Limnological Investigations of Fly River Floodplain Waterbodies: February & July 2005

<u>**Final Report Prepared for**</u>

Ok Tedi Mining Ltd

by

Wetland Research & Management

March 2006

Limnological Investigations of Fly River Floodplain Waterbodies: February & July 2005

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Frontispiece: …Taking water column water quality measurements in Kiunga Oxbow (OXB01) in February 2005 using the Hydrolab (photo: A. Storey).

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Executive Summary

As part of a broader study of ORWB ecology, a stratified sampling regime was established to investigate temporal and spatial variation in oxbow limnology and dissolved metal concentrations. Sampling was conducted at 9 oxbows in total, each encompassed within one of three exposure levels: exposed, incorporating Kuambit, Oxbow 2, Oxbow 5 and Oxbow 6; unimpacted control, incorporating Moian, Kiunga (Oxbow 1) and Drimdenasuk; and impacted blocked valley lakes, incorporating Bosset Lagoon and Lake Daviumbu. Sampling of oxbows was carried out during the wet and dry seasons 2005, and considered changes in water quality parameter profiles at different depths within the water column. Water temperature and dissolved oxygen were recorded at 10 minute intervals over 24 hrs using electronic data loggers, and indicated varying degrees of thermal stratification. Distinct thermoclines were detected in the majority of oxbows, with the exception of Bosset Lagoon, which appeared to maintain isothermal characteristics. Despite the persistence of stratification at most sites throughout the study regime, temperature gradients between upper and lower sections of the water column appeared strongest in February. This was particularly the case for exposed sites, where sharp decreases in water temperatures correlated directly with dissolved oxygen (DO). This was in contrast to control sites, where DO levels were consistently much greater, despite maintaining similar levels of thermal stratification. Exceptionally low DO concentrations were also observed at Lake Daviumbu, possibly due to the effects of large volumes of decomposing grasses. The reduced DO values in conjunction with low redox measurements at impact sites during the wet season, suggest that hypolimnetic waters are subject to high biological oxygen demand (BOD), possibly reflecting large inputs of organic debris / rotting vegetation to the oxbows. It was proposed that such inputs may contribute to a strong solute derived density gradient between the epilimnion and hypolimnion. This was supported by a conductivity gradient with depth, particularly at Kuambit. The potential for the existence of solute derived gradients at impact sites in particular, was hypothesised to result in a very stable form of stratification, that is perhaps more resistant to turnover. It was suggested also that this form of stratification may protect affected oxbows from mixing events, thus reducing the frequency with which hypolimnetic waters are reoxygenated, a trend which may be reflected in the lower DO values obtained at impact sites overall. Longer periods of time between turn over events were also hypothesised to have ramifications for metal fluxes from benthic sediments. Analysis of individual sites and regression analyses of DO against metal concentrations indicated increasing metal concentration with decreasing DO (and thus depth), particularly at exposed sites – indicating substantial potential for metal flux out of the sediments during anoxic conditions. This trend combined with the potential propensity for impact sites to maintain anoxic conditions for longer periods, suggests greater scope for metal (and DO) toxicity following complete water body mixing.

Based on the findings, recommendations were made. These included:

- Re-sampling wetland limnology on as frequent a basis as possible to build-up a more comprehensive picture of spatial and temporal patterns, particularly of dissolved metal concentrations, and episodic turn-over and mixing events,
- Determination of the labile component of elevated levels of metals in downstream oxbows, particularly dissolved copper (Cu) in surficial waters at OXB06, to assess risk of toxicity to biota, and,
- Use data on phytoplankton, zooplankton and aquatic macroinvertebrate assemblages of ORWBs (currently being gathered) to test specifically for a mine-effect in OXB06 in response to the observed levels of dissolved metals.

1 Introduction

1.1 Project Background

Monitoring data collected in recent years by OTML have indicated continuing declines in fish catch in the Fly River channel, particularly in the vicinity of Bosset and Ogwa. Data also show copper concentrations in livers of fish from the lower Ok Tedi and Middle Fly river channel to be elevated above pre-mine levels. At the same time, there has been progression of river bed aggradation into the middle Fly with forest die-back extending towards the lower Fly, and Rogers *et al.* (2005) have reported increasing concentrations of labile copper, (leading to growth inhibition of bacteria and algae) at riverine sites downstream of the mine, including downstream of Everill Junction. Up to this point, observed mine-related impacts on aquatic systems had been confined to the river channel. However, recent data indicated previously unrecorded declines in fish catch at off-river water bodies (ORWB), particularly Oxbow 6 (Kwem), Bosset Lagoon and Lake Pangua (OXB05), indicating potentially the first mine-related biological impacts on the aquatic resources of the floodplain. Finally, in the first quarter of 2005, isolated patches of ARD were observed for the first time on river bank levees in the Middle Fly, with highly elevated copper levels in floodplain pore waters within the areas of ARD. This has the potential to further impact on the floodplain aquatic system.

Declining fish catches in oxbow lakes is of particular concern. Despite continued monitoring of Oxbow 6 for changes in fish catch, there are other oxbow lakes connected by tie-channels to the main river that are closer to the Ok Tedi that are not currently monitored (*i.e.* OXB02 at Erekta, Kuambit oxbow, lower Ok Tedi oxbow). Given the proximity of these oxbows to the Ok Tedi, it follows that the perceived impacts of mining at these locations may be more severe than those observed at OXB06.

It has been hypothesised that the declining fish catch may be a consequence of either:

i). Increased concentrations of bioavailable copper impacting fish species either directly (*viz.* reduced overall fitness of populations due to chronic toxicity) or indirectly, via disruption to lower trophic level(s) (*e.g.* reduced primary productivity of the oxbow) and/or;

ii). Habitat loss/impairment due to accumulation of mine-derived sediments/increased turbidity/forest die-back.

To elucidate the likely cause(s) of the declining fish catch, a series of floodplain studies have been initiated. The overall objectives of these studies are to a) gain a greater understanding of the limnology of ORWBs, including knowledge of water quality and its ramifications for metal bioavailability; b) describe the structure of floodplain food webs (including trophic interactions and sources of carbon supporting the aquatic foodwebs); c) determine changes (if any) in fish edibility through tissue metals sampling and d) to reassess fish catch data at key sites to update historical information.

The current study is part of broader floodplain investigations and aims to look at vertical stratification of floodplain waterbodies, concentrations of mine-derived metals in these waterbodies, and the potential for release of copper and other metals from mine-derived benthic sediments under anoxic conditions.

1.2 Rationale

Basic water chemistry is an important component of aquatic ecosystem health, since changes to physical components such as dissolved oxygen and pH can elicit deleterious physiological responses in the biota such as altered rates of respiration, reduced growth rates and lowered fecundity.

In natural systems, pH is determined by atmospheric and geological factors (*e.g.* the result of inundated limestone-rich or, conversely, humus-rich substrates) and to some extent, rates of primary productivity. Anthropogenic determinants include acid rock drainage, acid deposition (*e.g.* acid rain) and agriculture. Low pH results typically in decreased abundance and diversity of aquatic fauna, usually through indirect effects of altered trace metal toxicity (Dallas & Day 1993). Even small changes in natural pH may have sub-lethal effects on aquatic fauna by altering ionic and osmotic balances (Dallas & Day 1993). Sub-lethal effects include reduced fecundity and impaired growth and development. In most freshwater systems, the presence of bicarbonate ions (HCO_3^-) acts as a buffer against large fluctuations in pH. This buffering capacity is measured as alkalinity.

In addition to geology, primary productivity (aquatic plants, algae and phytoplankton) also influences pH, especially in waters that are poorly buffered. In systems where productivity is high, diel (*i.e.* 24 hour) changes in the ratio of photosynthetic rates to respiration rates can result in markedly increased pH as plants utilise CO_2 during the day. For example, in billabongs in Kakadu, Northern Australia, pH can range from around 6 in the morning to 9 in the late afternoon (ANZECC/ARMCANZ/ARMCANZ 2000).

Changes in dissolved oxygen (DO) also have the potential to adversely affect aquatic biota. This is because DO is a fundamental requirement for aquatic organisms that respire aerobically: it affects their distribution, physiology and behaviour (Wetzel, 1975). Eutrophication, increased turbidity and sedimentation can all deleteriously affect oxygen levels in flowing waters. Final DO concentration in any water body is the net result of biological processes and physical re-aeration. Biological processes include metabolic rates, *i.e.* photosynthesis and respiration by aquatic biota, and physical re-aeration is the exchange of oxygen between the surface of the river and the atmosphere, at the water-air interface.

Oxygen concentrations in aquatic systems naturally undergo a diel cycle. Large diel fluctuations in DO are a natural characteristic of water bodies with high primary productivity. Typically, there is a mid to late afternoon maximum, as a result of peaking photosynthetic production of oxygen by algal and macrophytes exceeding consumption by respiring aquatic fauna (Figure 1). Elevated primary production may be driven by both high water temperatures and light inputs, resulting in substantial amounts of material being available for consumers (*e.g.* macroinvertebrates and fish). There is then a night-time minimum DO as a direct consequence of respiration by plants and animals (Figure 1).

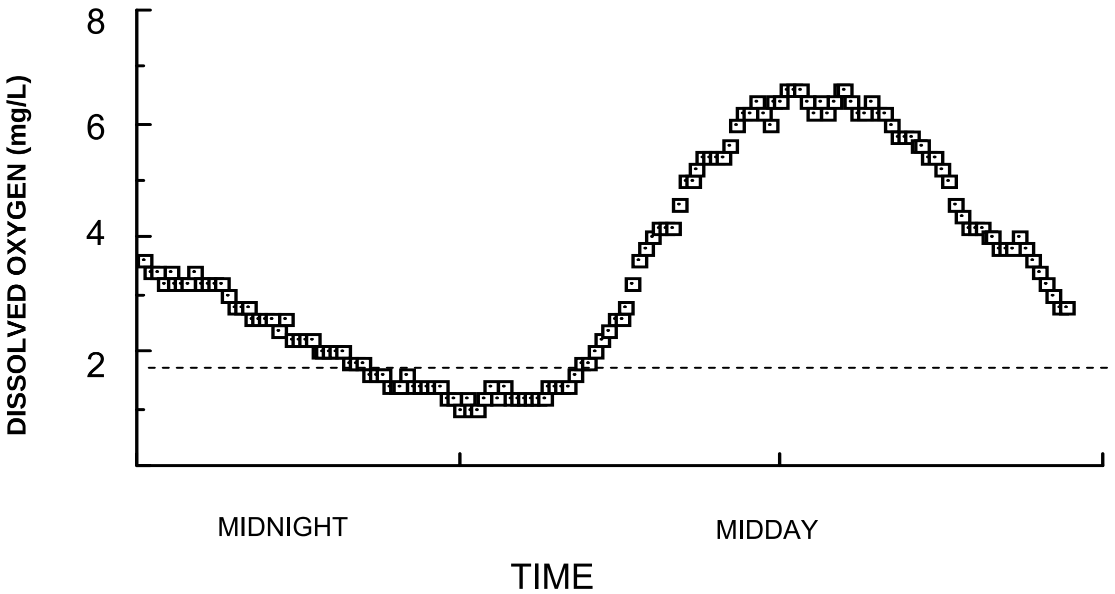

Figure 1. Typical 24 hour curve of dissolved oxygen showing daytime peak and night time minimum, with a threshold minimum at 2 mg L^{-1}, below which the system likely enters oxygen stress.

Dissolved oxygen is typically expressed in terms of concentration (DO mg L^{-1} water). Generally, DO values less than 4 mg L^{-1} represent increasing levels of stress to aquatic fauna and ecological processes. Rates of physiological processes vary as a function of DO concentration (and temperature) and at concentrations less than 4 mg L^{-1} these rates are typically limited by DO availability, thereby reducing ecological vigour. Continued low levels ultimately will lead to death of fauna and may also result in water quality problems as nutrients and some metals (*i.e.* iron and magnesium) are released from sediments during anoxia (zero DO). In well-aerated waters, many metals adsorb (bond) readily to suspended matter (*e.g.* clay or organic particles suspended in the water column) and to river bed substrates, thereby reducing their bioavailability. Under conditions of low or zero DO, heavy metals and nutrients are released from the sediments into the water column in bioavailable forms (it should be noted that not all metals liberated from the benthos are bioavailable; only a proportion). Aquatic fauna, especially macroinvertebrates exhibit a range of tolerances to DO concentrations with the least tolerant species being lost from a system first, and species with special adaptations (*e.g.* chironomid midge larvae with haemoglobin in their blood) persisting under very low DO concentrations. Periodic reductions in DO concentrations often may be survived by all fauna, with loss of species only occurring under continued low DO conditions.

