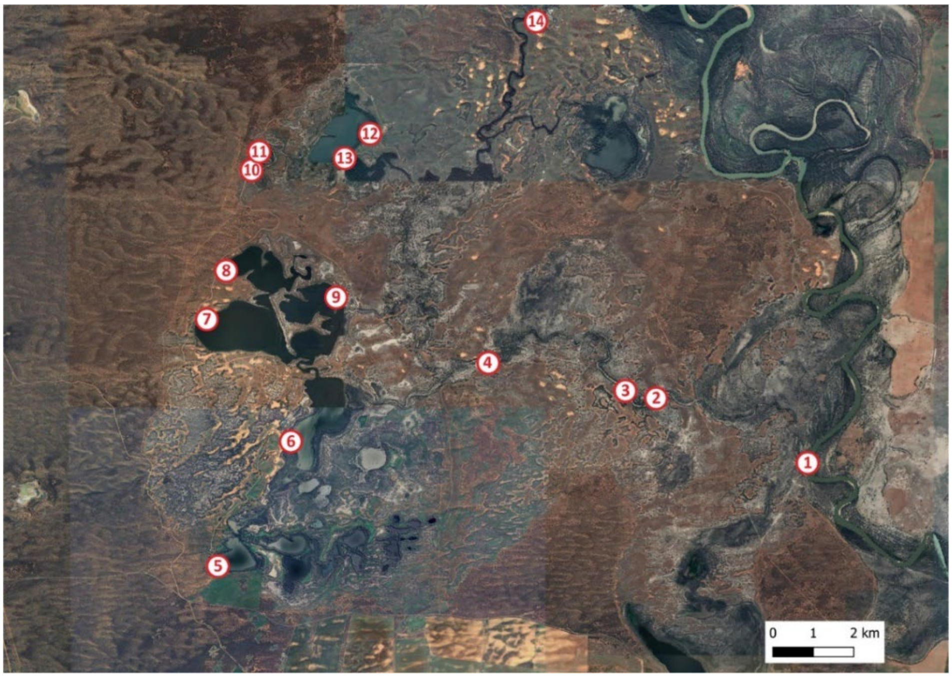

Figure 2. Map of Hattah Lakes National Park showing the location of logger sites used in this study; site names listed in Table 1.

FIELD SPOT MEASUREMENTS

Manual spot measurement of physico-chemical parameters, as well as water sampling for DOC analysis, occurred on five occasions over the study period adjacent to the logger stations; four (4) of these sampling occasions occurred during the planned delivery phase. Some sites were inaccessible for some of these sampling occasions (e.g., all of the Chalka Creek sites for the third sampling occasion). Physico-chemical parameters were measured using a YSI DSS Pro multi-probe meter, allowing the measurement of: pH, electrical conductivity, temperature, DO, DO saturation (DO-satn) and turbidity; data for water temperature, DO and DO-satn are shown in the main section of this report while all other water quality parameters are provided in See: Appendix 1. For lake depths less than 1 m, spot measurements were recorded from multiple locations adjacent to the logger station at approximately half lake depth. Where water depths at the logger sites exceeded 1 m, the sites were accessed by kayak, with spot measurements recorded at depth intervals of 0.5 m from the lake surface. For both approaches, spot data were averaged for each site, for each sampling occasion.

Water samples were collected using an integrated depth sampler (Perspex tube; 2 m length x 60 mm ID), providing a representative depth sample for comparison with the 2-D hydrodynamic model output. The collected integrated sample was transferred to a clean 10 L bucket (to allow mixing) and a 50 mL sub-sample collected for DOC analysis (filtered through 0.45 µm cellulose-acetate filter and collected into a 30 mL poly-carbonate vial). Triplicate water samples were collected from each site on each sampling occasion. DOC was measured in the laboratory as non-purgeable organic carbon (NPOC) by the combustion method using an Analytik Jena multi N/C 3100 analyser (DOC range: 0.1 – 100 mg C/L); this instrument also allows measurement of total dissolved nitrogen (TDN; range: 0.02 – 10 mg-N/L), reported in See: Appendix 1.

HYDRODYNAMIC-WATER QUALITY MODELLING

Modelling approach

The MIKE21 hydrodynamic and water quality model developed previously for the Hattah Lakes (Morales, 2022) was used in this work, with no modification of model characteristics (i.e., mesh characteristics, hydraulic structures, bathymetry, or water quality processes). Hydrodynamic and water quality components were decoupled to allow for faster computation with a 10 s step time for the numerical integration of rate processes.

Biogeochemical processes (reaeration rates, leaching rates, oxygen consumption rates) were based on previous models developed for the Hattah Lakes system, derived from both the Blackwater Risk

Assessment Tool (BRAT) model (Howitt et al, 2007) and later refinements of leaching rates for litter components (Holland et al, 2020). See: Appendix 2.

Water temperatures based on a model developed for the Murray River @ Barmah (Howitt et al., 2007); modelled temperatures were consistently lower than that measured for the simulation period, likely resulting in an underestimation of reaction rates for biogeochemical processes (i.e., leaching, oxygen consumption) and an overestimation of dissolved oxygen equilibration levels. The alternative use of measured water temperatures would have been computationally intensive and beyond the scope of this study.

The modelling period covered the 2022 water delivery phase as well as the direct connection period until 17 October 2022, just before the opening of the Cantala Regulator (Table 2).

Table 2. Simulation periods for the Hattah Lakes 2022 water event

Period	Description
15/08/22 – 21/09/22	Water delivery phase. Inflow through Messengers Pump.
21/09/22 – 26/09/22	Water retention phase. No inflows, no outflows.
26/09/22 – 29/09/22	Water release phase. Outflows through Messengers Regulator.
29/09/22 – 17/10/22	Water release phase. Outflows through Messengers and Oateys regulators.

Litter loads

Litter loads used in this work were based on a previous field survey conducted in 2019 (Holland et al., 2019). It is important to note that this previous survey was conducted after a period of 2 years without water delivery to the Hattah Lakes system. Subsequent to this survey a (managed) watering event occurred in 2021, with some water remaining in the lakes prior to the 2022 planned water delivery. Consequently, it was expected that the litter loads prior to the delivery of water in 2022 would be substantially lower than that measured in the 2019 survey. To account for this likelihood, several litter load scenarios were tested here, including:

Scenario A –100% of the vegetation litter loads from 2019

Scenario B – 50% of loads in areas wet at the start of the simulation; 100% loads elsewhere.

Scenario C – 25% of loads in areas wet at the start of the simulation; 100% loads elsewhere.

Scenario E – 15% of loads everywhere.

Scenario F – 0% loads in areas wet at the start of the simulation; 15% loads elsewhere.

The litters loads for barks, grass, leaves and twigs, corresponding to scenario F, are shown in Figure 3.

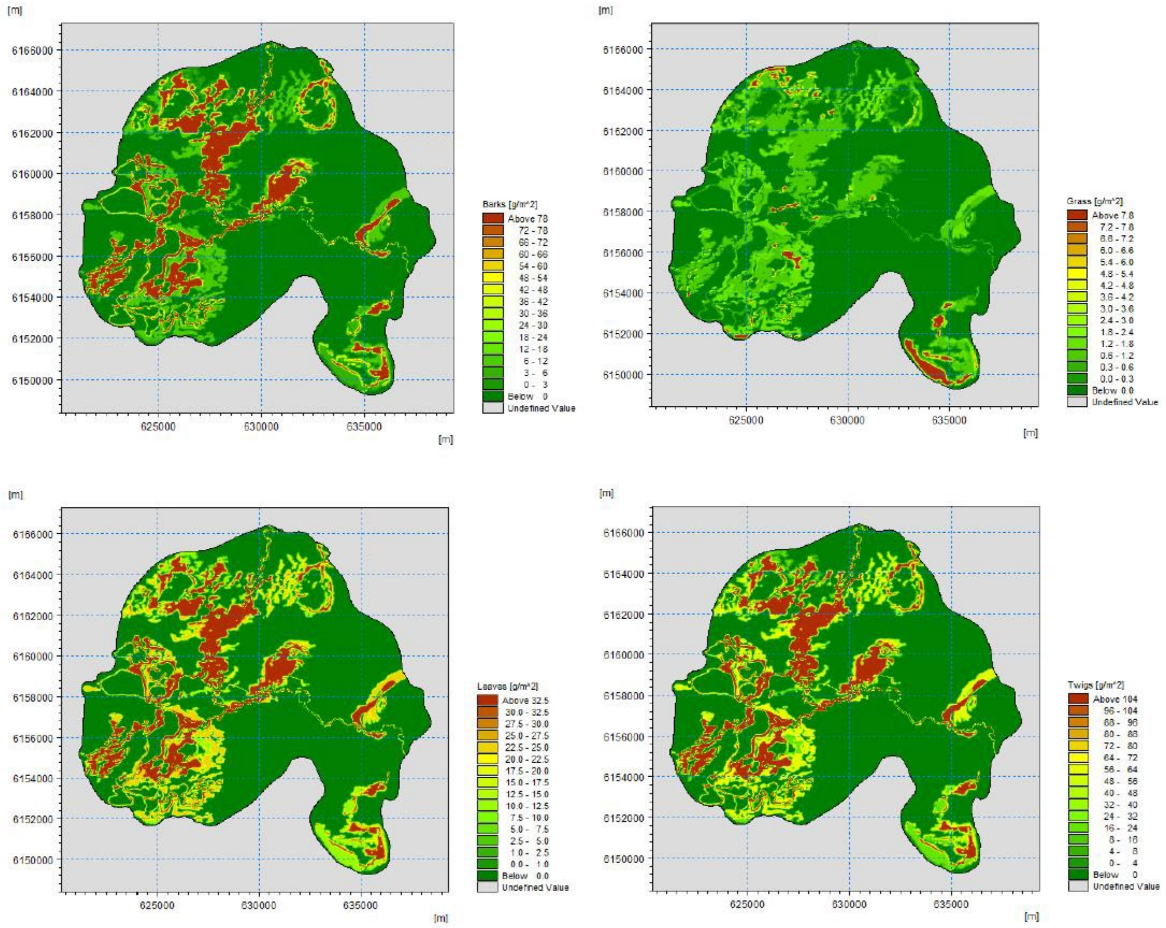

Figure 3. Litter loads for the Hattah Lakes corresponding to scenario F (0% 2019 litter loads in areas wet at the start of simulation; 15% 2019 litter loads elsewhere).

Initial conditions

A water surface elevation layer representing the hydrological status of the system prior to water delivery was created using bathymetry data, water level data from telemetry as well as data from MCMA water quality monitoring. (See: Appendix 2).

Initial DOC and DO levels were based on spot measurements recorded as part of this study over the period 16-18 August 2022, interpolated to the model mesh. This interpolated DOC level was used for simulations A-E only; for simulation F the initial DOC level was set to zero to simulate the effect of the standing DOC stock having very low oxygen demand (discussed below). See: Appendix 2.

Boundary conditions

During the water delivery period, inflows to the lake system were taken to be the volumes delivered through Messengers pumps (See: Appendix 2) with the downstream regulators (Oateys and Cantala) set to 'closed'. During water release Messengers regulator was set to 'free outflow' and Cantala set to closed. Oateys regulator was tested under both a free outflow assumption and using the measured water height data; better simulation of the northern portion of the lakes area was achieved using measured water height data.

DOC time series were taken from River Murray @Chalka and Oateys regulator sites from spot measurements collected as part of this work. Upstream DO time series data were taken from both spot measurements at the River Murray @Chalka site (this study) and telemetry data from the River Murray@Colignan site. Downstream DO data were from spot measurements and logger data at Oateys regulator; for Cantala regulator a default value of 10 mg/L was used.

RESULTS AND DISCUSSION

INFLOWS TO HATTAH LAKES SYSTEM

The delivery of water to the Hattah lakes system initially occurred as a managed event (delivered 29,110 ML; target 35,000 ML) to achieve a lake height of 43.5 m AHD, however near the end of the managed delivery period a natural flood event upstream of Hattah lakes resulted in a direct connection between the River Murray and the Hattah Lakes. The lake heights during this natural connection period were substantially higher than that for the planned inundation (exceeded 45.5 m AHD). The period of the planned delivery of water to the Hattah lakes system was 17-August-2022 to 22-September-2022 (called: ***planned water delivery*** period); opening of the regulators, due to high discharge in the River Murray, occurred over the period 27-Sept-2022 to 1-Nov-2022 (fully open) and remained open for several months (called: ***direct connection*** period).

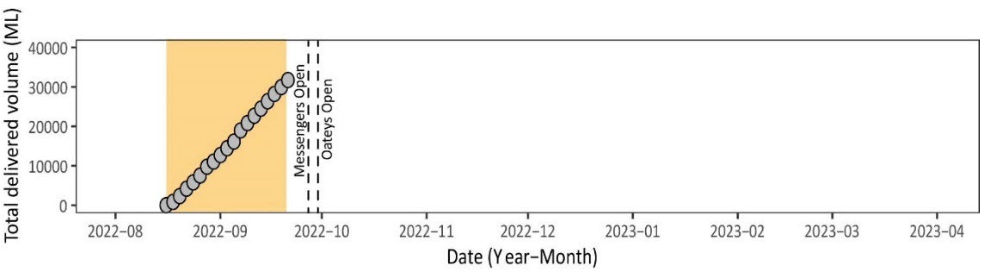

Figure 4. Total volume of water delivered to the Hattah Lakes systems during the planned water delivery period (shaded). Also shown are the dates of opening of Messengers and Oateys regulators.

The hydrodynamic modelling was originally planned for both the lake filling and lake draining periods, however, due to the natural connection with the River Murray and the prolonged connection period, the lake draining period could not be modelled.

LOGGER AND SPOT MEASUREMENT DATA

Logger data for dissolved oxygen and temperature was obtained from all field sites over the period 14-August 2022 – 3 March 2023. Spot measurements of water quality were recorded on five (5) occasions over this period, largely during the water delivery period; water samples for dissolved organic carbon (DOC) analysis were also collected at these time points. Shown in the following figures are the logger data for: water temperature (°C), dissolved oxygen concentration (DO; mg-O_2/L), dissolved oxygen saturation (DO-satn.; %), along with spot measurement of these parameters as well as laboratory measurements of DOC concentrations. Spot data generally showed excellent agreement with logger data for T, DO and DO saturation. Lake heights (or river discharge) are also shown, where available (either from existing telemetry stations or from Trutrack loggers temporarily installed as part of this study).

River Murray @ Chalka Creek

A strong depletion in DO (and DO saturation) was observed in the River Murray (@ Chalka Creek) between August 2022 and November 2022, corresponding to increasing river discharge and likely associated with upstream floodplain inundation. Over the period of the planned water delivery to the Hattah Lakes system, DO saturation levels decreased from ~100% to ~80%, indicating that oxygen depleted water was being supplied to the lake system before opening of the regulators and the direct connection with the River Murray. DOC concentrations also increased over the water delivery period, consistent with that expected from the leaching of floodplain litter from upstream sources.

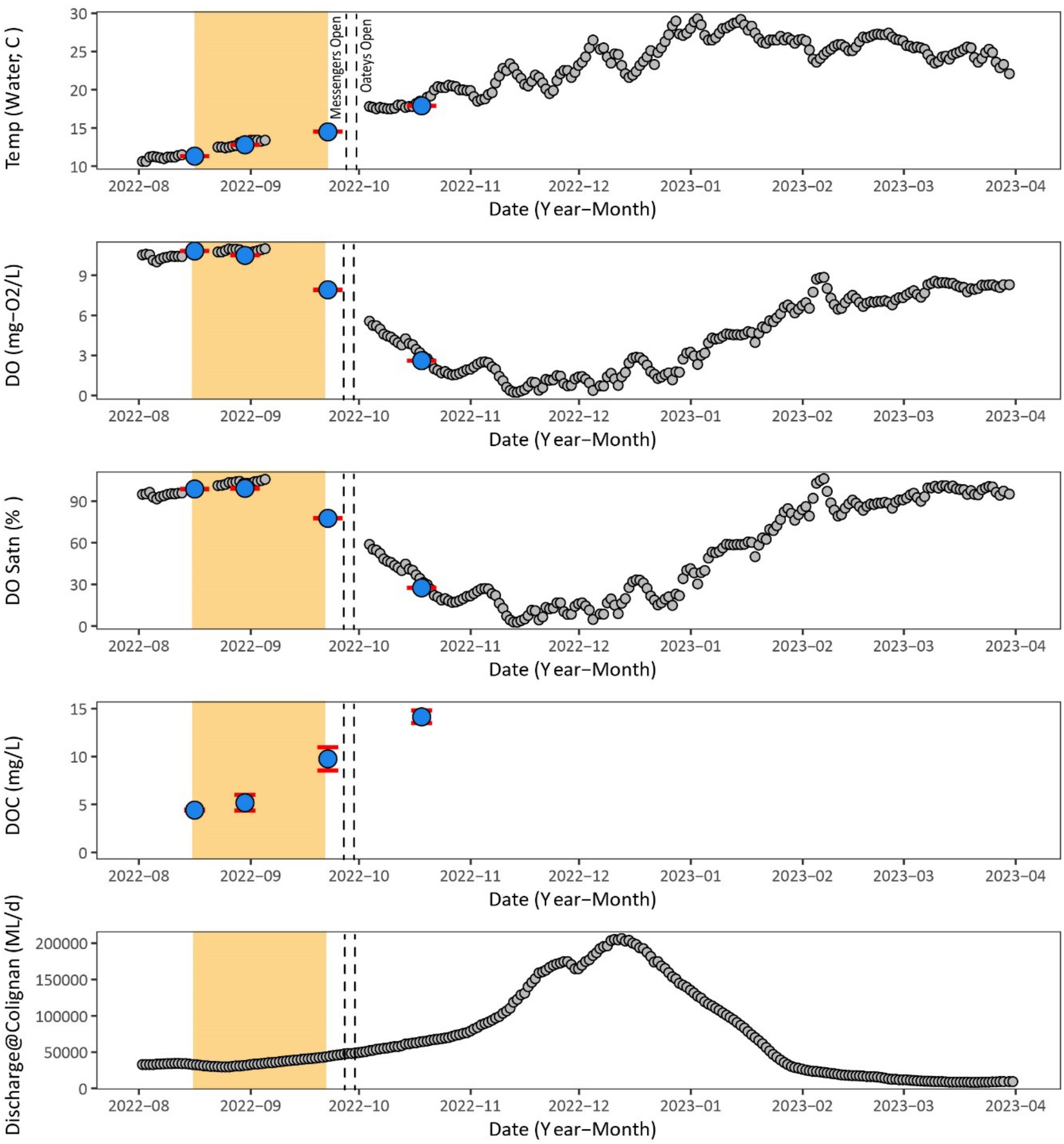

Figure 5. Water quality measurement from in-stream loggers (DO and T; River Murray @ Colignan; low reliability data removed) and spot measurements (T, DO, DO-satn., DOC; River Murray @ Chalka Creek) over the period 1-August-2022 to 31-March-2023. Also shown are river discharge values for the River Murray @ Colignan over this same period. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Chalka Creek – Site 1

DO and DO-satn values at the Chalka Creek-1 site largely mirrored that observed for the River Murray, as expected given their close proximity. Over the water delivery period the DO saturation values decreased from ~100% to ~90%. A stronger DO depletion event was observed at this site near the end of the delivery period (between 21-Sept-2023 and 26-Sept-2023), corresponding to the period between the planned delivery and direct connection periods, and suggesting a relatively strong DO drawdown in the absence of inflow water from the River Murray. During the direct connection period, the Chalka Creek-1 site was relatively more oxygenated than the River Murray (ranging: 10 – 50 %).

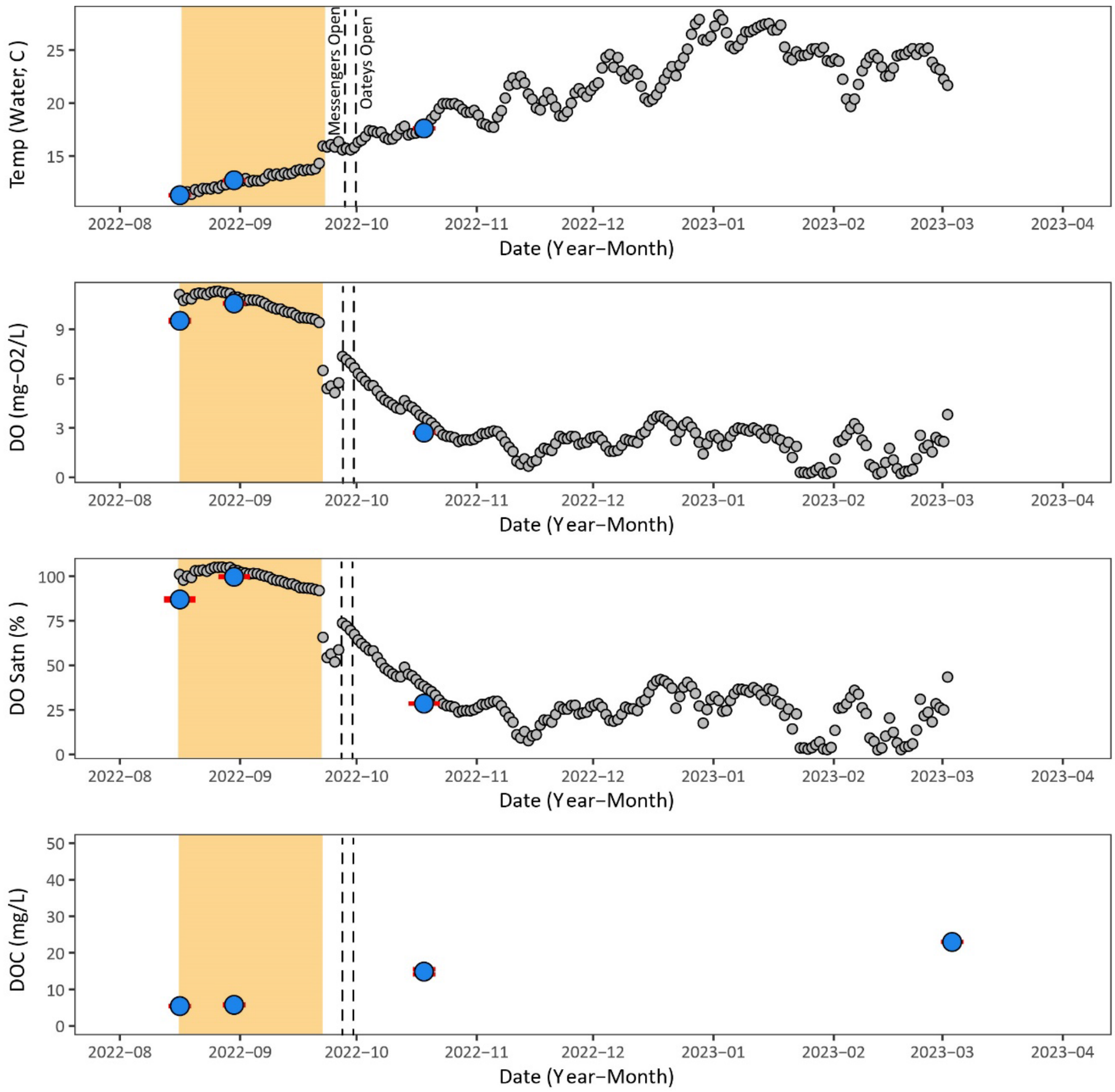

Figure 6. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Chalka Creek – 1 site, over the period 1-August-2022 to 3-March-2023. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Chalka Creek – Site 3

DO and DO-satn values at the Chalka Creek-3 site were similar to that observed at Chalka Creek-1, with DO-satn values decreasing from ~90% to ~80% over the planned delivery period. The brief DO depletion event observed at Chalka Creek-1 at the end of the planned delivery period was much weaker, suggesting that re-oxygenation occurred between the two sites. DO satn levels during the direct connection period generally ranged between 20 – 40 %, but with some brief excursions to levels less than 10%.