Anoxic conditions prevail typically as a result of vertical, or thermal stratification of water bodies. Thermal stratification occurs when surface waters are warmed by solar radiation, whilst the bottom of the water body remains relatively cool. In the absence of mixing (such as that facilitated by wind related turbulence) this warming process leads eventually to a distinct, and often sharp difference in temperature between the upper (epilimnion) and lower sections (hyperlimnion) of the water body. The point at which the two layers of water are separated is termed the thermocline, and is often represented by a difference in temperature sometimes equating to several degrees (Figure 2b). This is quite distinct from a gradient in temperature where a continual decrease in temperature occurs with increasing depth (Figure 2a). At the thermocline (best described as a plane), the marked difference in temperature is also manifested as a sharp difference in density (*i.e.* cooler water has a higher density than warm water), leading to a physical differential that effectively prevents the two areas mixing. During long term stratification, this density gradient is strengthened by the addition of biological material (sinking phytoplankton and zooplankton exoskeletons) which may in turn increase the concentration of hypolimnetic salts, thus exacerbating the density differential (referred to as biogenic stratification). Such conditions often exceed the conditions required for mixing of the two water layers (meromixis).

During stratification (both biogenic and other forms), chemical and biological breakdown of organic matter in the hyperlimnion consumes large quantities of oxygen. Because there is no opportunity for the replenishment of dissolved oxygen (due to limited light penetration and barriers to mixing), the supply is exhausted eventually leading to total anoxia. Under these conditions, aquatic fauna are forced to migrate to the middle and surface layers of the water column. Of interest also, are the effects of thermal stratification on the distribution of microscopic fauna. During periods of low water turbulence, heavier microalgae (such as diatoms) sink through the epilimnion (Round 1965) only to become trapped at the thermocline, where the density difference impedes further sinking. This often results in concentration of algae and zooplankton (which feed on the algae) at the level of the thermocline, thus having significant ramifications for dissolved oxygen and nutrient distributions on a micro-habitat scale.

Thermal stratification, apart from having biological ramifications, may also facilitate certain chemical processes. For example, anoxic conditions often result in the mobilisation of metals and nutrients from benthic sediments, which, under oxygenated conditions, would otherwise remain trapped within the sediments (*i.e.* absorbed to sediment particles). Typically, the mobilisation of heavy metals and nutrient to the water column is of limited concern for aquatic fauna, most of which inhabit selectively the water levels above the hypolimnion. However, elevated hypolimnetic metal / nutrient concentrations becomes an issue during meromixis (mixing of the water body) when the system de-stratifies (*i.e.* due to forces such as currents, high winds or rains). Under this scenario, nutrients and metals evenly mix throughout the water column (including middle and surface layers) leading potentially to fish kills and serious algal blooms.

Previous studies of Fly River waterbodies have detected thermal stratification with anoxic conditions in the bottom waters. In fact, algal blooms in Lake Pangua (OXB05) in 1993/94 may have been a result of de-stratification and mixing of this deep oxbow lake, with the release of nutrients within anoxic bottom sediments. Metal toxicity, however, was not considered an issue at this site because at that time sediments were not known to contain mine-derived metals.

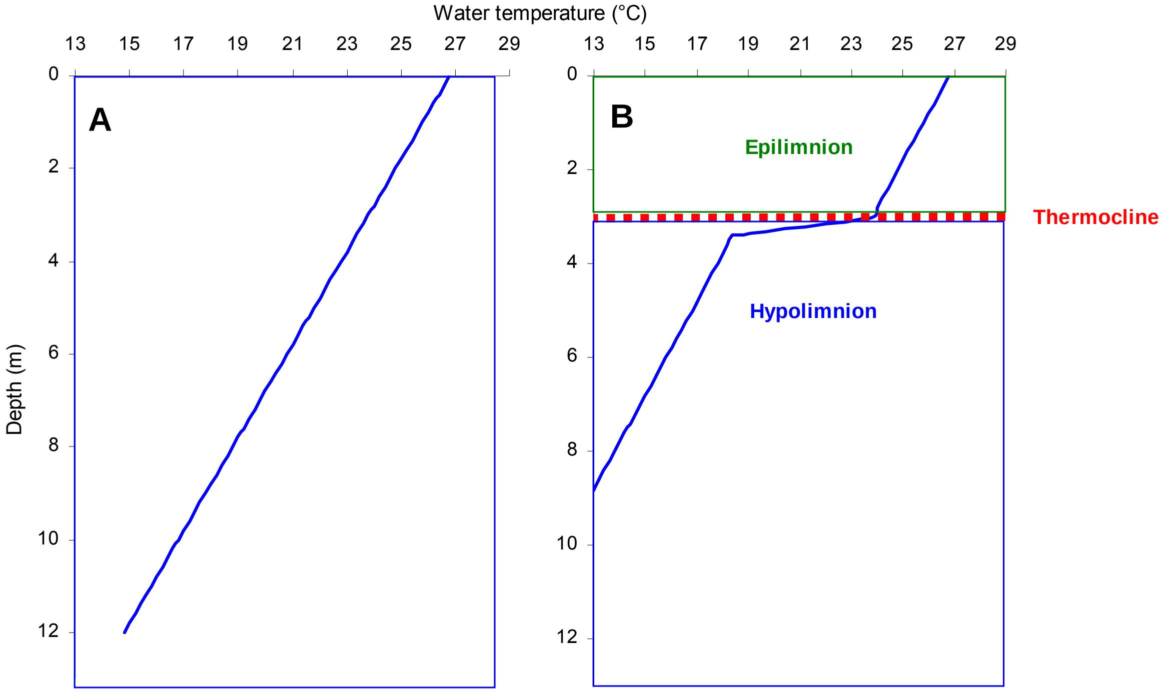

Figure 2. Conceptual representation of temperature gradient (A) and stratification (B) within a water body.

However, over the last ~ 10 years, and with increasing distance from the mine, it has become evident that there is active transport of mine derived sediments into various off-river water bodies (ORWBs), with extension of tie-channels and development of 'deltas' of sedimentation into the waterbody, with a gradual infilling of oxbow lakes close to the mine. Studies indicate that oxbow lake sediments are a net sink for metals, with water column metal concentrations decreasing with depth, and sediment pore-water concentrations increasing (Rogers *et al.* 2005). However, a concern is that under particular conditions (stratification/de-stratification), the potential exists for release of metals from mine-derived sediments with associated acute or chronic toxicity to aquatic fauna in these water bodies. These conditions may be episodic, developing over several days/weeks under appropriate conditions, and then breaking down. A single sampling occasion, therefore may not necessarily detect stratification or release of metals, but repeated sampling, in different seasons will assist in establishing a pattern.

In response to this concern, OTML commissioned ***Wetland Research and Management*** to conduct surveys of selected ORWBs to establish waterbody physico-chemistry to assist in the interpretation of the basic limnology and dissolved metal profiles in the ORWBs.

1.3 Project Aims

This project forms part of a larger study designed to further the understanding of floodplain biological and physico-chemical processes. The specific objective of the present study was to determine mine-related impacts to floodplain ecology, with the overall intention of elucidating factors responsible for declining fish catches. Two sub-objectives were proposed:

- To determine whether vertical stratification is a feature of ORWBs (including an assessment of the temporal and geographic extent of thermal stratification).
- To determine dissolved metal concentrations at different depths within the ORWBs (incorporating an assessment of the effect of thermal stratification on the fate and flux of metals).

Sampling was initially conducted in February 2005 as part of a food web analysis of the target floodplain sites. However, a subset of sites were re-sampled opportunistically in July/August 2005 during the Fly River Biodiversity study to provide an indication of temporal variability.

2 Methods

2.1 Survey Sites

The study was initially (February 2005) implemented as a replicated Control versus Exposed design, whereby three potentially impacted oxbow lakes were selected (*i.e.* downstream of the mine), for comparison with three control oxbow lakes (*i.e.* upstream of the mine) (Table 1). All sites were located within the forested reaches of the upper and middle Fly River floodplain (Figure 2), to remove the possibly confounding influence of forested versus grassed floodplain habitats. Although the three control oxbows were upstream of the mine in terms of not receiving mine-derived sediment, Moian oxbow is affected by forest dieback as a result of increased flooding caused by backwater effects due to aggradation in the lower Ok Tedi/upper Middle Fly. In addition to the core design of control versus impact forested oxbow lakes, two blocked valley lakes were also added to the study; Lake Daviumbu (DAV01) and Bosset Lagoon (BOS10). This was to increase the current knowledge of the limnology of these habitats, for which there is minimal basic limnological information. The locations of the eight sites sampled are presented in Figure 3.

During the Fly River Biodiversity Survey conducted in July/August 2005, the opportunity arose to re-sample most of the original sites, as well as visit additional sites. The selection of sites was partly determined by the itinerary planned for the Biodiversity Survey, but also by landholder issues (*i.e.* access to Kiunga Oxbow was denied). The additional sites sampled in July/August are listed in Table 1. The initial study was carried out over a period of 15 days between the 2nd and 16th February 2005, while the current survey was conducted over nine days between 26th July and 6th August 2005.

Table 1. Sites sampled, showing whether Control or Exposed, with approximate locations on the river channel as determined by ARM.

Site Name	Site Code	ARM	Control/Impacted	February 2005	July/August 2005
Lake Daviumbu	DAV01	229	downstream lagoon	✓	✗
Bosset Lagoon	BOS01	280	downstream lagoon	✓	✓
Drimdenasuk	FLY02oxb	460	Forested Control	✓	✓
Ulawas (Kiunga)	OXB01	451	Forested Control	✓	✗
Moian Oxbow	Moian	446	Forested Control#	✓	✓
Kuambit Oxbow	Kuambit	434	Forested Exposed	✓	✗
Erekta	OXB02	405	Forested Exposed	✓	✓
Kwem	OXB06	346	Forested Exposed	✓	✓
Pangua	OXB05	231	Grassed Exposed	✗	✓

although an upstream control in terms of not receiving mine-derived sediment, Moian oxbow has been affected by forest dieback due to increased flooding as a result of backwater effects from aggradation in the lower Ok Tedi/upper Middle Fly.