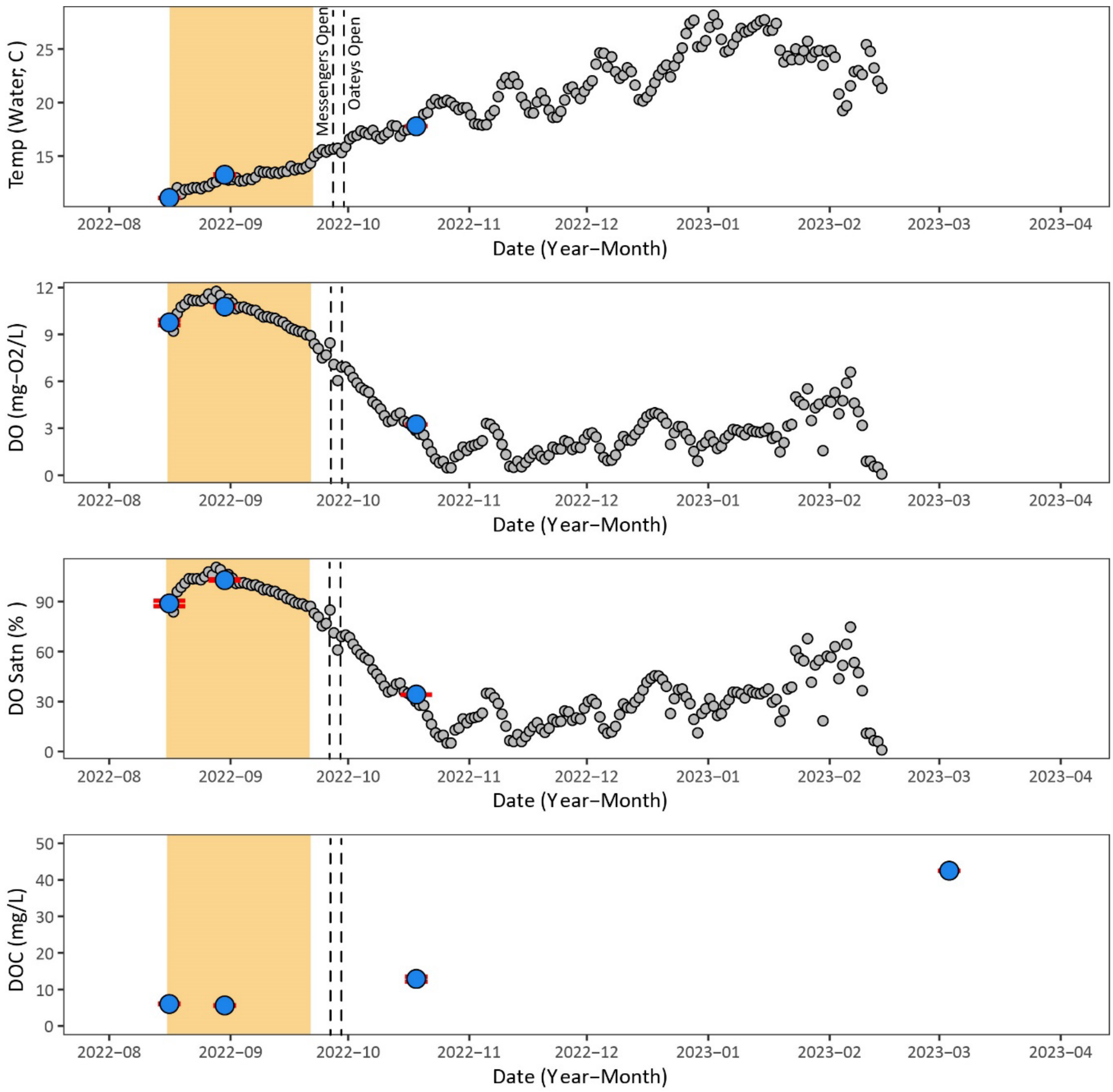

Figure 7. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Chalka Creek – 3 site, over the period 1-August-2022 to 3-March-2023. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Hattah

DO and DO satn values remained effectively static at the Lake Hattah site during the planned delivery period, in the range 75 – 90%, suggesting that the DO depleted water supplied from the River Murray (via Chalka Creek) over this period was re-oxygenated within the lake system. Much stronger DO depletion was observed during the direct connection period, particularly between December 2022 – January 2023 when DO concentrations (and saturation) were extremely low.

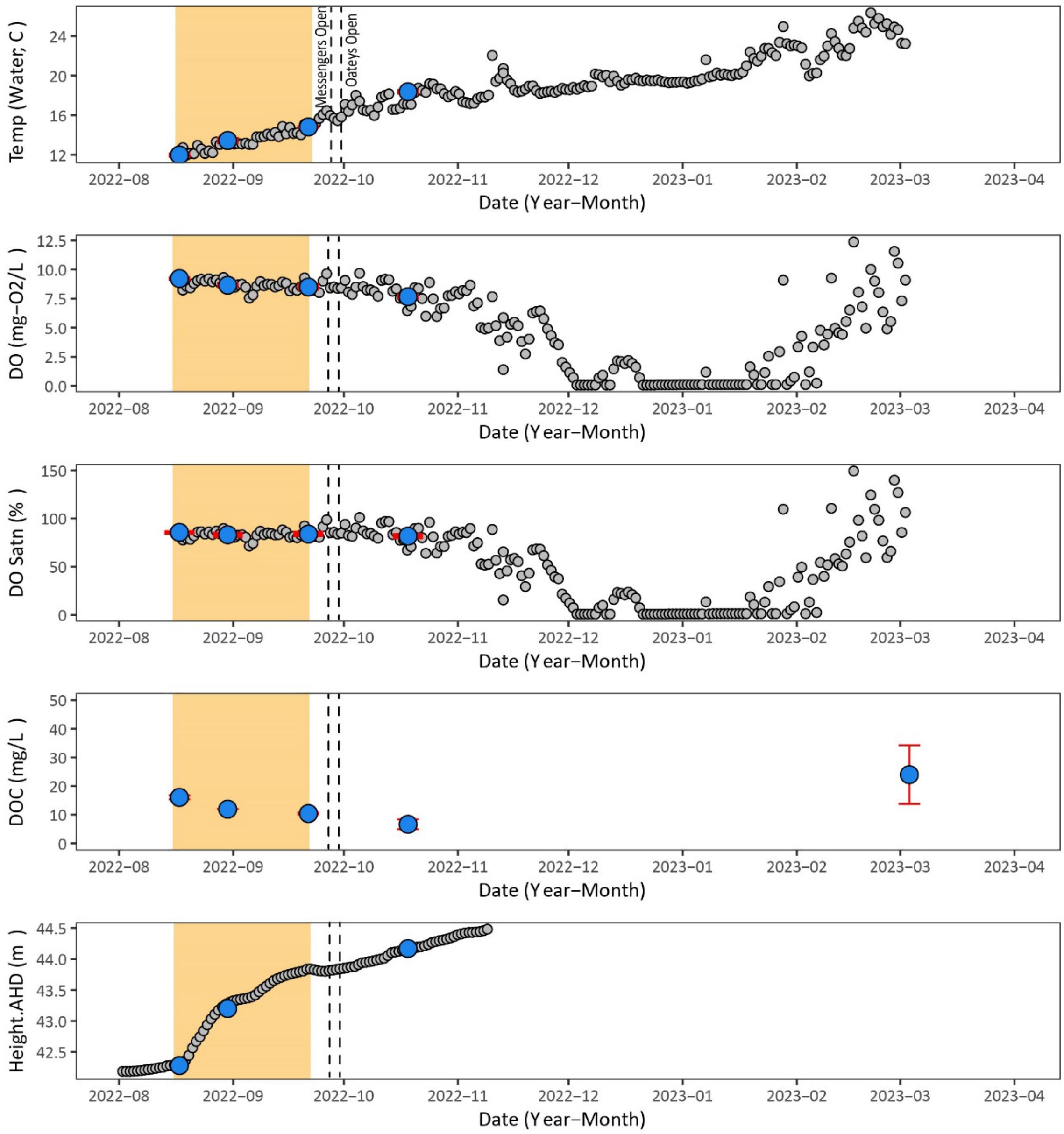

Figure 8. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Hattah site, over the period 1-August-2022 to 3-March-2023. Also shown are lake telemetry data for the permanent telemetry station. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Lockie

DO and DO-satn values increased slightly at Lake Lockie over the planned delivery period, changing from ~95% to ~100%. This contrasts with the DO depletion observed for the Chalka Creek sites and suggests that much of the water delivered from Chalka Creek over this period was re-oxygenated during transit through Chalka Creek, or within the lake itself. As observed in Lake Hattah, much stronger DO depletion was observed during the direct connection period, with DO satn values <20% over the period December 2022 – January 2023 coinciding with the period of maximum lake height.