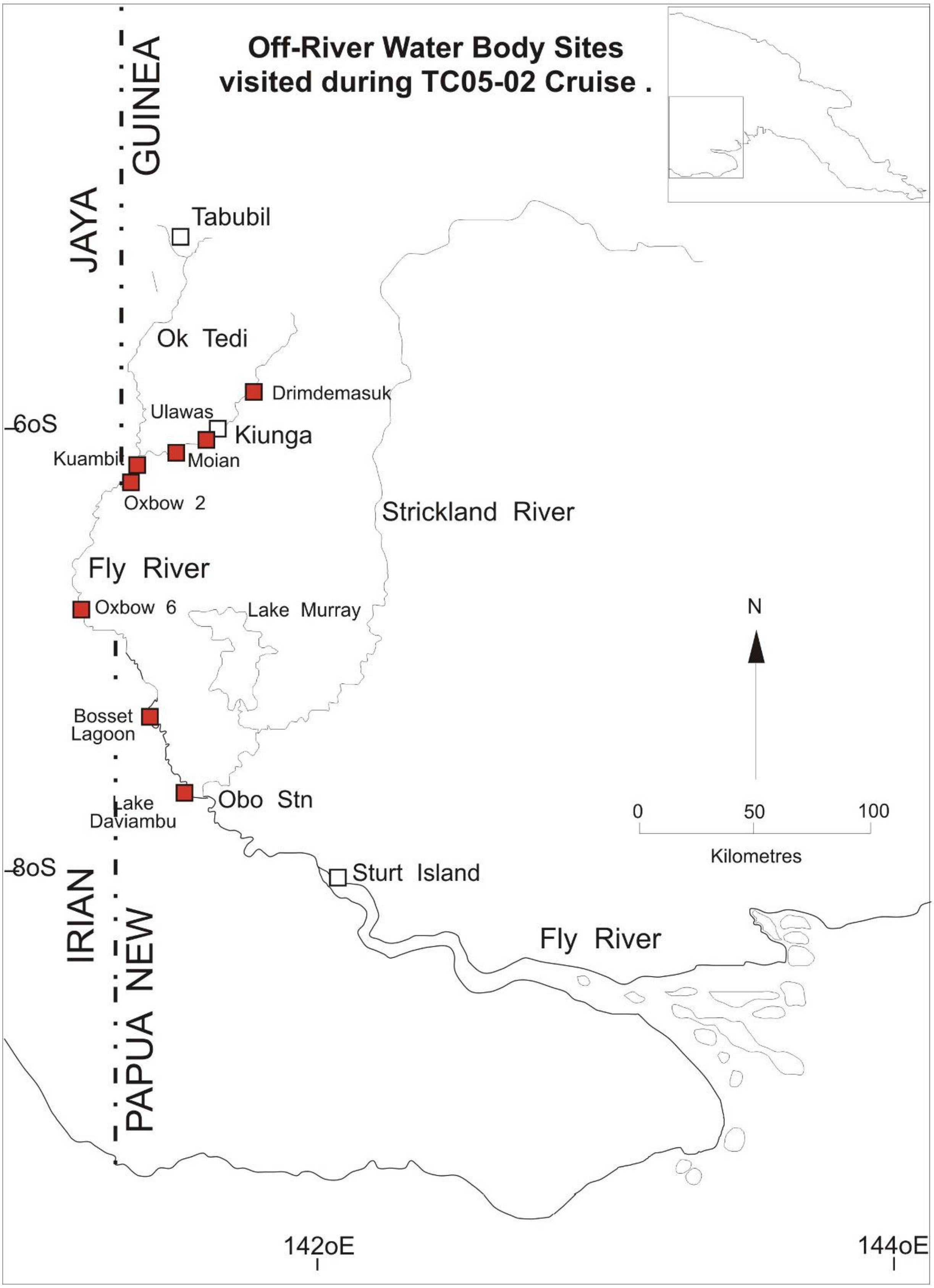

Figure 3. Map of oxbow lakes included in the Limnological survey.

2.2 Field Sampling

2.2.1 Diel vertical logging

Diel (24 hour) variations in water temperature and concentration of dissolved oxygen (DO mg L^{-1}) were determined using YSI 5739 Oxygen/Temperature field probes and TPS WP-82Y dissolved oxygen-temperature meters/loggers. The meters where placed on a floating platform made of a solid plywood base with a rubber tyre for flotation, and anchored at two points. The apparatus was positioned approximately mid-way along the linear length of the oxbow lake, and in the approximate deepest part of the accessible water body (Plate 1). Prior to deployment, the DO probes were air calibrated, and if air calibration was not successful, the probes were fully calibrated (zero oxygen and air calibration).

Three probes were then deployed off the platform at each site: one at the surface (approximately 30 cm); one at mid-depth and one near the bottom (approximately 1 metre from the bottom). Mid depth was taken as half the maximum depth at the site. Exceptions occurred if the maximum depth was greater than 10 m, as this was the maximum length of the cable for the probes; therefore the deepest probe was deployed at 10 m. The loggers were then programmed to record DO and temperature at 10 minute intervals over a 24 hour period.

The dissolved oxygen probes are polarographic, which means they consume oxygen across the membrane, and so will appear to give a gradual depletion in oxygen if placed in standing water. This is not an issue in flowing waters, but is potentially a confounding problem in floodplain ORWBs. To overcome this issue, continuous flow pumps were attached to the probes to circulate water across the membrane. Due to energy consumption of the pumps, the available batteries maintained the pumps for approx 12 hrs. However, the weather throughout the study was windy, with frequent storms, and it was determined that wind and wave action (the platform moved very readily under wind and wave action), was sufficient to maintain movement and so avoid progressive oxygen depletion across the membranes. In July/August specially designed stirrers were fitted to each probe to maintain circulation throughout the 24 hr period. After each 24 hour period, the meters were retrieved and the data downloaded to a laptop on board the research vessel 'Tahua Chief' and plotted as a diel curve.

Notes on weather conditions (*e.g.* sunrise/sunset; rainfall; cloud cover, wind), and any changes in water conditions (*i.e.* river flowing into or out of the ORWB) were made to help interpret diel temperature and dissolved oxygen data.

Plate 1. Anchored platform showing loggers *in situ* in a weather proof container without a lid (left). The cables to the three probes can be seen trailing over the side into the water. The complete unit, with shade cloth to protect the data loggers (right), *in situ* in Lake Daviumbu.

At OXB02 in February 2005 there was a refugee camp on the shore, which the people abandoned as soon as the Environment Team entered the oxbow. As a result, it was not possible to speak with the people before sampling. The loggers therefore were not deployed due to concerns of potential interference with sampling gear by the refugees at the camp onshore. At all other sites caretakers from local villages and fishing camps were employed to watch over the probes.

2.2.2 Hydrolab

A Hydrolab 'Scout 2' multiprobe water quality meter (Plate 2) was also used in conjunction with the loggers and probes to measure vertical profiles for *in situ* water quality parameters. Readings were taken, where possible, close to the data loggers; from the surface to the bottom at 50cm intervals. Readings were taken every six hours over the 24 hour period, giving a maximum of 5 recordings, however, this was not always possible due to safety concerns such as proximity to refugee camp, and difficulties accessing some sites due to shallow tie channels. Data were then recorded in the field notebook and transcribed to a spreadsheet for subsequent plotting. Parameters recorded, and their units of measurement are presented in Table 2

Table 2. *In situ* water quality parameters measured at each site.

Parameter	Units
pH	H^+
Water Temperature	ºC
Conductivity	mS cm^{-1}
Dissolved Oxygen	mg L^{-1}
Redox	mV

2.2.3 Dissolved metal analysis

In association with hydrolab measurements, water samples were taken from surface, mid-depth and bottom water levels in early morning (0600 – 0700) at each site using a Van Dorn water sampler, with depths selected to match the depths of the three probes. Three replicate water samples were taken at each depth (9 samples per site in total). Samples were immediately returned to the boat where they were filtered through 0.45 um filters and nitric acid acidified for storage and subsequent determination of dissolved metal concentrations at the OTML Environmental Chemistry Laboratory.

2.2.4 Data Analysis & Interpretation

Oxygen and temperature data obtained by electronic data loggers were plotted against time (10 minute increments over each 24 hr period) to indicate diel water column fluctuations in DO and water temperature. In addition, Hydrolab data were also plotted using 3-D graphs to show changes in temperature, dissolved oxygen and pH over time and depth. Data were also plotted as 2-D graphs to highlight changes with depth, specifically the presence of thermal stratification. Diel curves were then compared with climatic observations to indicate any response in photosynthesis to weather events.

The diel curves in logged data were examined to determine:

i). diel maximum DO and temperature,

ii). diel minimum DO and temperature,

iii). diel range in DO and temperature, and

iv). duration of the period for which the dissolved oxygen (DO) minimum was below 4 mg L^{-1}.

Along with plots of diel trends in water temperature and DO, all other parameters, including conductivity (mv), pH (H+), Redox (mv) were averaged (where replicate samples were taken) and plotted with 95% confidence intervals to compare inter site and inter exposure differences. ANZECC/ARMCANZ (2000) water quality guidelines for each metal, for tropical wetlands of northern Australia were used to assign trigger values for the protection of 99% and 95% of aquatic species respectively on each plot of dissolved metal concentrations. These trigger values are indicative only, based on tropical northern Australian wetlands, and as stated by ANZECC/ARMCANZ (2000), system-specific trigger values should be developed using data from reference locations for the study area to allow for specifics of water chemistry and local area buffering and complexing capacity.

Plate 2. Hydrolab multiprobe in use.

Note on DO readings:

If the diel DO maximum is > 8 mg L^{-1} at approximately 25°C a site is likely to be eutrophic, (excessive algal activity), with a high probability of DO stress at night as the respiring algae, combined with other biotic respiration (bacteria, invertebrates, fish *etc*) consume oxygen. A diel minimum of less than approximately 4 mg L^{-1} for short periods (minutes up to about one hour) indicates stress, and a DO minimum persistently below 4 mg L^{-1} indicates excessive stress with potential for loss of species of invertebrates and possible fish kills.

Data for dissolved metals were analysed statistically with separate 3-way analysis of variance (ANOVA) procedures, with Site (S) (9 levels), Depth (D) (3 levels) and Season (Sn) (2 levels) treated as fixed factors. To determine the source of significant differences, Tukey's post hoc tests were performed for factors depth and site. All data, where possible, were $\sqrt{X+0.5}$ transformed (Fowler *et al.* 1998) and analysed using SPSS software.

The effect of DO on metal concentration was investigated by regressing parameters for DO against metal concentration. For this analysis, the mean metal concentration for each depth at each site on each occasion was calculated, and paired with the corresponding single measurement for that depth and time (as determined by the Hydrolab). This provided instantaneous water quality data to match against dissolved metals data for each depth in each site.

3 Results and Discussion

3.1 Water Chemistry

Water chemistry data collected during the February and July/August 2005 field surveys are summarised below and listed in Appendix 1 (hydrolab data) and 2 (dissolved metals data). In February, conductivity within each site showed little change with time of day, with all sites being fresh, with a mean and maximum conductivity of 110 and 145 mS cm^{-1}, respectively. Intersite differences were apparent however, with both control and impact sites showing a slight increase in conductivity with depth (Figure 4). This was particularly the case for Kuambit, Moian and Drimdenasuk, all of which maintained strong thermal gradients. Mean pH ranged from 6.3 in bottom waters at Moian to around 8 in bottom waters of Drimdenasuk (Figure 5). Daviumbu, Moian and Bosset generally tended to have lower pH waters (< 6.7) than other sites (Figure 5) (Note: Low pH reflects the influence of floodplain runoff and pH > 7.5 reflects the influence of riverine waters). Redox data, on the other hand were indicative of substantial inter exposure differences, with impact sites recording substantially reduced values (Figure 6). These values appeared to correlate strongly with water temperature and DO both of which displayed strong thermal gradients with depth (including the presence of a distinct thermocline) (Figure 7). Similar temperature/depth trends were observed at control sites, all of which appeared heavily stratified. However, despite the prevalence of thermal stratification at most sites in February, grassland oxbows maintained uniform temperatures throughout the water column. As could be expected given the inter site differences in stratification, DO values also varied between sites, with the lowest values recorded within the hypolimnetic waters of impact sites (Figure 8).

Results obtained during July were in contrast to those obtained in February. The standout feature of data obtained in July was the apparent breakdown, or reduction in the severity of thermal stratification at impact and control sites (Figure 7). Exceptions to this were observed at Oxbow 2 and Drimdenasuk, both of which appeared to maintain thermal stratification. The July breakdown of thermal stratification in most cases also resulted in an increase in DO throughout the water column (Figure 8). Of interest, however, was the marked increase in DO at Oxbow 2 and Drimdenasusk, despite the persistence of thermal stratification at these sites. Although thermal stratification was maintained in some instances throughout the study period, the relative increase in DO (since February) suggests that thermal stratification may not be a permanent feature at these locations (*i.e.* stratification would have to have broken down at some point for the DO to increase). Temperature data was also indicative of an overall decrease in water temperature in July, with most sites reducing in temperature by a substantial margin (Figure 7). As with DO, the redox potential of oxbow lakes appeared also to increase in July. This was particularly the case at impact sites where values increased in the range 94 - 362 mv (Figure 6). pH values in July appeared to increase slightly from an approximate average of around 6.5 to 7.5 (Figure 5). Conductivity values remained unchanged with all sites recording values indicative of fresh water ecosystems (Figure 4). Water quality parameters, including diel fluctuations in water temperature and DO are discussed further below.