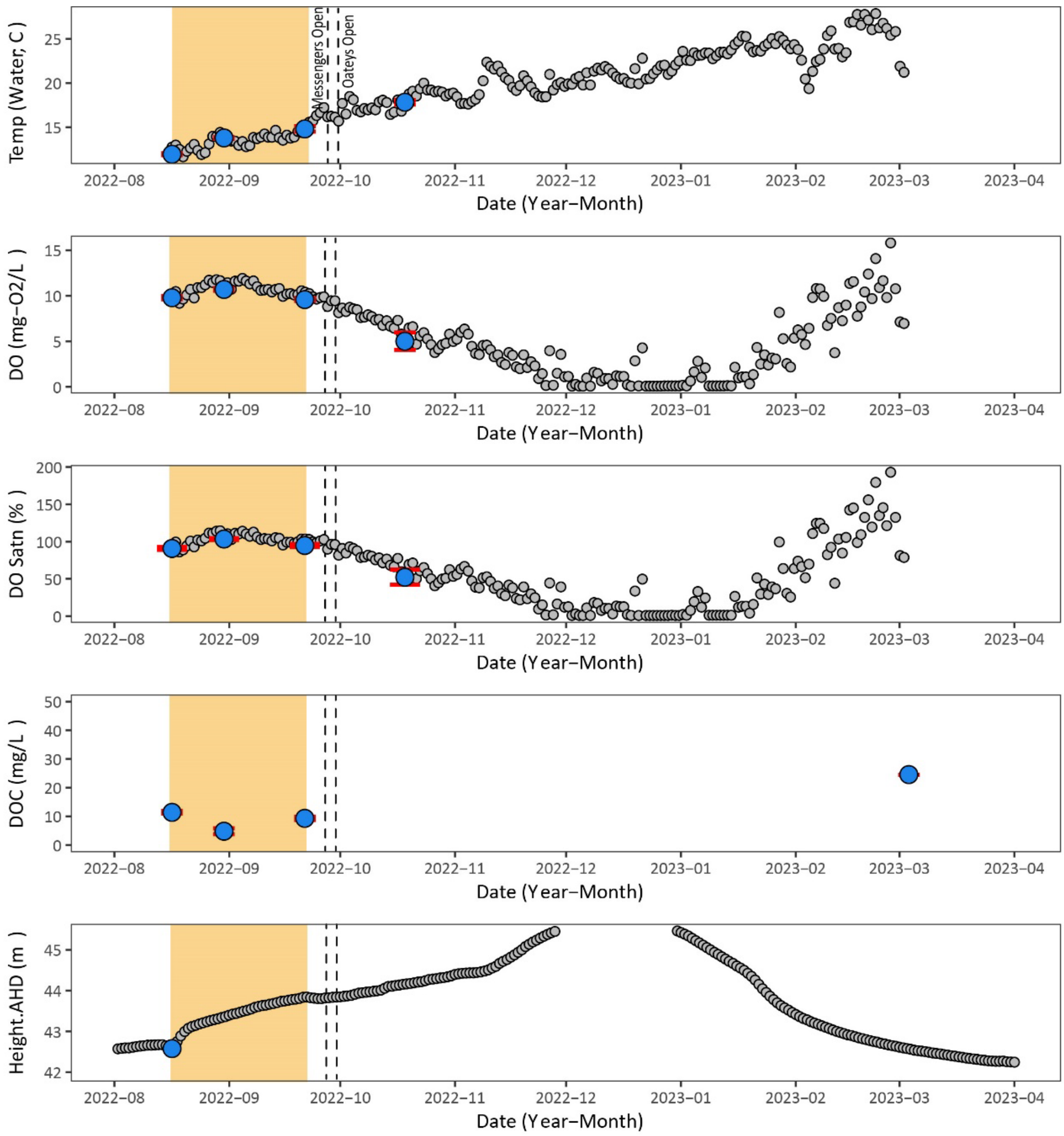

Figure 9. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Lockie site, over the period 1-August-2022 to 3-March-2023. Also shown are lake telemetry data for the permanent telemetry station (heights >45.5 m removed). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Mournpall

DO and DO satn values at Lake Mournpall decreased weakly over the planned delivery period, changing from ~85% to ~80% DO-satn. As observed for other lake systems, much stronger DO depletion occurred during the direct connection period, between December 2022 and January 2023.

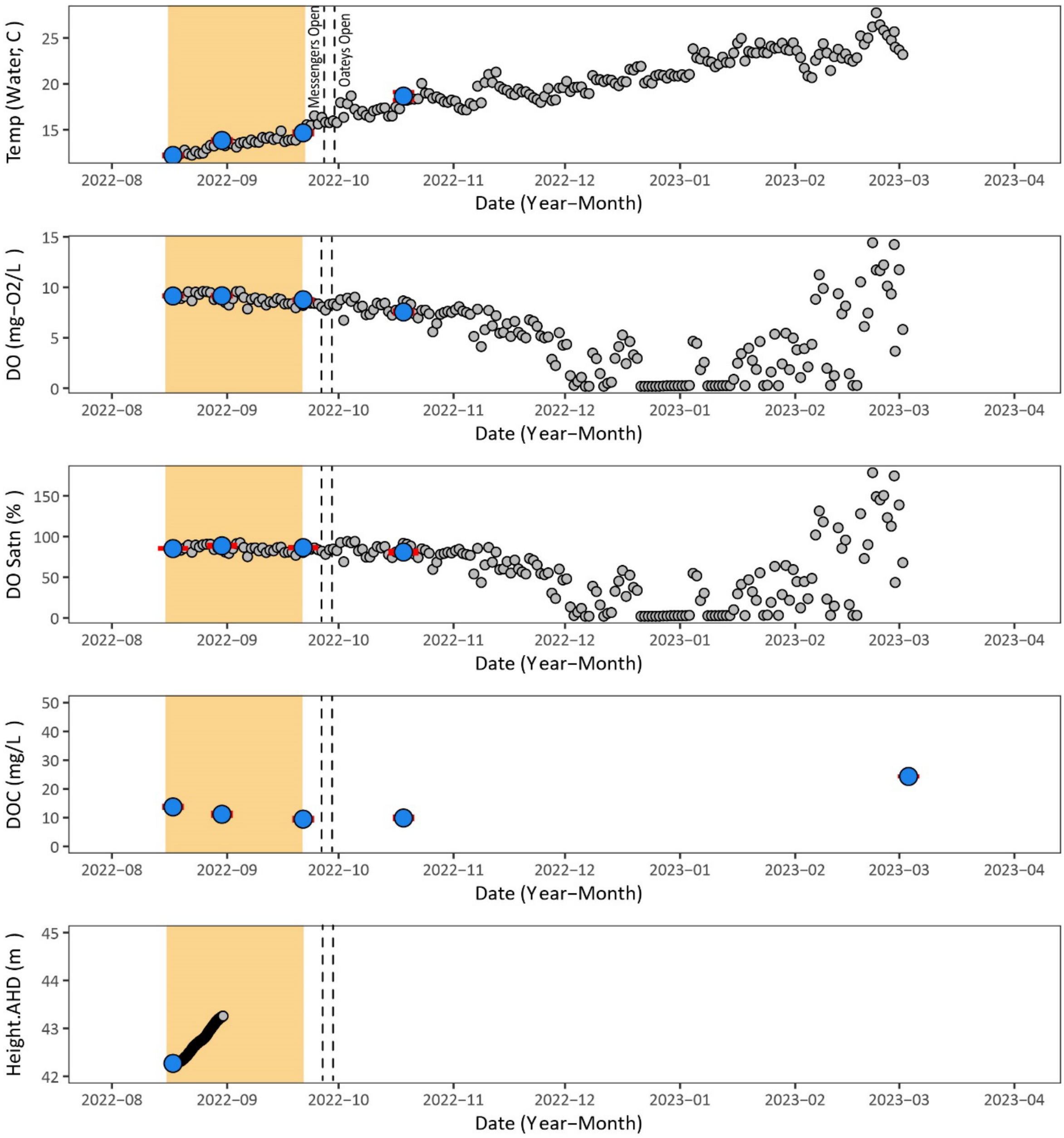

Figure 10. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Mournpall site, over the period 1-August-2022 to 3-March-2023. Also shown are lake height data for the Trutrack logger deployed at this site (15-August- 2022 to 31-August-2022). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Konardin

Relatively strong DO depletion was observed at Lake Konardin over the water delivery period, with DO satn changing from ~120% (oversaturated) to ~70% and the onset of DO depletion corresponding closely with the commencement of lake filling. Much stronger DO depletion occurred during the direct connection period, with lowest values observed between December 2022 and January 2023.

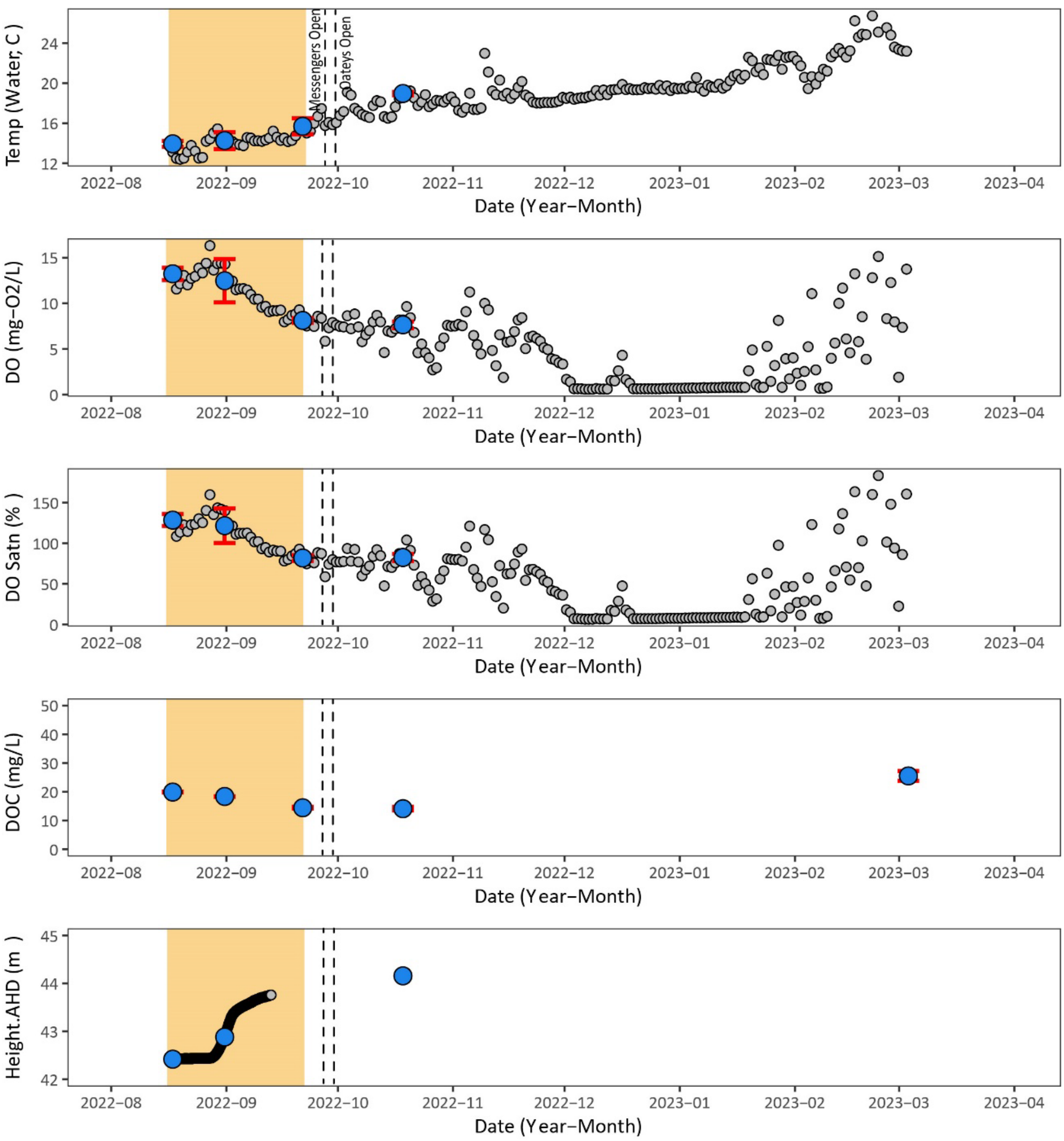

Figure 11. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Konardin site, over the period 1-August-2022 to 3-March-2023. Also shown are lake height data for the Trutrack logger deployed at this site (15-August- 2022 to 31-August-2022). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Yelwell

Moderate DO depletion occurred at Lake Yelwell over the water delivery period, with DO satn values decreasing from ~95% to ~80%. Much stronger DO depletion occurred during the direct connection period, particularly between December 2022 and January 2023.