NB. For each site, diel plots have been standardised to run from midnight (00.00 hrs) to midnight, however, probes and loggers were usually deployed in the mid- to late afternoon to get late afternoon maxima, before expected minima during the night. Therefore, the plots actually show the afternoon of the first day (~1500 - 2400 hrs) to the right side of each plot, and then the morning and early afternoon of the second day (0100 - ~1500) to the left side of each plot.

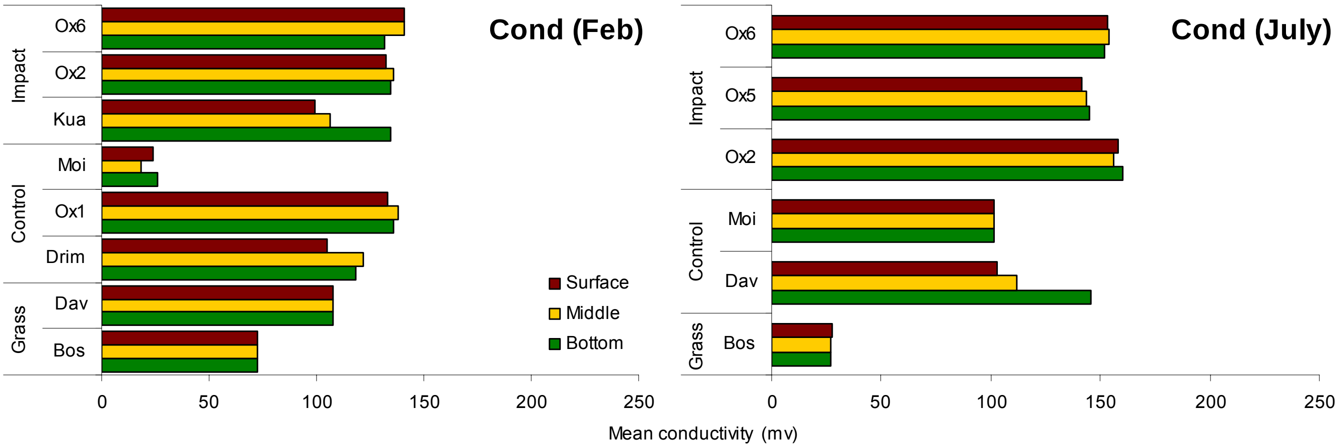

Figure 4. Comparison of conductivity readings between sites, depths and seasons.

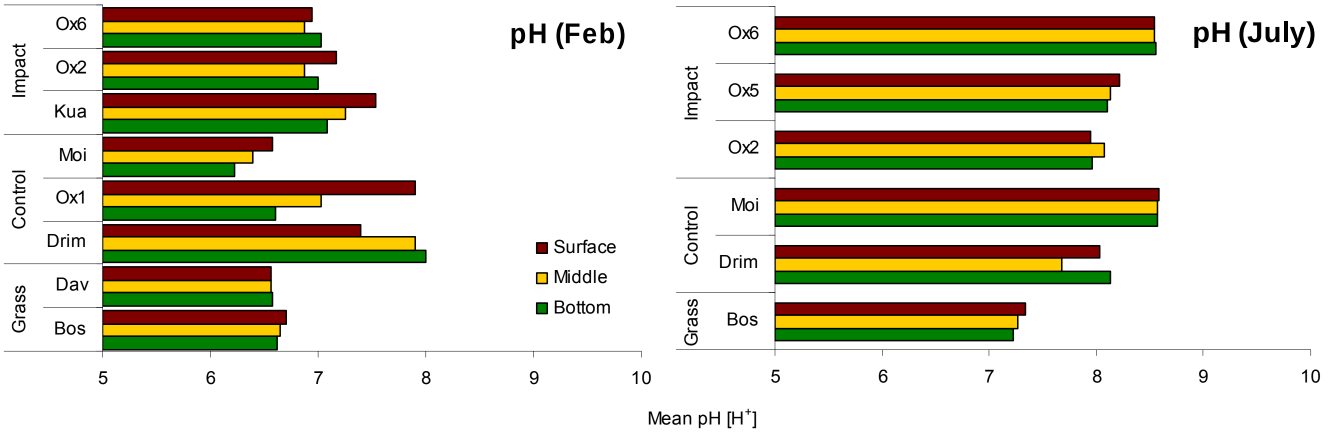

Figure 5. Comparison of pH levels between sites, depths and seasons.

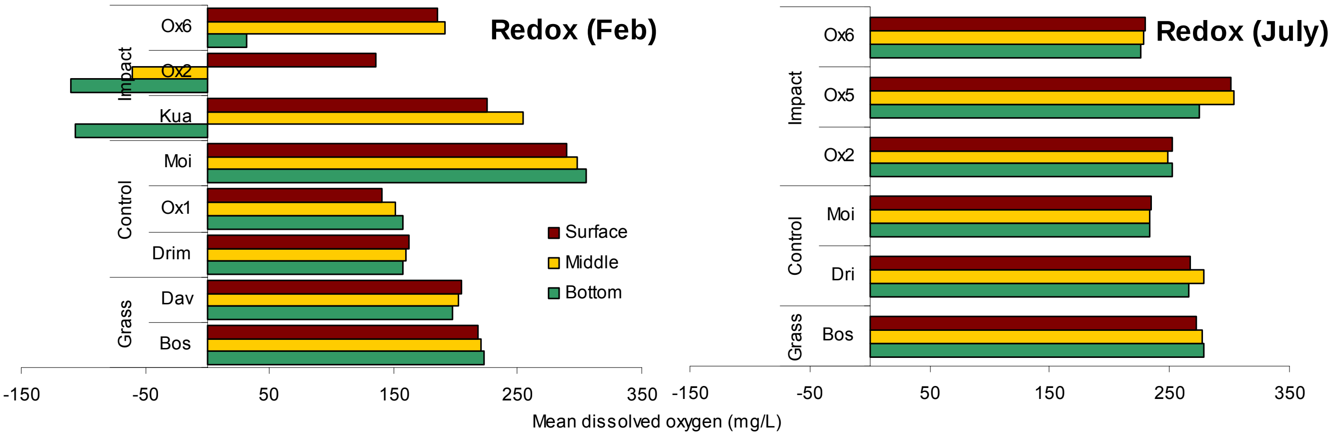

Figure 6. Comparison of redox potential of oxbow lakes. Values are presented for sites, depths and seasons.

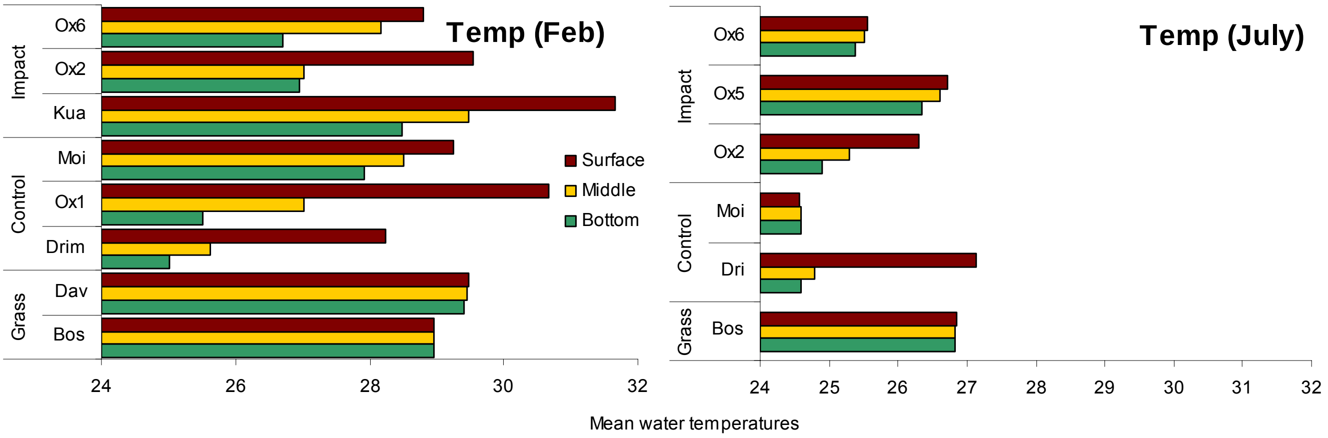

Figure 7. Comparison of water temperatures between sites, depths and seasons

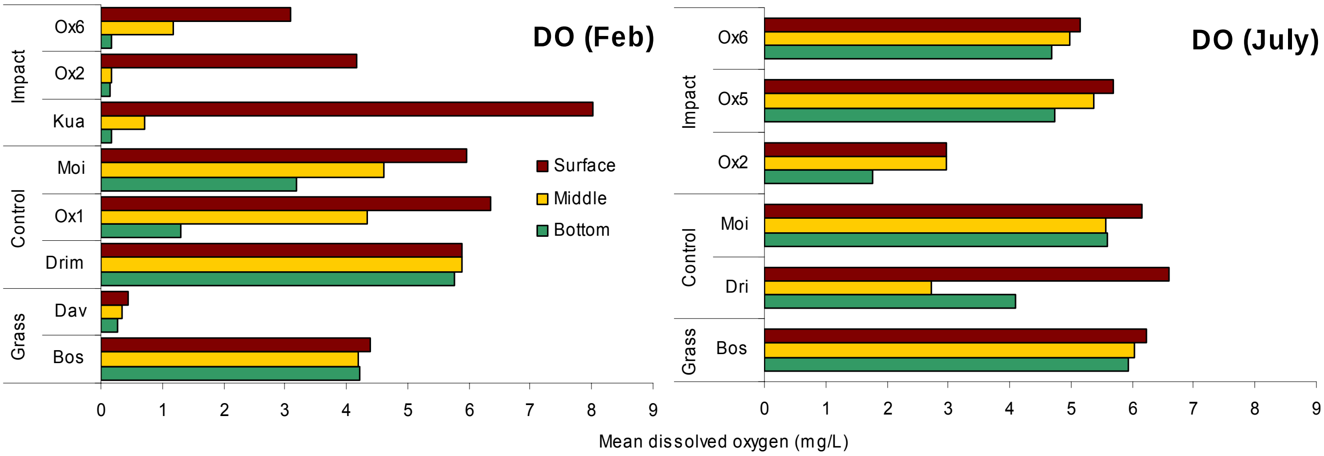

Figure 8. Comparison of dissolved oxygen concentrations between sites, depths and seasons

3.1.1 February 2005 Data

3.1.1.1 Blocked Valley Lakes

3.1.1.1.1 Lake Daviumbu

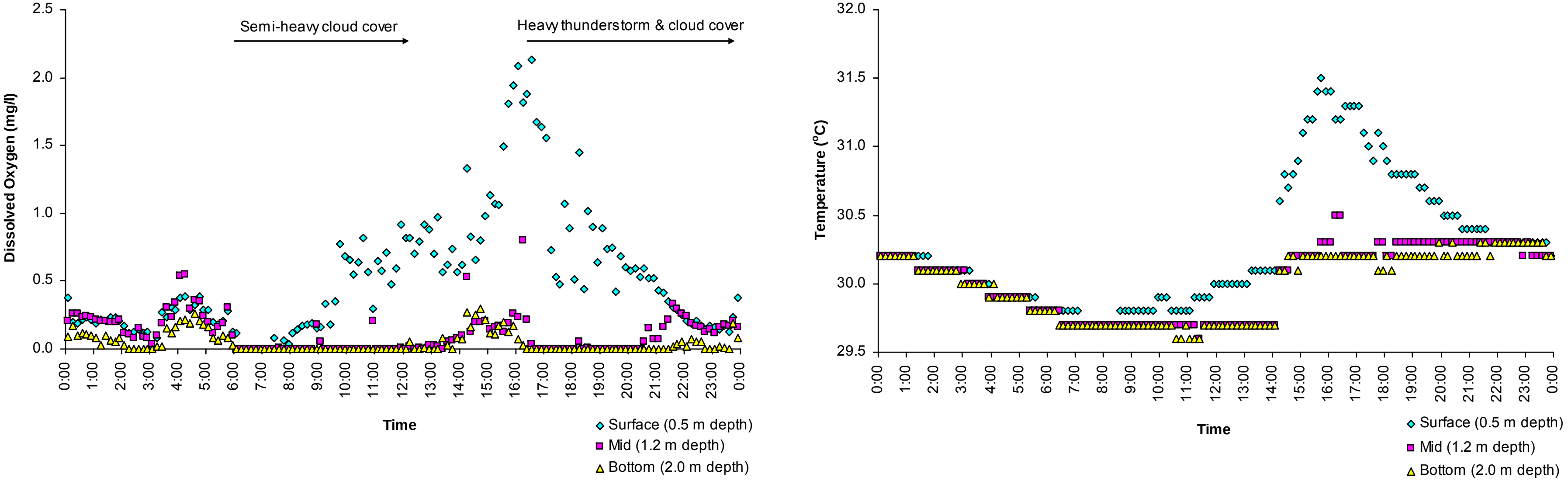

Figure 9. Diel curves for DO (left) and temperature (right) at Lake Daviumbu (DAV01) in February 2005. Probes were deployed at 1400 hr and retrieved at 1400 hrs the following day.