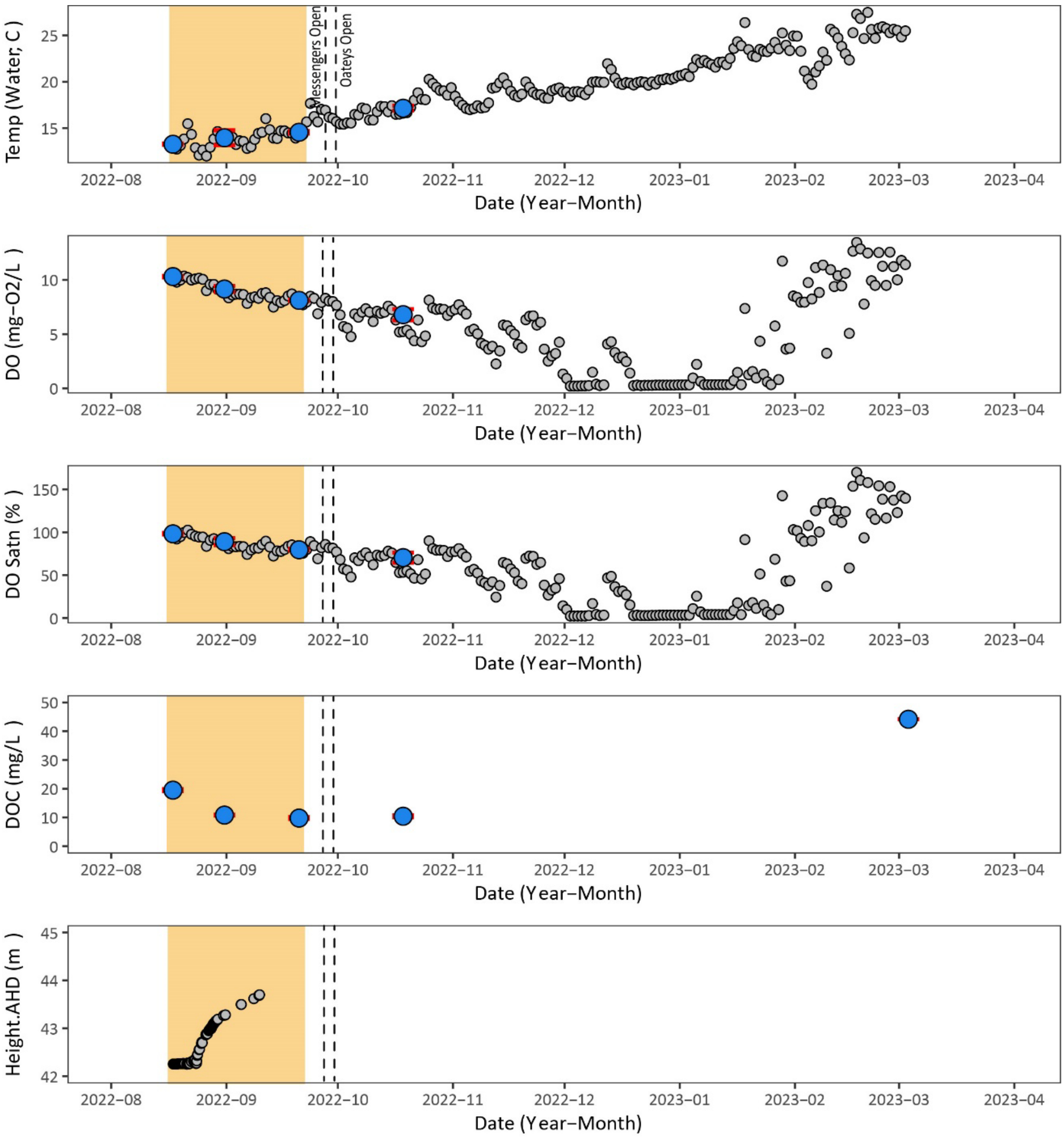

Figure 12. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Yelwell site, over the period 1-August-2022 to 3-March-2023. Also shown are lake height data for the Trutrack logger deployed at this site (15-August- 2022 to 10-September-2022). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Woterap – South

DO concentrations and saturation levels initially increased at the Lake Woterap South site during the water delivery period. This increase was likely due to lake processes as the delivered water did not reach lake Woterap until mid-September. Upon receiving water, the DO saturation decreased from ~70% to ~40% over the remainder of the water delivery period. As observed for other lakes, much stronger DO depletion occurred during the direct connection period, with effectively zero DO during the period December 2022 – January 2023.

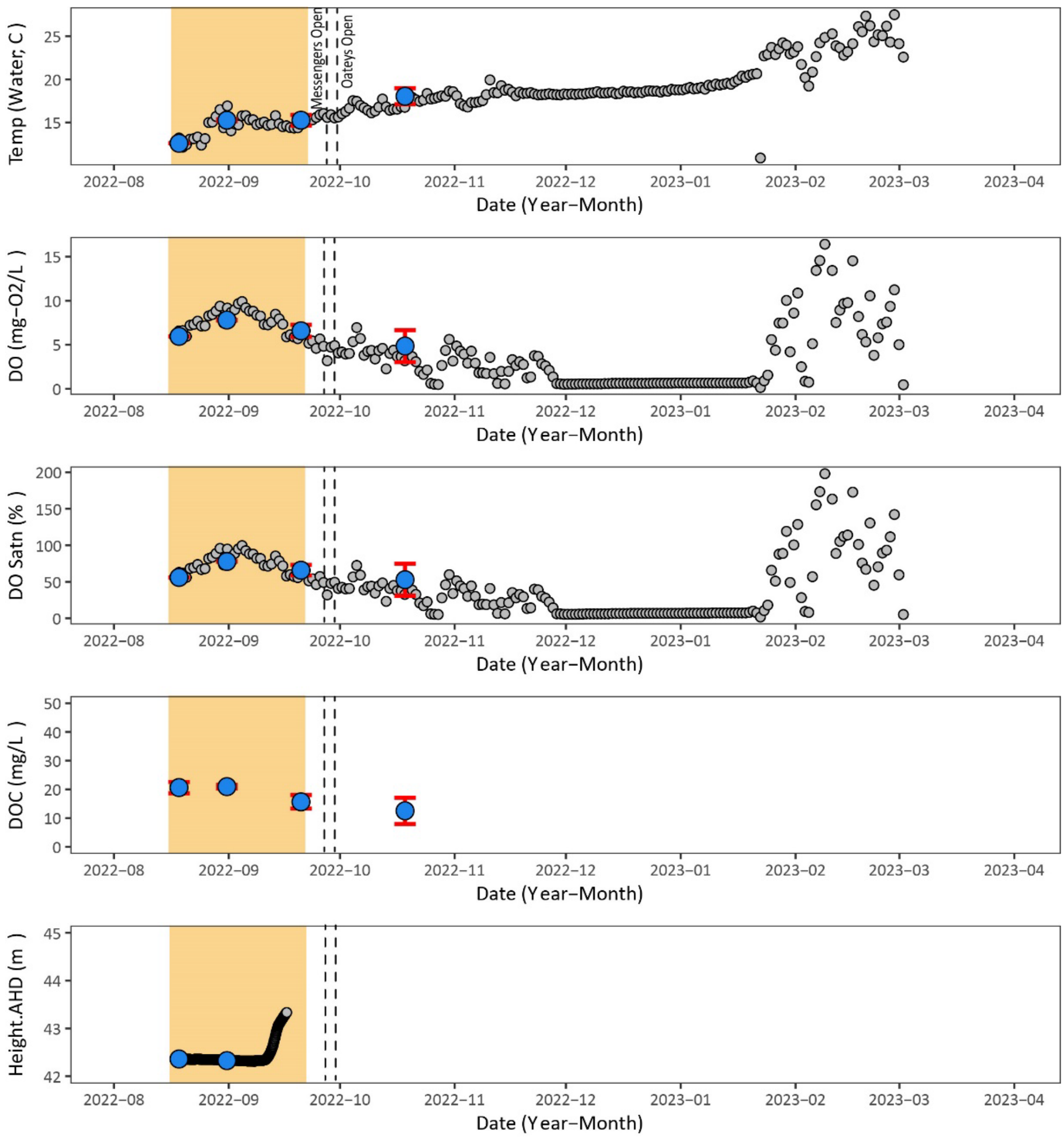

Figure 13. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Woterap-South site, over the period 1-August-2022 to 3-March-2023. Also shown are lake height data for the Trutrack logger deployed at this site (15-August- 2022 to 15-September-2022). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Woterap – North

The DO and DO-satn behaviour at Lake Woterap-North site was very similar to that observed for Lake Woterap South, with an initial re-oxygenation prior to the arrival of planned delivery water, followed by a depletion of DO during the planned delivery period (~50% to ~35%). A very strong depletion of DO during the direct connection period (December 2022 – January 2023).

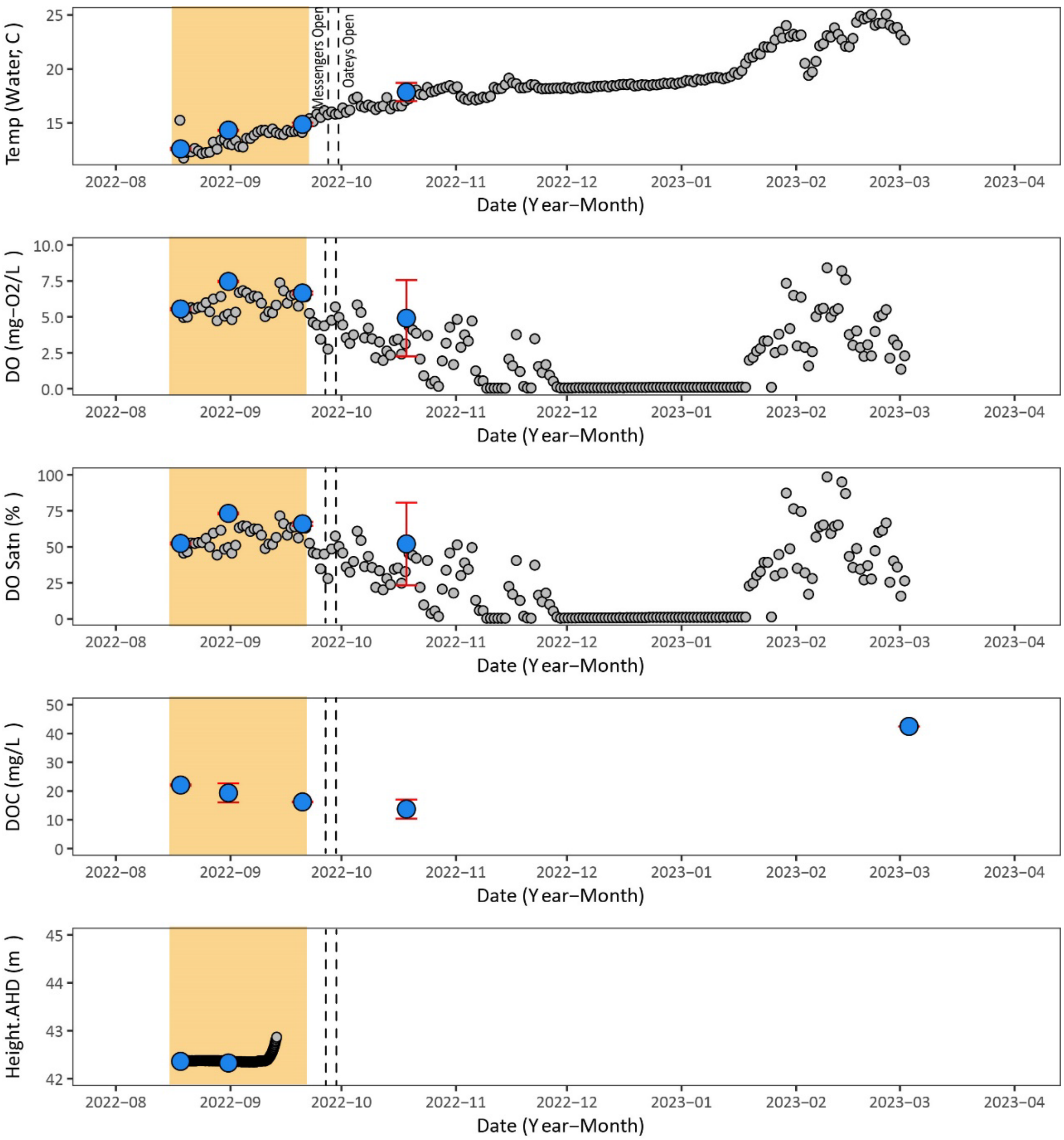

Figure 14. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Woterap-North site, over the period 1-August-2022 to 3-March-2023. Also shown are lake height data for the Trutrack logger deployed at this site (15-August- 2022 to 15-September-2022). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Bitterang – North

Prior to receiving delivered water, the Lake Bitterang North site showed high variability in DO and DO saturation, with DO-satn values as high as 200%. While this may have been associated with a logger malfunction, very similar behaviour was observed at the Lake Bitterang South site, suggesting a lake process (i.e., algal growth) to be a more likely cause. After receiving delivered water, DO-satn values at this site decreased from ~105% to ~65%. Stronger DO depletion was observed during the direct connection period, particularly during the period December 2022 to January 2023, coinciding with maximum lake height.