Diel curves for dissolved oxygen (DO) at Lake Daviumbu showed levels were consistently below 2 mg L^{-1} (Figure 4), with mid and bottom probes detecting close to anoxic conditions most of the time. These are levels at which aquatic fauna and ecological processes experience severe stress. In the mid-late afternoon, DO on the surface increased marginally, possibly reflecting photosynthetic production or the passage of a storm which would have aerated the surface through wind and rain action, however, DO did not at any time exceed 2.5 mg L^{-1}. Water temperatures were relatively high at all levels through out the day and night (> 29°C). The surface probe indicated an increase in temperatures during the latter part of the afternoon, however, mid and bottom probes showed only a small diel range (Figure 9).

Vertical profiles of DO and temperature indicated stratification during the day, with a weak thermocline (2°C change over the top 1 m), which broke down at night. There was little change in pH with depth or time, except for a brief decrease in pH around midnight, with a decline from 6.5 to 5.5 in the bottom of the lake (Figure 10).

Lake Daviumbu is a relatively shallow lake and at the time of sampling had a lot of vegetation (*e.g.* grasses and lilies) covering the surface, with only small areas of open water. The presence of these grasses reduces the opportunity for physical re-aeration (the exchange of oxygen between the water's surface and the atmosphere), by reducing wind friction. These grasses also contribute large amounts of organic material which is subsequently broken down by bacteria, and other benthic invertebrates, thus consuming DO due to respiration, and so reducing the amount available in the water column, to the extent where anoxic conditions would prevail. Since the grasses are generally floating on the surface, they likely contribute little oxygen to the water column *per se*, unlike submerged aquatic macrophytes, however, they will consume DO from the water column at night, as will decaying detritus produced by the plants as they die-off.

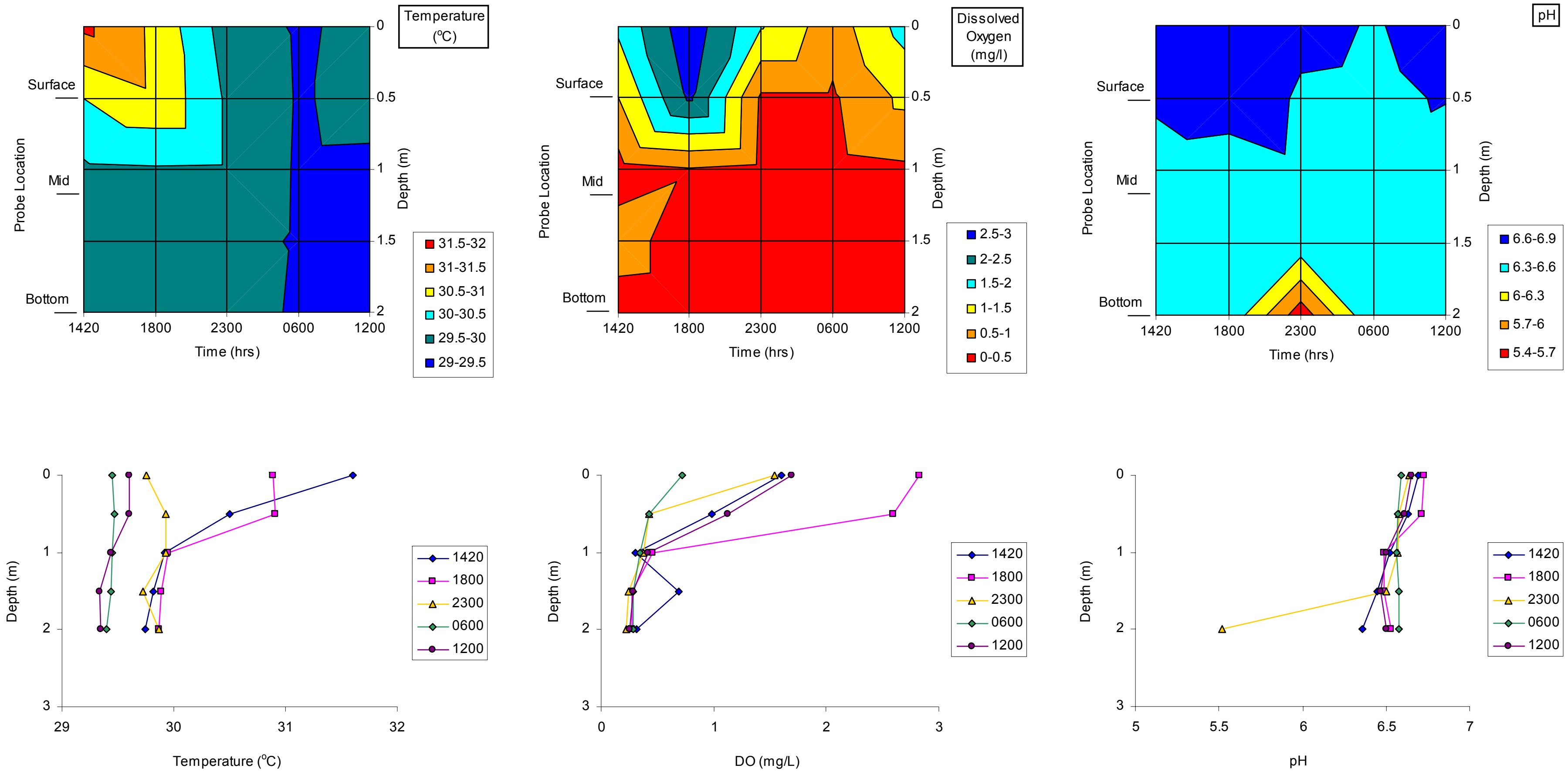

Figure 10. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Lake Daviumbu (DAV01) in February 2005.

3.1.1.1.2 Bosset Lagoon

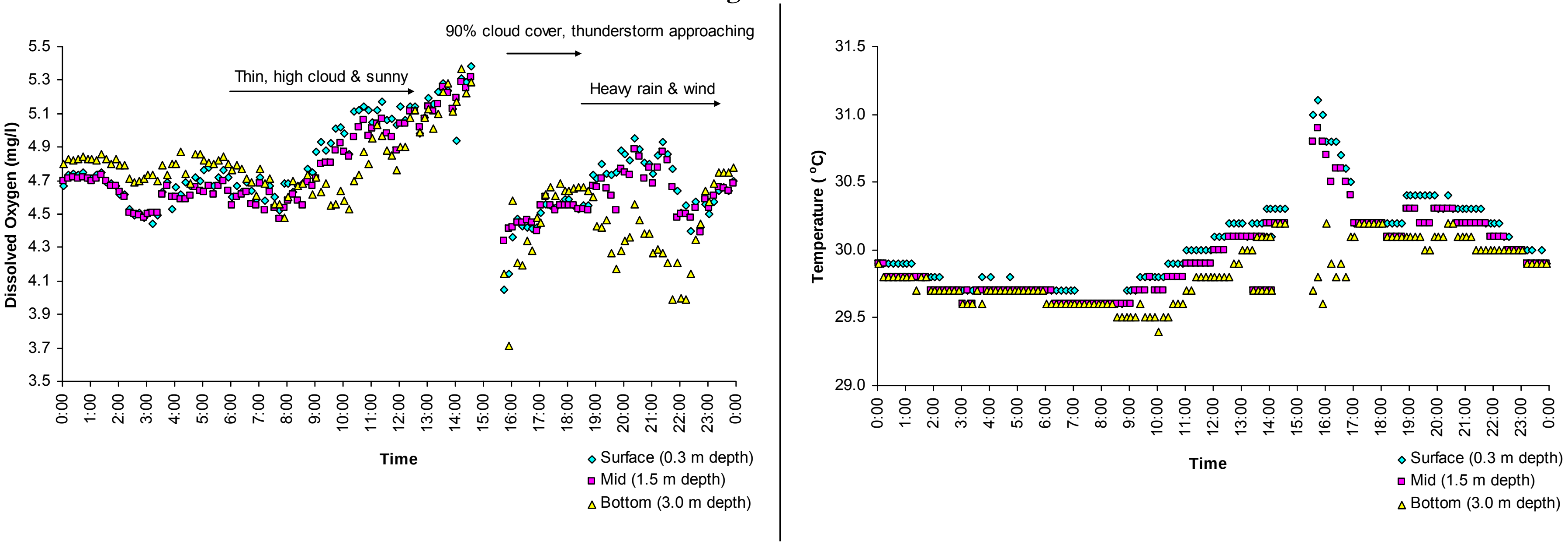

Figure 11. Diel curves for dissolved oxygen (left) and temperature (right) at Bosset Lagoon (BOS10) in February 2005. Probes were deployed at 1530 hrs and retrieved at 1500 hrs.

At the time of sampling, Bosset Lagoon was predominantly open water, with significant coverage of grass around the edges and within embayments. DO values were relatively high (4.0 - 5.5 mg L^{-1}) for surface, mid and bottom probes throughout the 24 hrs, and were above the critical level for fauna and ecological process (4 mg L^{-1}). From the time of deployment and for the remainder of the afternoon/evening, Bosset Lagoon was subjected to an intense thunderstorm, with high winds, excessive wave action, heavy cloud cover and heavy rain. The effects of this can be seen in the DO and temperature plots, with both parameters suppressed; DO due to cloud cover induced photosynthesis limitation, and temperatures due to reduced air temperature, wind and rain. The exposed nature of the water body, combined with the action of the storm and less vegetative cover compared with Daviumbu likely combined to give the overall high DO levels (Figure 11). Weather conditions on the second day were fine throughout the morning, as can be seen in the gradually increasing DO and temperature throughout the morning and early afternoon until the probes were removed.

Bosset Lagoon was also relatively shallow (~4 m deepest), and this combined with wind and wave action would have caused mixing of the water column, as can been seen in the vertical profiles, whereby there is little change in temperature, DO or pH with depth (Figure 12). There was a slight gradient in temperature at 1540 hrs, ranging from 31°C at the surface to 29°C at the bottom, but storm action broke-down this gradient and it did not re-establish during the measurement period.