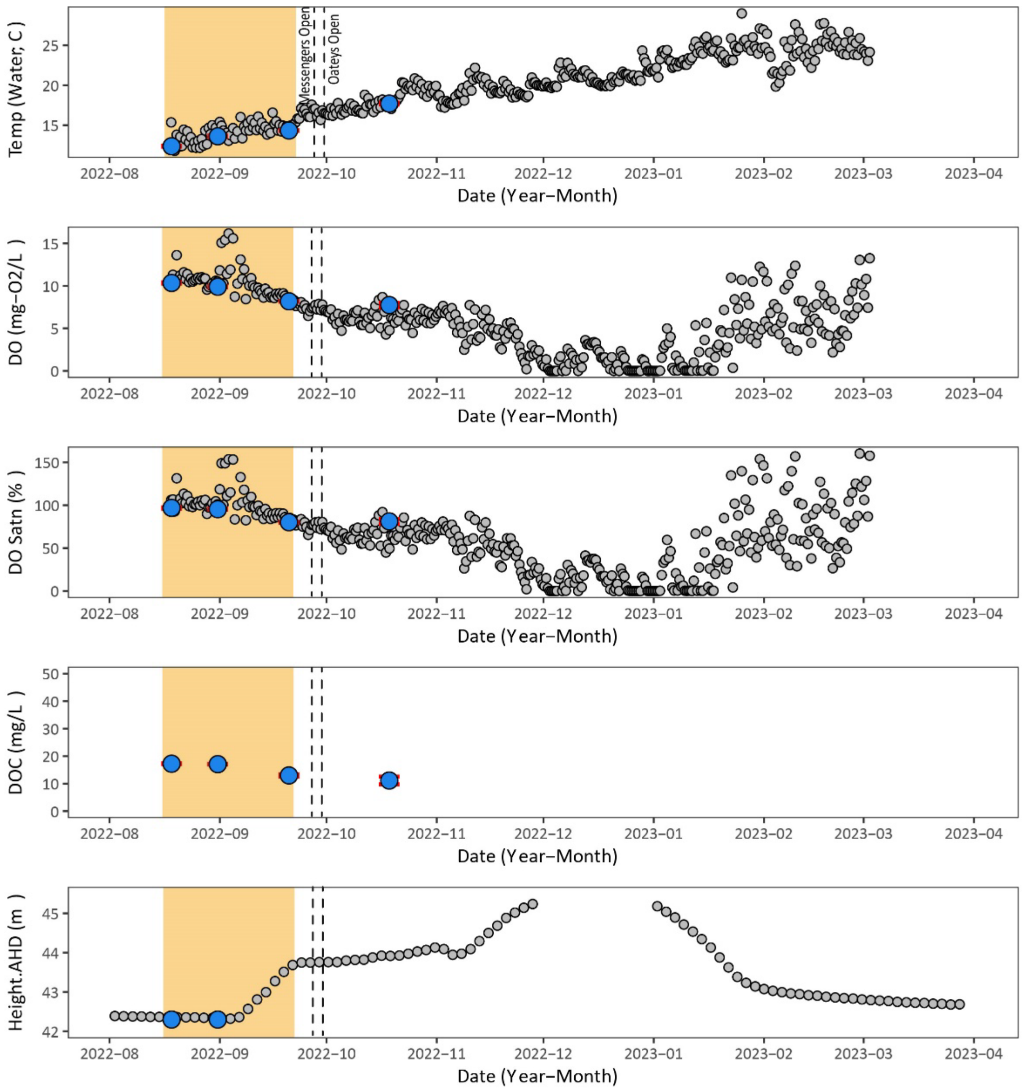

Figure 15. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Bitterang-North site, over the period 1-August-2022 to 3-March-2023. Also shown are lake telemetry data for the permanent telemetry station (heights >45.5 m removed). Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Lake Bitterang – South

The behaviour of DO (and DO saturation) at the Lake Bitterang South site was very similar to that observed for Lake Bitterang North, with highly variable DO levels prior to receiving water, followed by a relatively strong depletion of DO (~105% to ~70%) during the remainder of the water delivery period; maximum DO depletion occurred during the period of maximum lake height (December 2022 – January 2023).

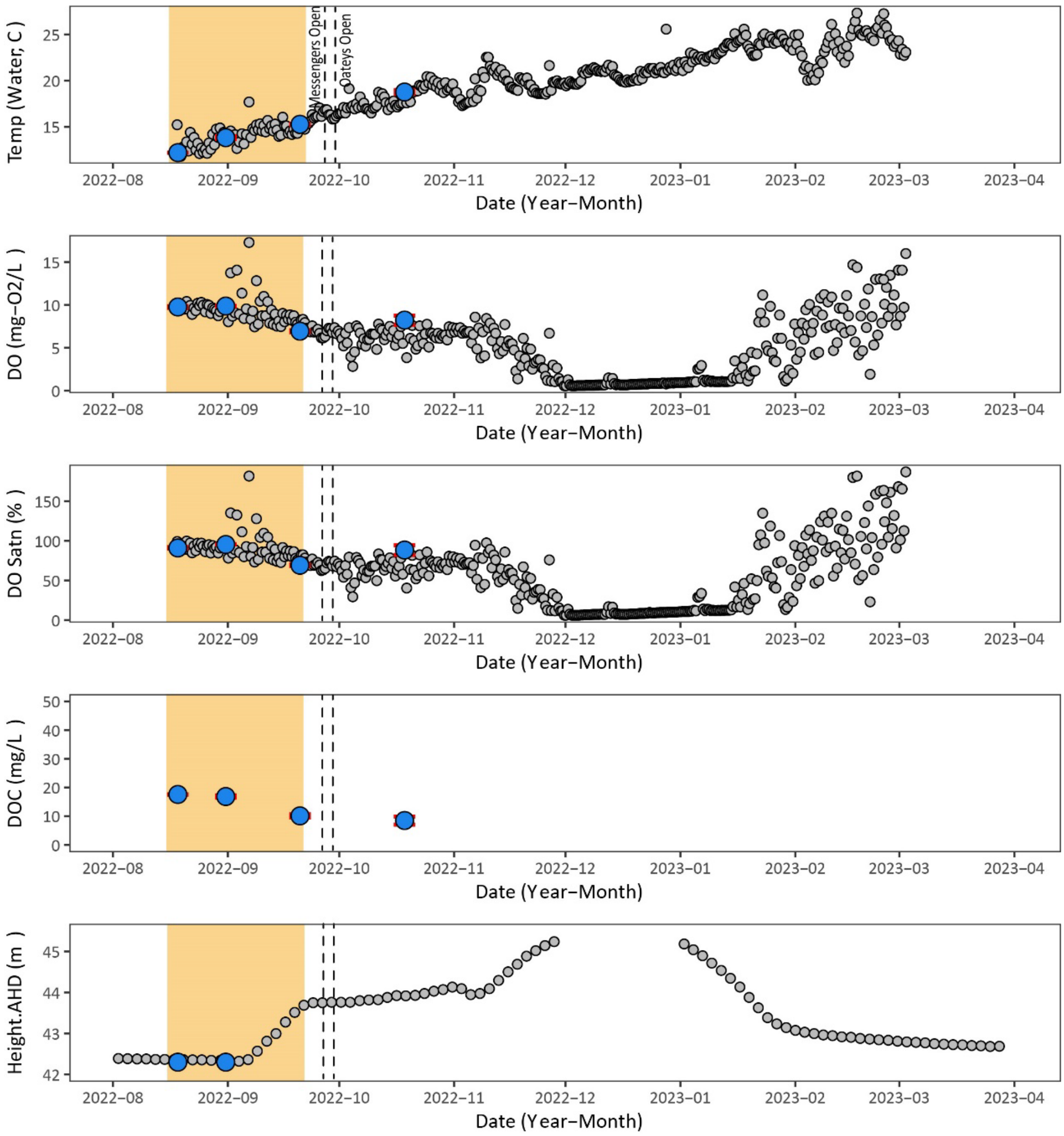

Figure 16. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Lake Bitterang-South site, over the period 1-August-2022 to 3-March-2023. Also shown are lake telemetry data for the permanent telemetry station (heights >45.5 m removed. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

Oateys regulator

Strong depletion of DO was observed at Oateys regulator over the water delivery period, with DO decreasing from ~100% to ~50%. Over the direct connection period the DO-satn levels were in the range 10 – 50 %, with generally higher values that observed in lake sites over this same period. The agreement between logger and spot data was generally poorer than all other sites for DO (and DO-satn), possibly reflecting higher local variations in the concentrations of DO.

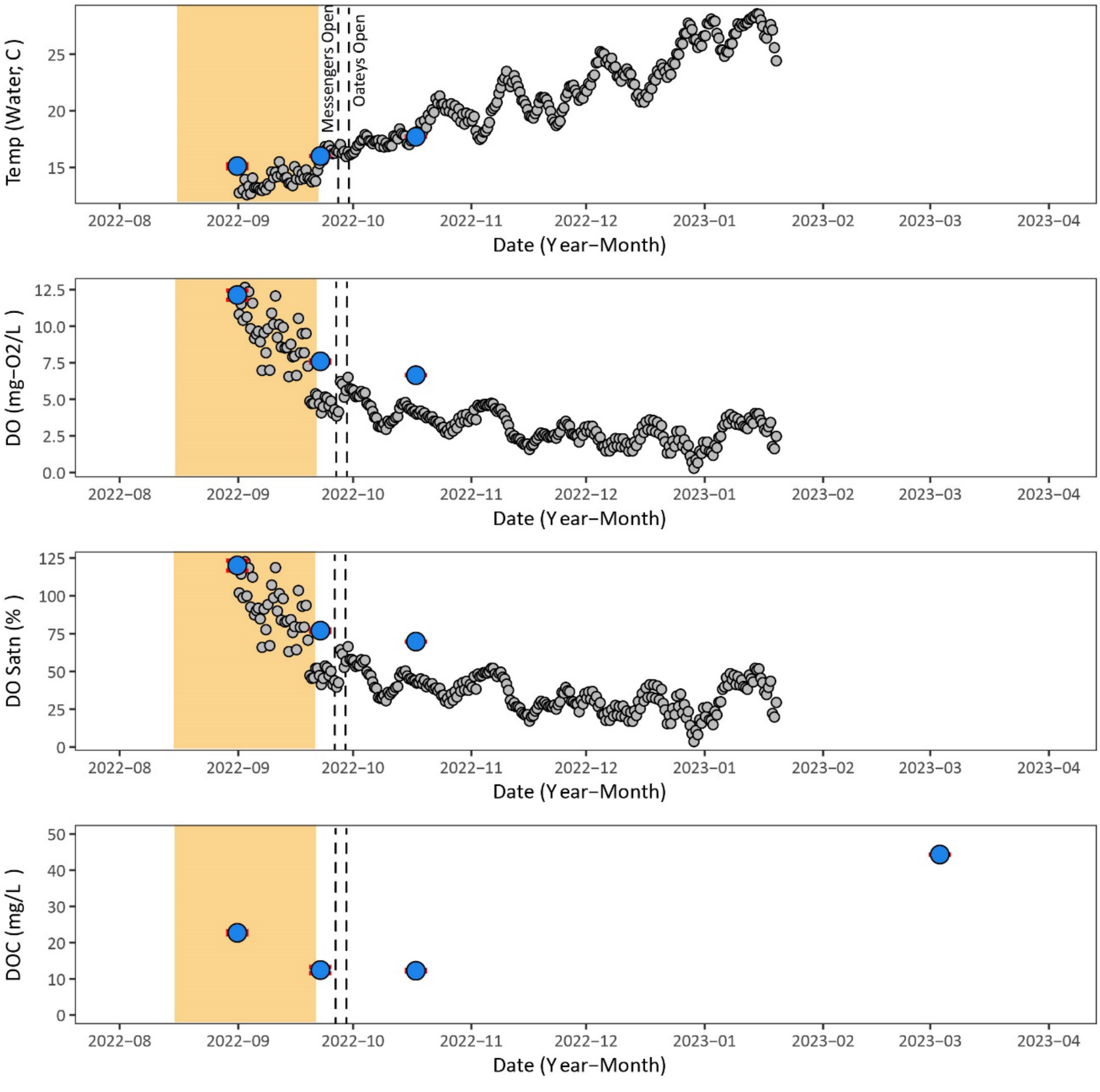

Figure 17. Water quality measurement from deployed loggers (DO and T) and spot measurements (T, DO, DO-satn., DOC) for the Oateys regulator site, over the period 1-August-2022 to 3-March-2023. Also shown are lake telemetry data for the permanent telemetry station. Error bars correspond to ± 1SD. Shaded area shows the period of planned water delivery; dashed lines show the opening of the Messengers and Oateys regulators.

SUMMARY OF LAKE RESPONSES TO WATER DELIVERY

Lake fill order

Lake height data from fixed telemetry stations was available for some lakes (Hattah, Lockie & Bitterang); at all other lake sites Trutrack water height loggers were installed as part of this study. These lake height data allowed the date of commencement of lake filling to be determined, with the arrival of planned delivery water assumed to be the date at which the lake height started to increase (Table 3). This 'fill order' reflects the hydrological path for water flows in Hattah lakes system, and shows that the lakes Lockie, Mournpall, Hattah and Yelwell received water relatively rapidly (within the first week), while lakes Konardin, Bitterang and Woterap received water after a longer delay period; up to 24 days delay for the most hydrological distant site in this study (Lake Woterap).

Table 3. Lake fill order for the lakes used in this study. Delay (days) refers to time delay between start of water delivery (17-August-2022) and commencement of lake height increase. * Both Lakes Mournpall and Hattah commenced filling within the second day of water delivery

Site name	Fill order	Delay (days)
Lake Lockie	1	0
Lake Mournpall	2*	1
Lake Hattah	2*	1
Lake Yelwell	3	5
Lake Konardin	4	11
Lake Bitterang	5	20
Lake Woterap	6	24

Dissolved oxygen levels – water delivery period

The sensitivity of the lakes investigated in this study to the delivery of water was assessed from the change in DO saturation prior to receiving water and at the end of the water delivery period (36 days later). The date at which water arrived at each lake was based on the delays listed in Table 3, while the end of the water delivery period was taken to be the date 36 days later. DO saturation levels at the beginning and end of the planned delivery period are shown in Figure 18a; the change in DO saturation is shown in Figure 18b.

All sites, except Lake Woterap, were highly oxygenated prior to water delivery, with saturation levels typically >80% and many close to ~100%. Despite DO depletion occurring in the River Murray over the planned delivery period (100% to 80%), very little depletion of oxygen was observed at the Chalka

Creek sites or the lakes that had a short hydrological path (Table 3); in fact, some sites showed increased DO saturation over this period (lakes Hattah and Lockie). By contrast, the hydrologically distant lakes, showed stronger DO depletion over this same period, with the lowest DO saturation levels observed at Lake Woterap (as low as ~35%).

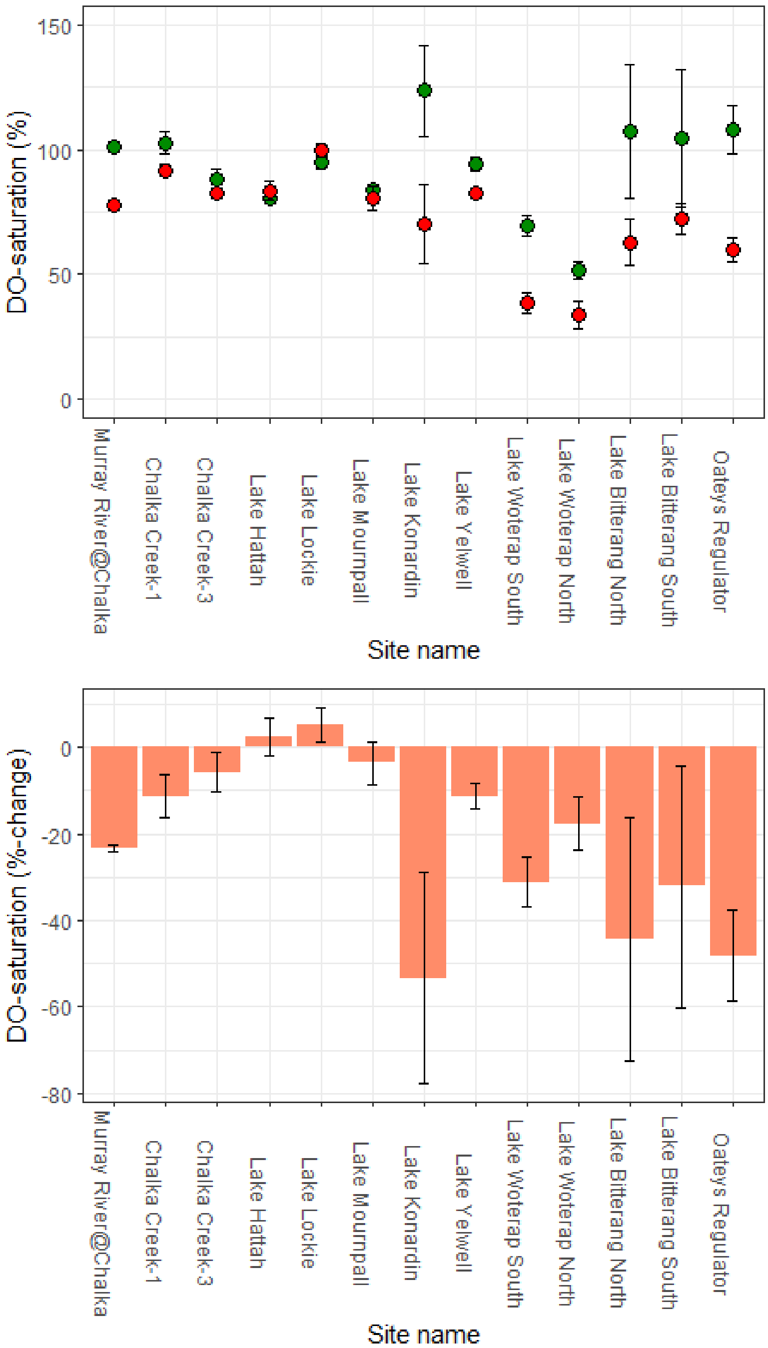

Figure 18. Change in dissolved oxygen saturation over planned delivery period between date of arrival of delivered water to each site (refer Table 2) and end of water delivery (36 days later). Part (a) shows initial (green) and final (red) DO-saturation values (averaged over 24 hours); part (b) shows the net change in DO saturation at each site. Error bars correspond to ± 1SD.

Given that the water provided through Chalka Creek remained relatively oxygenated during the planned delivery period (despite DO depletion in the River Murray; Figure 18), any depletion of oxygen in the lakes system over this period is likely to be due to lake processes. DO depletion was most pronounced in the hydrologically distant lakes and suggests either higher litter loads at these lakes or longer hydraulic retention times, being the likely cause of the observed DO depletion.

Dissolved oxygen levels – direct connection period

Much stronger DO depletion occurred during the direct connection period, with all lakes showing extremely low DO levels during the period: early-December 2022 to mid-January 2023. This DO depletion occurred slightly later than in the main channel of the River Murray (mid November 2022 – end December 2022). Minimum DO levels in the lakes closely matched the period of maximum lake height and suggests two contributing factors: (i) the supply of water from the River Murray that was already depleted in oxygen, and (ii) in-situ lake processes (litter leaching and oxygen consumption) placing further oxygen demand on the water column. This increased oxygen demand was likely exacerbated by higher temperatures during maximum lake height (Whitworth, 2014). Unfortunately, no water sampling was possible during maximum lake height period to confirm the expected higher concentrations of dissolved organic carbon during this period.

HYDRODYNAMIC-WATER QUALITY MODELLING

For the planned delivery period, the hydrodynamic models closely matched that observed for lake heights, except in the case of the Lake Bitterang where an increase in lake height was predicted to occur earlier than observed. During the direct connection period, the use of measured water levels at Oateys regulator gave better simulation of lake levels for all of the northern section of the lakes system compared to that using a ‘free outflow’ assumption. The simulated spatial extent of inundation closely matched that derived from satellite imagery. See: Appendix 2.

Four (4) litter load scenarios (scenarios A – E) were tested for the first two weeks of the planned water delivery period, allowing comparison with the first two spot measurement occasions. For all simulations an initial DOC pulse was predicted, the magnitude of which increased with litter load. Observed DOC levels were best simulated by lower litter loads: scenarios C (25% 2019 values) and scenario E (15% 2019 values) See: Appendix 2. Despite the reasonable agreement between modelled and observed DOC values for these scenarios, predicted DO levels were much lower than that observed, suggesting a far lower oxygen demand than expected for the observed DOC levels; this was particularly the case for lakes more distant from Messengers regulator.

The most likely reason for the observed weaker DO drawdown than predicted is that the existing pool of DOC in the lakes prior to the planned delivery did not have the same oxygen demand as freshly leached DOC; this ‘standing stock’ of DOC can be considered ‘exhausted’ from the point of view of biodegradability. To compensate for the low reactivity of the pre-existing DOC pool, a modelling approach was tested where only the freshly leached DOC was assumed to place an oxygen demand. This approach was used with scenario F, corresponding to litter loads of 0% of 2019 values in wet areas and 15% of 2019 values in dry areas. Under these conditions only the newly wetted areas contributed to oxygen demand. A comparison of the predicted DO profiles for scenarios E (15% 2019 values) and scenario F are shown in Figure 19 for the sites included in this study. In most cases, the observed DO profiles were between that predicted by the two scenarios, but more generally closer to that predicted by scenario F. There are a number of factors that may contribute to the differences between DO levels predicted by these scenarios and that observed, including: (i) the standing stock of DOC likely places some oxygen demand on the water column (as opposed to the assumption of zero oxygen demand for scenario F), (ii) the assumption of uniform litter load reductions (15%) across the lake system is likely an oversimplification with higher variability between lakes depending on previous wetting history, and (iii) other lake processes may influence DO levels (e.g., water temperature, algal photosynthesis and respiration processes) and are not simulated by the modelling approach.