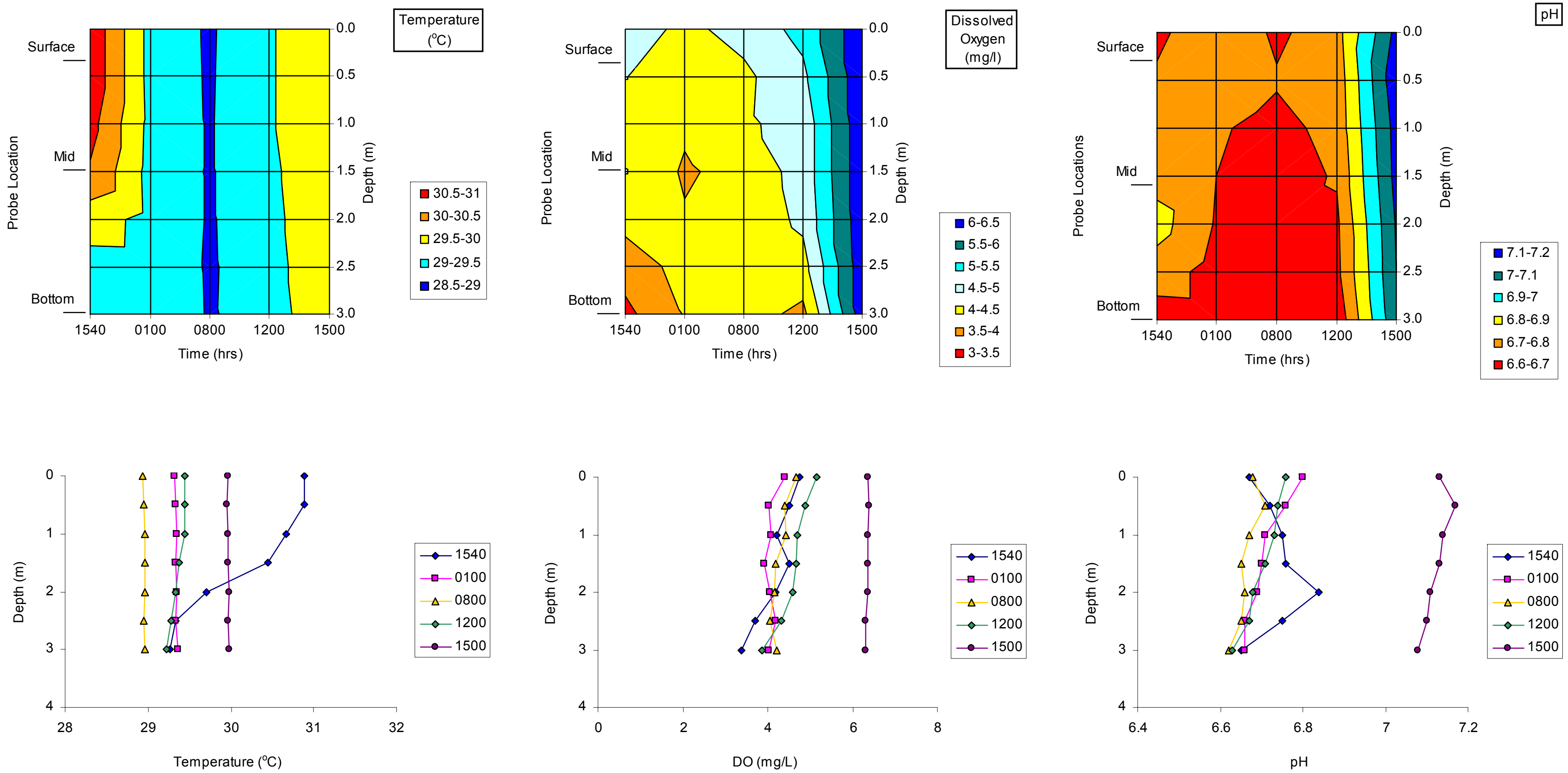

Figure 12. Changes in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Bosset Lagoon (BOS10) in February 2005.

3.1.1.2 Control Forested Oxbows

3.1.1.2.1 Drimdenasuk

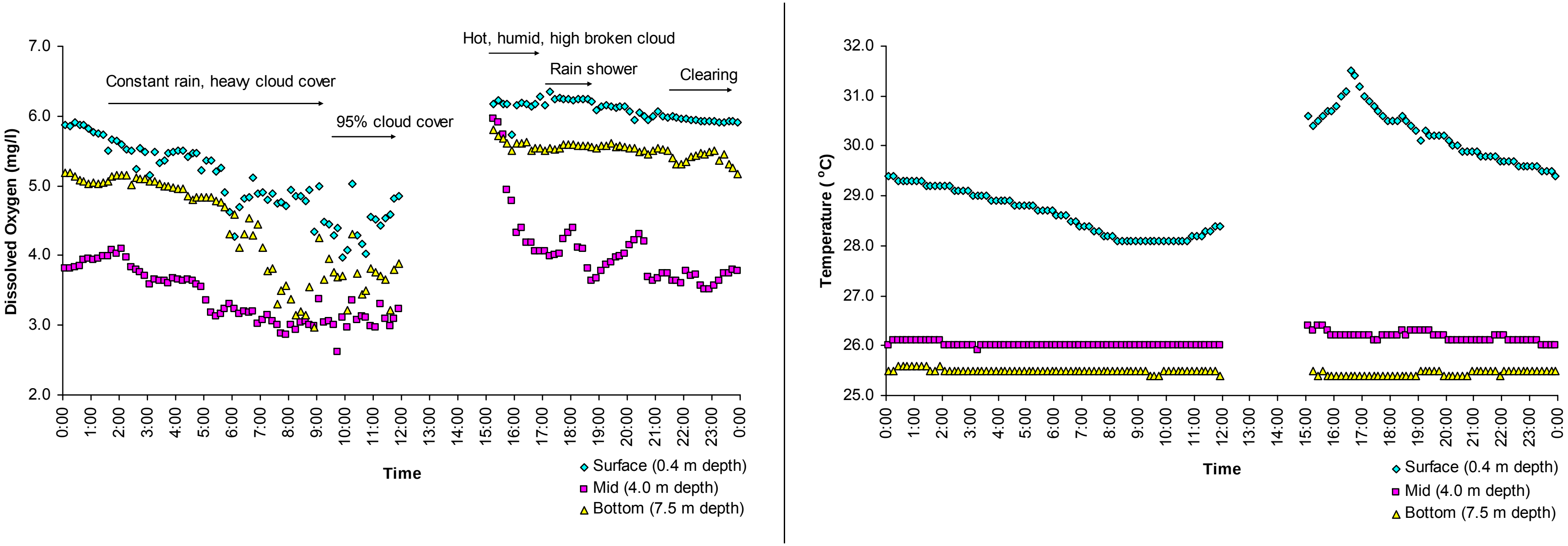

Figure 13. Diel curves for dissolved oxygen (left) and temperature (right) at Drimdenasuk (FLY02oxb) in February 2005. Probes were deployed at 1500 hrs and retrieved at 1200 hrs.

Drimdenasuk displayed an unusual result, with the middle layer having lower dissolved oxygen than both the upper and bottom layers. This phenomenon was noted both with the diel loggers (Figure 13) and the hydrolab (Figure 14). The decrease in DO in the middle of a water column may have been the result of a layer of zooplankton sitting at this position in the water column. However, although depleted, levels were relatively high, with maximum DO of approx 6.5 mg L^{-1}, and a minimum of approx 3 mg L^{-1}.

Diel curves for DO showed the effects of rain showers and cloud cover, especially on the morning of the second day, with a gradual depletion in DO during the night, but with no recovery in DO levels during the day (Figure 13). Temperature showed a strong gradient from top to bottom, with minimal diurnal change in temperature in mid and bottom levels, but with a day-time increase in surface temperatures.

Vertical profiles in temperature showed strong stratification, with a thermocline at approx 1 - 2 m depth, with temperatures declining from ~30°C on the surface to ~25°C at the bottom (Figure 14). This temperature stratification was constant throughout the 24 hr period. As noted above, DO showed an inversion at ~2 m. This equates to the position of the thermocline, and may reflect the level at which zooplankton accumulate above the thermocline.

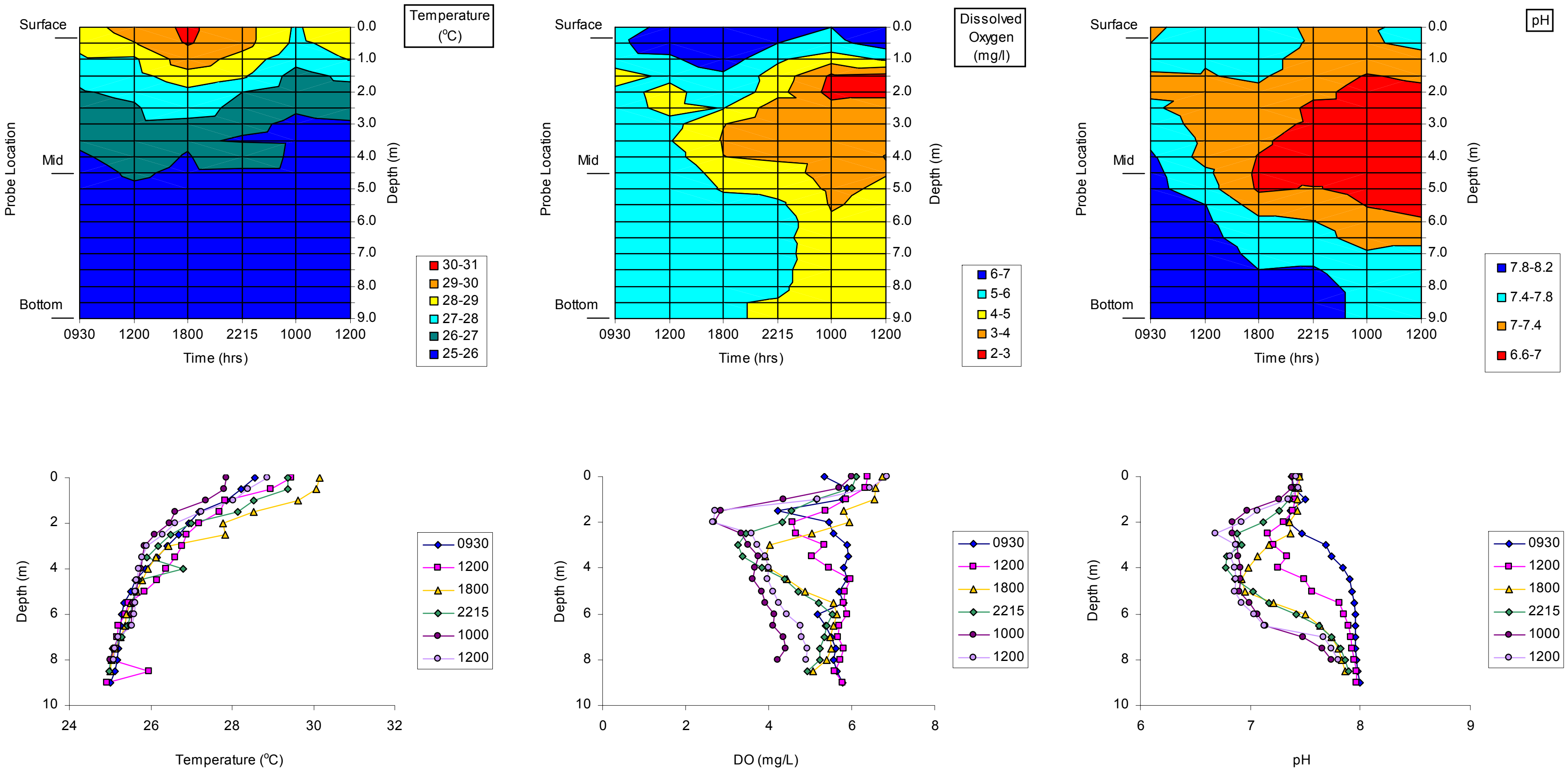

Figure 14. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Drimdenasuk (FLY02oxb) in February 2005.