Figure 19. See caption (below)

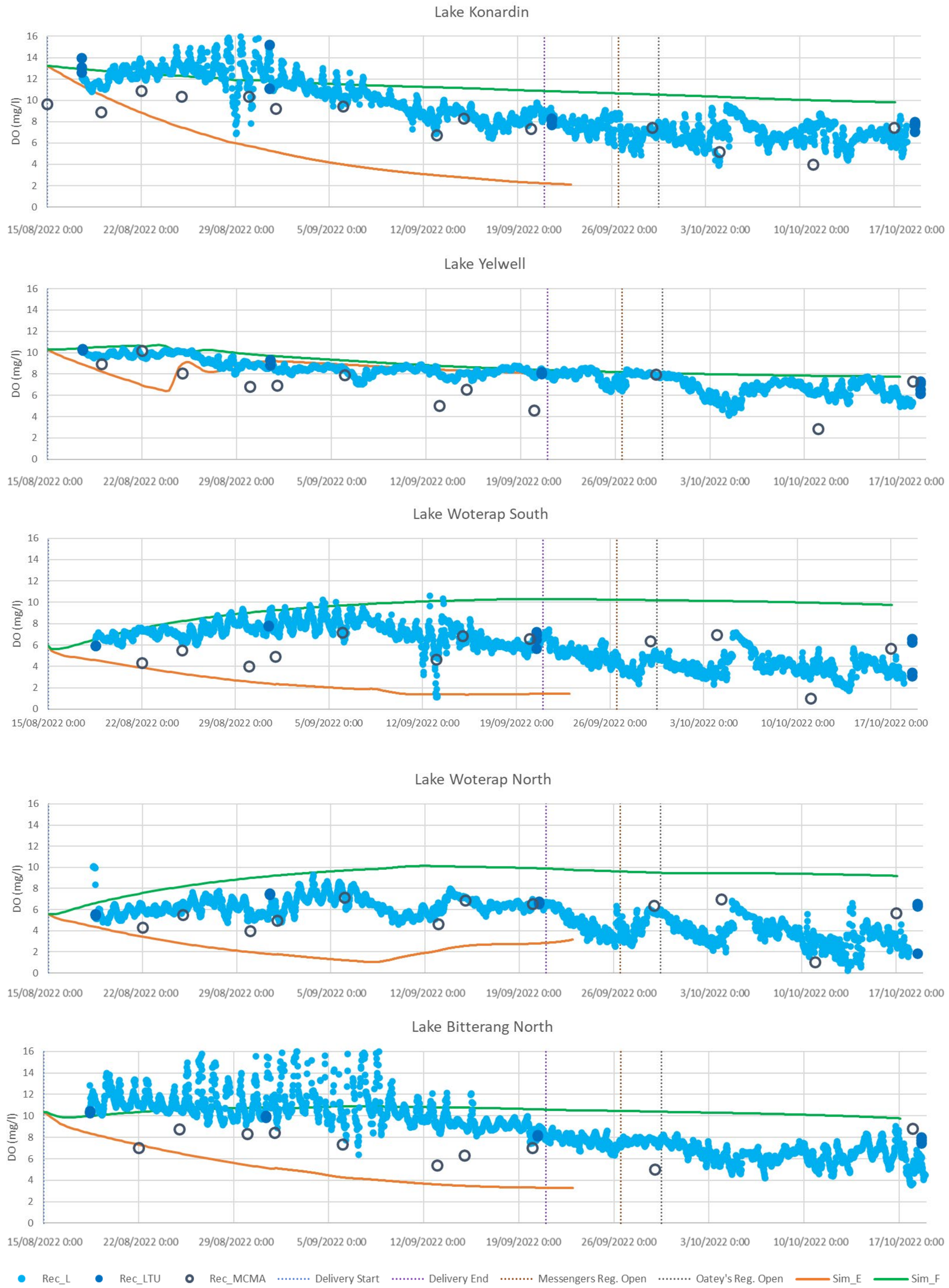

Figure 19. See caption (below)

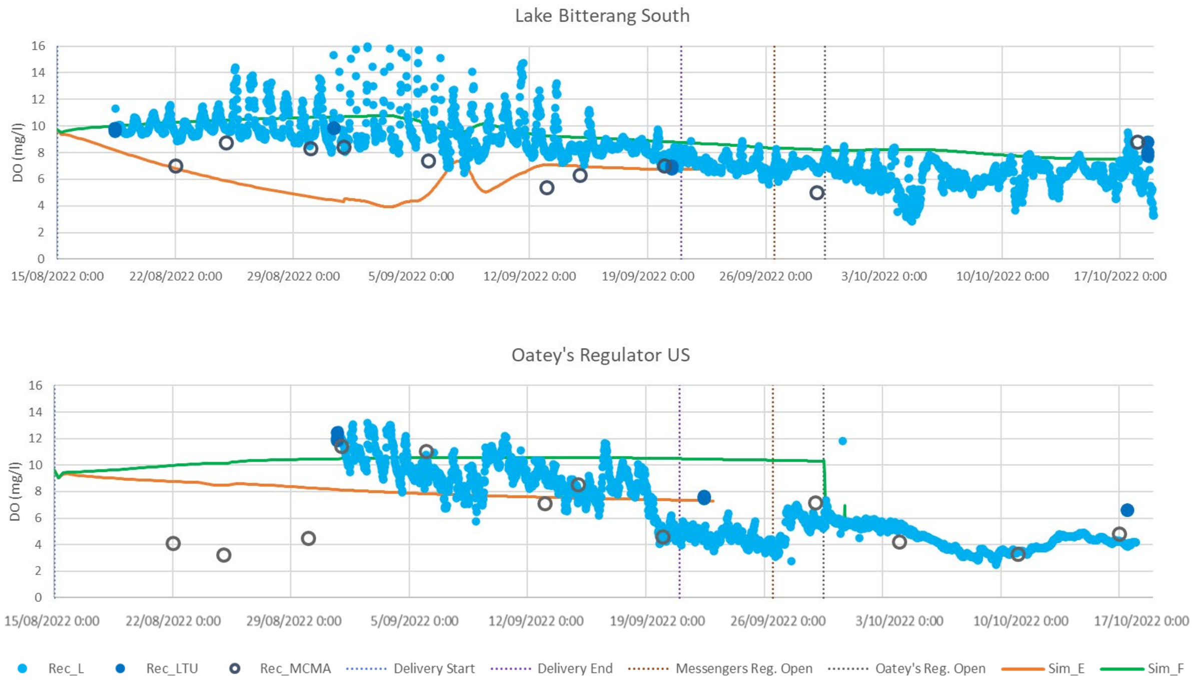

Figure 19. Simulations of dissolved oxygen levels for the period 15-August-2022 to 17-September-2022 at Hattah Lakes sites. Shown are: simulations using scenarios E (Sim_E: 15% of 2019 litter loads) and F (Sim_F: 0% of 2019 litter loads in wet areas; 15% of 2019 litter loads in dry areas; pre-existing pool of DOC assumed to have zero reactivity). Also shown are spot measurement data (Rec_LTU: this study; Rec_MCMA: Mallee CMA), DO logger data (Rec_L) and key time points over the simulation period.

IMPLICATIONS FOR DELIVERY OF WATER TO HATTAH LAKES

The planned water delivery occurred during the winter-spring period. This is the same timing as natural in-flows and likely mimics the timing for lake watering events prior to regulation of the River Murray. The delivery of water at this time of year minimises the risk of hypoxia forming due to lower microbial respiration rates (lower temperatures). The 2022 planned delivery of water had very little impact on DO levels for the sites with short hydrological paths from the River Murray (Chalka Creek and immediately adjacent lakes). Significant DO depletion was only observed in more hydrologically distant sites, possibly due to the pick-up of DOC during the long flow path length, the longer residence time of water in the affected lakes and/or higher litter loads in these lakes. If the intention of the planned delivery was to provide a ‘watering event’ without the detrimental effects of DO depletion, then the planned delivery was very successful. Clearly more frequent watering of the hydrologically distant lakes would further decrease the risk of DO depletion at these sites.

The direct connection of the Hattah lakes with the River Murray resulted in very strong DO depletion at all sites. The timing of this depletion matched the period of minimum DO levels in the main channel, but also coincided with maximum lake heights and occurred during summer months. It is likely that the combination of all of these factors led to the prolonged period of DO depletion, lasting as long as 2 months at some sites. Reoxygenation of the lakes coincided with the lowering of lake heights (draining phase) and the transition into cooler conditions.

The biogeochemical-hydrological model used in this work was successful in describing the lake hydrology during the planned delivery period, with some minor differences in the timing of water arrival at the more northern lakes. The testing of a range of litter load scenarios suggests that the available carbon in the litter prior to the planned delivery period was far lower than that determined by field survey in 2019 (Holland, 2020). Further, the DO levels were most closely simulated by a model where it was assumed that the standing stock of DOC placed no oxygen demand on the water column (and no available litter remained within the wetted areas prior to water delivery). The composition of DOC is very complex, including a range of bioavailable and recalcitrant organic molecules. The low abundance of bioavailable DOC in the standing stock of DOC in the lake system prior to water delivery is a reasonable assumption for DOC that was leached up to a year prior to the 2022 planned water delivery.

While the responses of DO to the planned water delivery were generally between that predicted by scenarios E and F, the majority of sites more closely matched DO levels corresponding to scenario F. The exceptions to this were lakes: Konardin, Woterap and Bitterang, where a stronger DO depletion occurred upon arrival of water, suggesting that the assumption of 15% of 2019 litter loads in the dry areas of these lakes was an underestimate of the available litter. The estimation of available litter remains the most challenging aspect of predicting the response of these lake systems to planned (or unplanned) water delivery. In particular, the estimation of changes in litter load over time through litter accumulation (i.e., leaf fall) and changes in response to wetting events likely becomes increasingly unreliable over longer periods of time since last surveyed. The modelling performed in this work suggests that significant reduction in litter loads have occurred since 2019 survey (Holland et al., 2020), although the extent of this decrease is likely highly variable across the Hattah lakes system.

CONCLUSIONS

This study was conducted to investigate the effects of a planned water delivery to the Hattah lakes system with respect to dissolved organic carbon (DOC) and dissolved oxygen (DO) levels, and whether these responses could be modelled using a hydrodynamic-biogeochemical model previously developed for this system. The planned water delivery occurred as scheduled but was closely followed by an unplanned connection with the River Murray due to upstream flooding. The responses of the Hattah lakes to both the planned and unplanned water delivery periods was monitored through spot measurements of physical parameters and DOC as well as deployed DO loggers.

Dissolved oxygen depletion during the planned water delivery period was weak at all sites with short hydrological distances from the water delivery point (Messengers regulator); DO depletion was stronger in the more hydrological distant sites, possibly due to either the pick-up of DOC during transit, the poor connectivity (longer residence times) of these sites and/or higher litter loads. In general, the observed DOC and DO responses during the planned delivery phase suggest that the Hattah lakes had a relatively low risk of oxygen depletion for the lake heights targeted for the 2022 planned delivery. This conclusion is supported by the modelling of these data which suggests that the oxygen demand of the standing stock of DOC in the lakes prior to water delivery was very low, and that the available DOC from litter wetted by the planned delivery was much lower than that measured by field survey in this system in 2019.

Much greater depletion of oxygen in the Hattah lake sites occurred during the direct connection period, likely due to a number of factors, including: (i) delivery of water from the River Murray that was already depleted in DO, (ii) very high lake heights, leading to inundation of lake areas with high litter loads that had not received water in recent years, and (iii) high water levels coinciding with summer (hotter) months, resulting in higher leaching and DO consumption rates. The opportunity in this study to capture both a planned and unplanned delivery to the Hattah lakes system has clearly demonstrated that while the risks of DO depletion can be managed at a local scale for planned deliveries of water, the risks associated with unplanned deliveries are much harder to manage.

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Appendix 1. Spot measurement data (provided as an electronic file)

Appendix 2. Water technology Report: Hattah Lakes DOC-DO Modelling (4-August-2023; provided as an electronic file)