3.1.1.2.2 Ulawas (OXB01)

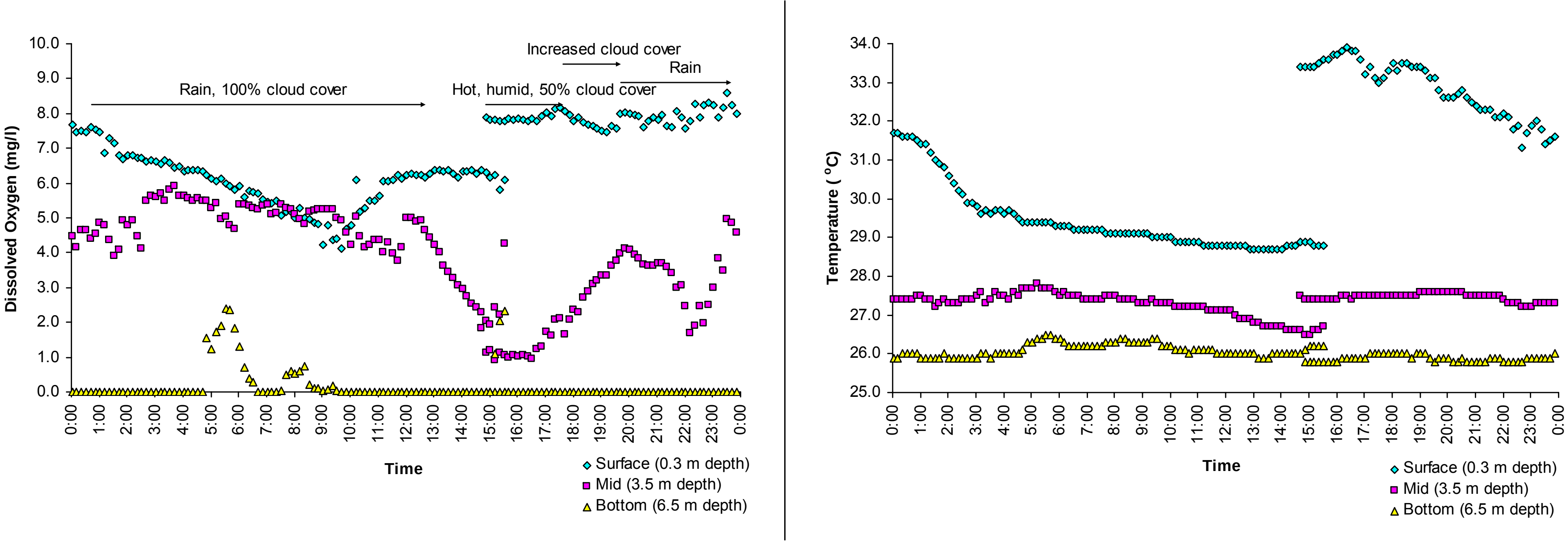

Figure 15. Diel curves for dissolved oxygen (left) and temperature (right) at Ulawas (OXB01) in February 2005. Probes were deployed at 1445 hrs and removed at 1530 hrs.

Diel curves in DO and temperature showed Ulawas oxbow to be strongly stratified in the early part of the monitoring period, with surface DO of ~ 8 mg L^{-1}, and mid and bottom DO of 2 mg L^{-1} and zero DO respectively, and surface, mid and bottom temperature of 34, 27.5 and 25.5°C respectively. Bottom dissolved oxygen was consistently at zero, and therefore anoxic throughout the study period (Figure 15). At 1700 hrs however, the river started to rise and flow into Ulawas oxbow. This inflow had a series of effects on limnological conditions. Initially, surface water temperatures, and then mid water temperatures started to decline. Surface declines were most dramatic, falling from 34°C to approx 29°C as colder riverine water entered the oxbow. The other effect was a disruption to the previously strong stratification. Surface DO declined from approx 8 mg L^{-1} to ~6 mg L^{-1}. However, of more significance was the increase in mid-water column DO from 2 mg L^{-1} to ~6 mg L^{-1}. By mid-morning, the surface and mid water column were well mixed with the same temperature and DO, due to the inflow from the river. Although not measured, it is likely that DO matched that of riverine waters. Interestingly, however, the previous stratification was likely so strong, that towards the end of the measurement period the mid-water DO had started to decline to pre-inflow levels and the strong stratification had started to re-establish. In addition, the inflow had little effect on bottom DO, with a slight and short duration rise in bottom DO during the inflow, but anoxia re-establishing shortly after (Figure 10).

Vertical profiles in temperature showed the strong stratification, with a thermocline at approx 1 - 2 m depth, with temperatures declining from ~34°C on the surface to ~26°C at the bottom. This temperature stratification was constant throughout the 24 hr period. But as noted above, DO showed surface and mid-water variability related to river inflows (Figure 16).

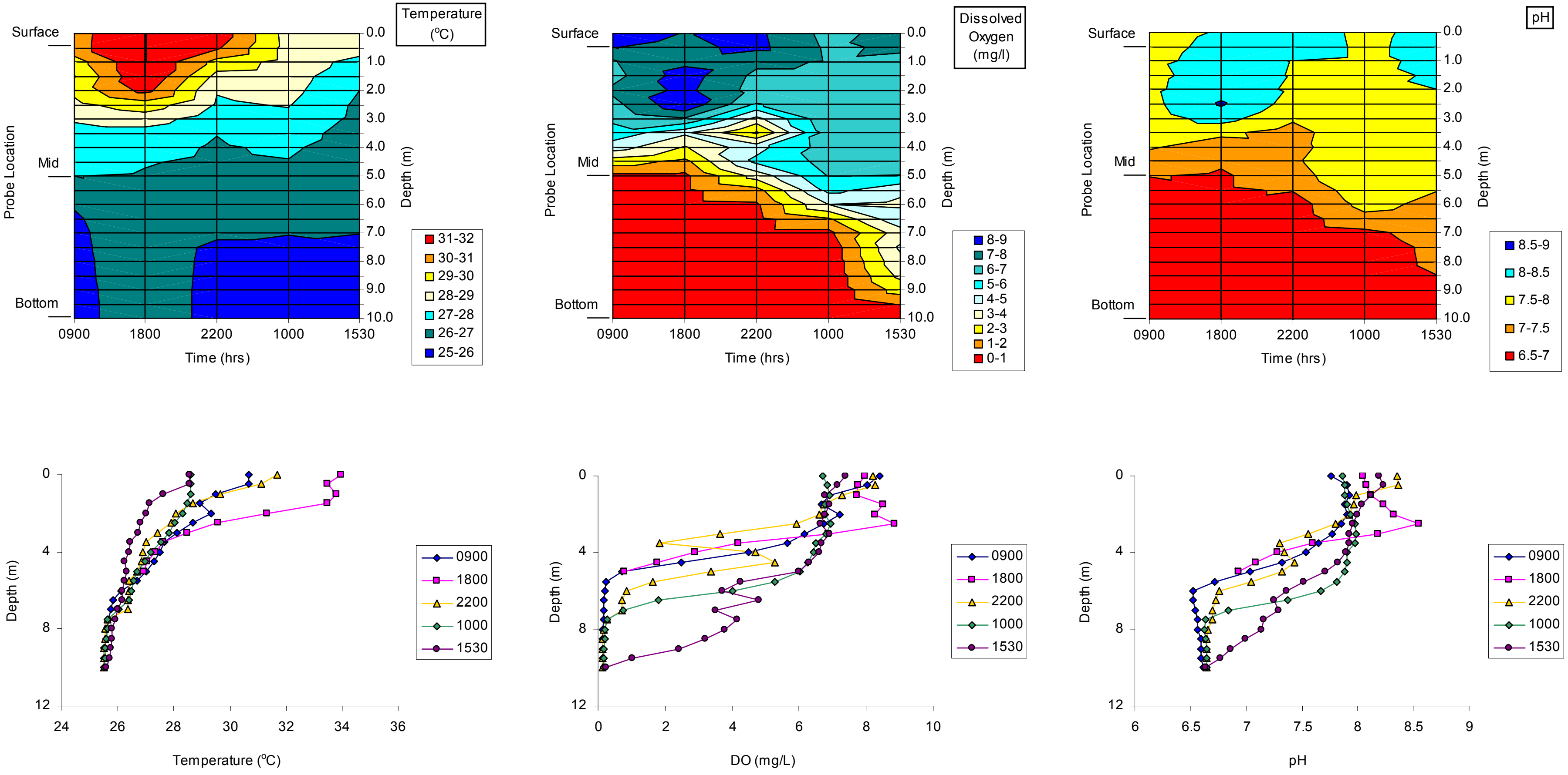

Figure 16. Changes in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Ulawas (Oxb01) in February 2005.

3.1.1.2.3 Moian Oxbow

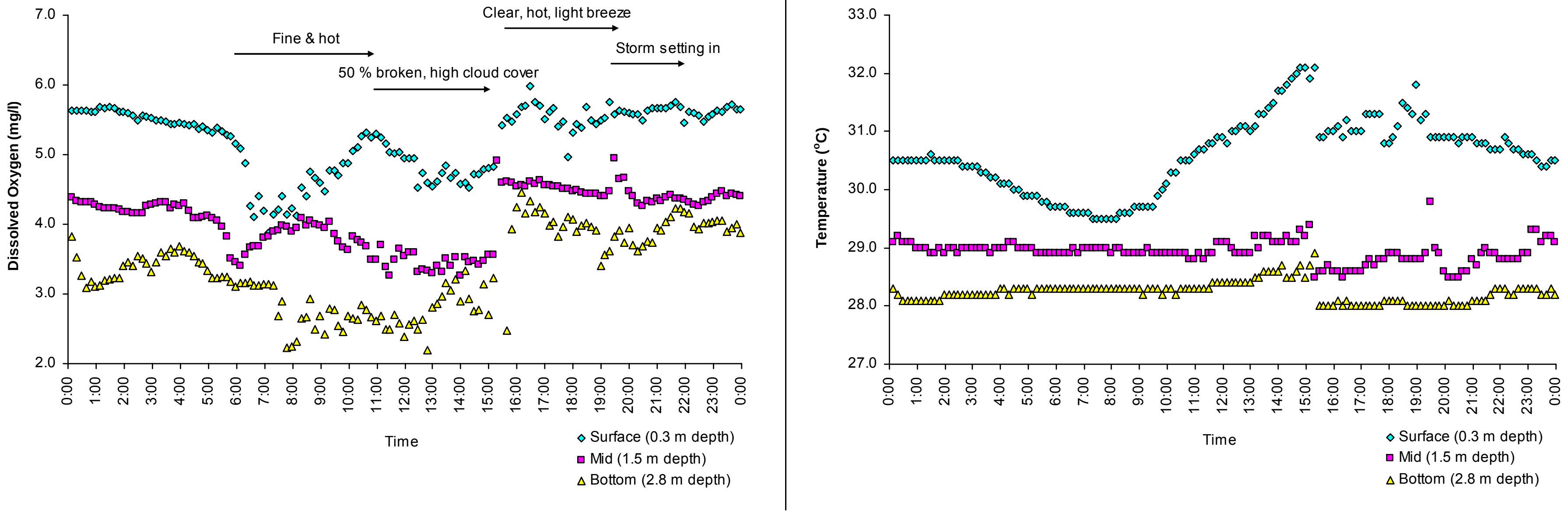

Figure 17. Diel curves for dissolved oxygen (left) and temperature (right) at Moian Oxbow in February 2005. Probes were deployed at 1530 hrs and removed at 1500 hrs.

Moian Oxbow was a relatively shallow waterbody, with a maximum depth at time of sampling of approx 3 m (NB river levels were low, and as such water levels in the oxbow were low). As a result, the limnology of the oxbow was very responsive to periods of wind, rain and sunshine. Temperature was stratified during the day, with a sharp decline from surface temperature of ~30ºC to ~28ºC at < 1 m depth, but this stratification broke down at night, with little difference between surface and bottom. DO was very variable within a level, however, surface was consistently higher than mid, which was higher than bottom DO (Figure 17). Temperature and DO showed a trend of high daytime and low night time levels; however, there was a lot of variability, likely due to effects of periods of sunshine and wind action on this shallow water body (Figure 18).

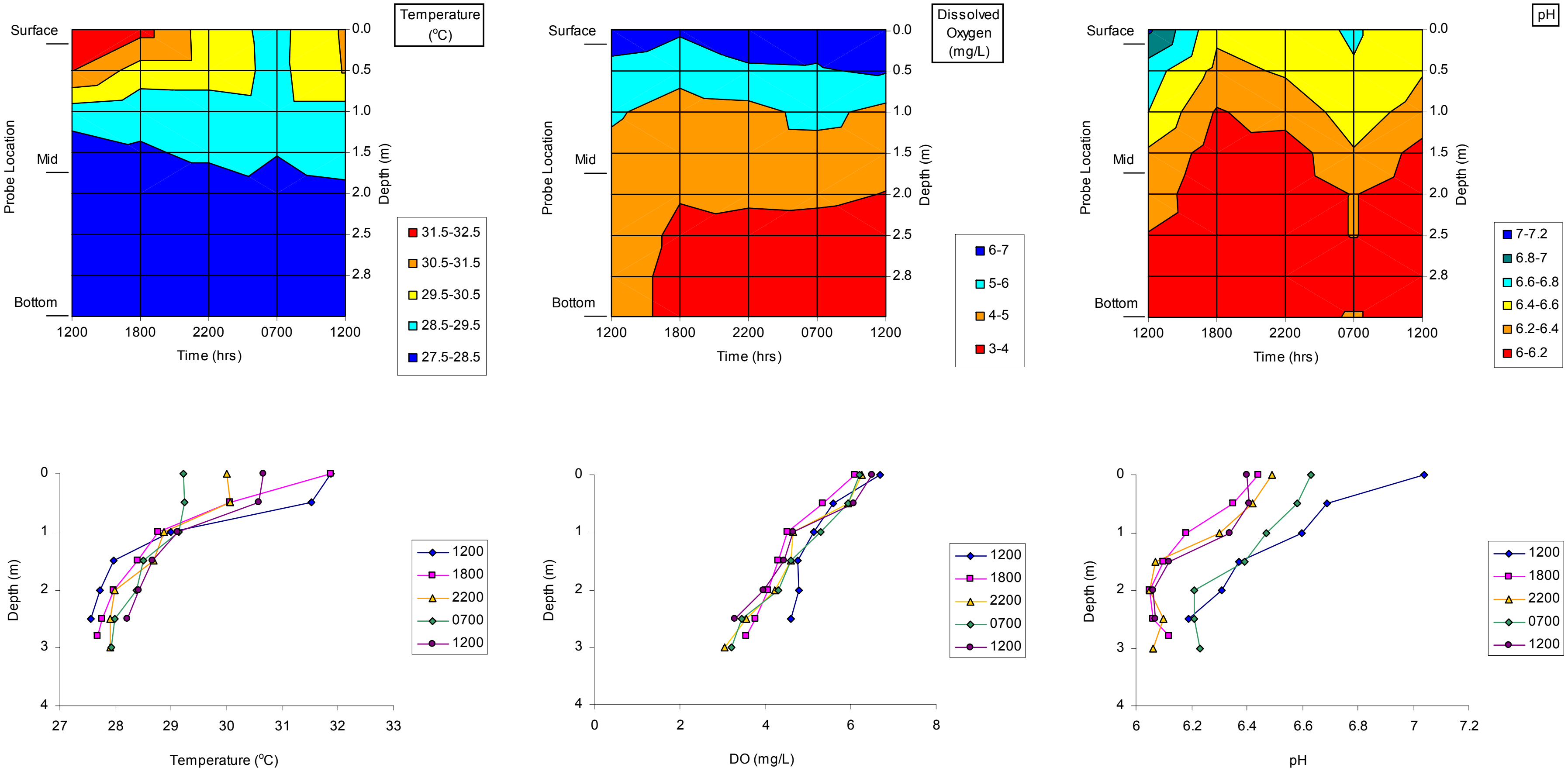

Figure 18. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Moian Oxbow in February 2005.

3.1.1.3 Exposed Forested Oxbows

3.1.1.3.1 Kuambit Oxbow

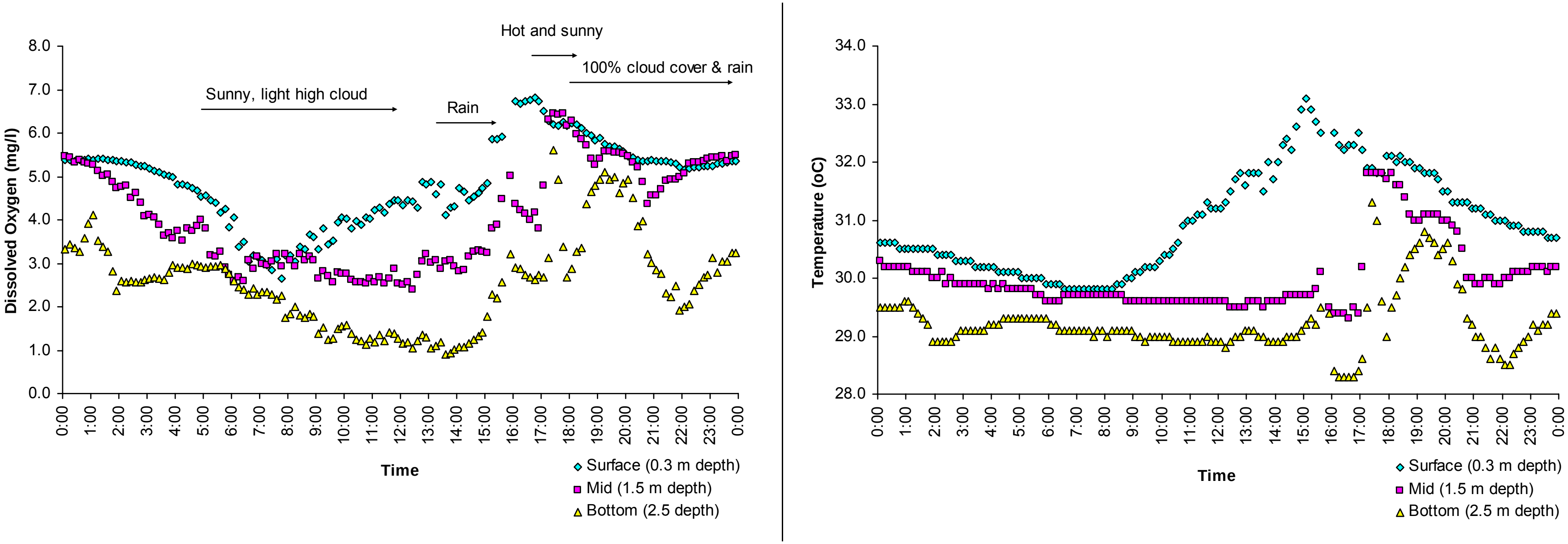

Figure 19. Diel curves for dissolved oxygen (left) and temperature (right) at Kuambit Oxbow in February 2005. Probes were deployed at 1600 hrs and removed at 1530 hrs.

Kuambit Oxbow was a shallow waterbody, with a maximum depth at time of sampling of approx 3 m. This partly reflected low river levels, but also infilling of the oxbow by mine-derived sediment. As a result, the limnology of the oxbow was very responsive to periods of wind, rain and sunshine, and inflow/outflow. At the commencement of sampling the oxbow was out-flowing, however, towards the end of the 24 hr period the river had risen and was flowing into the oxbow. This is reflected in the variable DO and temperature plots during the morning/early afternoon of the second day. At the start of monitoring, the oxbow exhibited a strong temperature gradient from 32°C at the surface to 28°C at the bottom. However, this differential was disrupted in the early evening (~1700 - 2200 hrs) due to an extreme thunderstorm with heavy rain and high winds. The mixing and cooling effects of the wind and rain are reflected in the DO and temperature plots (Figure 19).

Diel DO curves for Kuambit Oxbow showed that bottom dissolved oxygen was permanently at levels at which most aquatic fauna would experience a degree of stress (< 4 mgL^{-1}), and extreme low DO conditions (< 2 mgL^{-1}) were reached at the bottom of the lake around 8.00 am, and persisted for the rest of that morning (approx. 7 hours). The early morning DO minima is typical, reflecting night time depletion due to respiration. Surface and mid-level probes also showed an early morning minimum, followed by a gradual increase during the day reflecting build-up of DO by photosynthesis under the bright, sunny weather. The relatively shallow depth of the Kuambit oxbow allowed more thorough mixing of the water column, particularly during the storm which occurred about 5.00 pm.

Due to difficulties accessing Kuambit oxbow by boat (the entrance channel was shallow and silted, with falling water levels in mid afternoon preventing entry to the oxbow during the night and early next day), it was not possible to take Hydrolab readings during the night and next morning. This is reflected in the plots for vertical profiles in Hydrolab parameters (Figure 20).

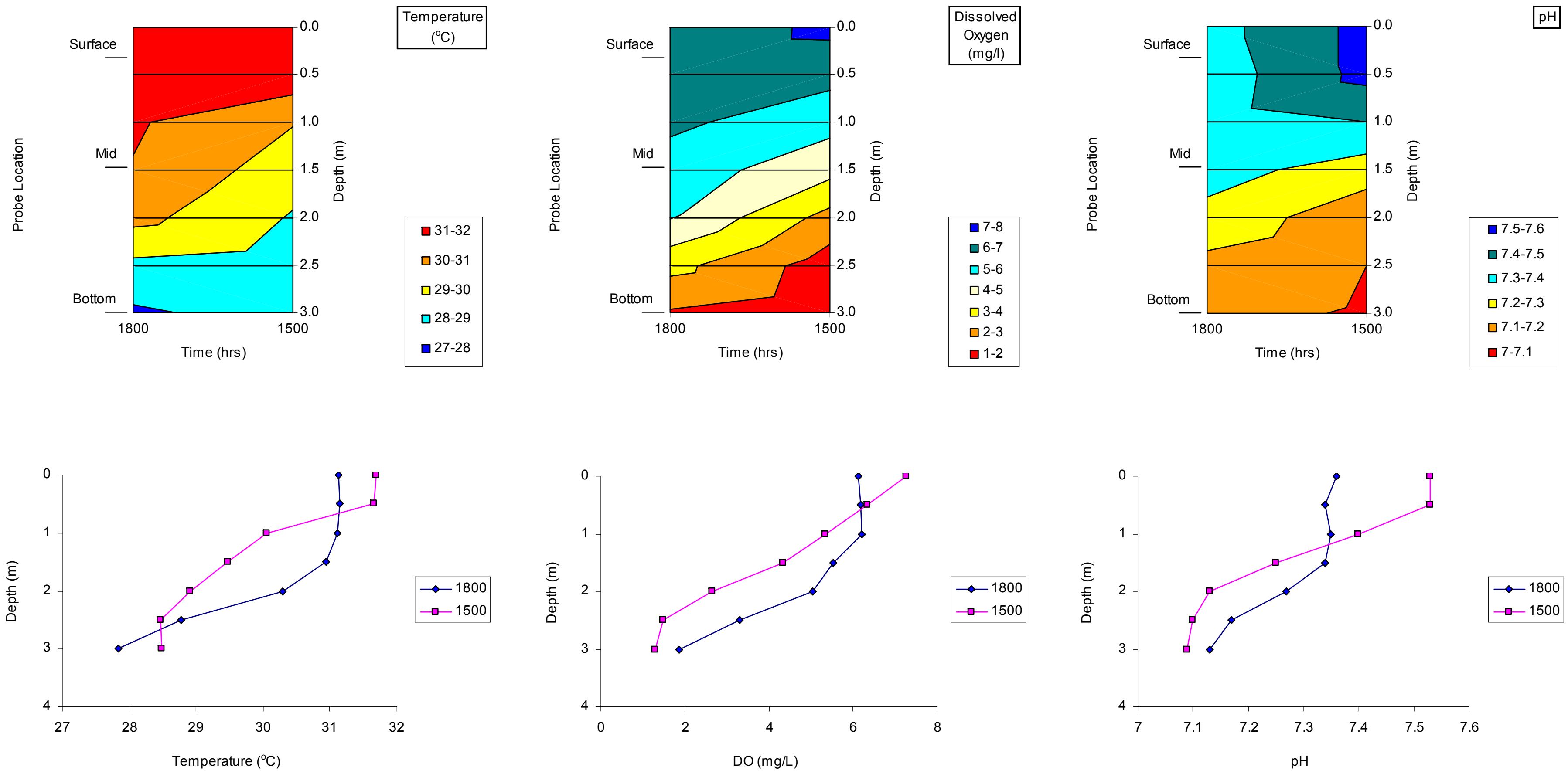

Figure 20. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Kuambit Oxbow in February 2005.

3.1.1.3.2 Erekta (OXB02)

Due to a refugee camp beside OXB02, it was considered unsafe to deploy probes/loggers in the lake unattended overnight. However, Hydrolab measurements were taken. Data show OXB02 to have a strong thermocline, with temperature dropping from 32ºC to 27ºC by 2 m depth. Temperature was then constant to the bottom of the lake (Figure 21). This thermocline was accompanied by a strong DO stratification. Although surface waters were well oxygenated (~6 mg L^{-1}), by 2 m DO had dropped to < 1 mg L^{-1}, and was zero at the bottom. This site was heavily impacted with substantial forest die-off. This resulted in a high loading of dead timber/organic matter in the water column which would have a high respiration demand and likely accounted for some of the depletion in oxygen levels beneath the thermocline.

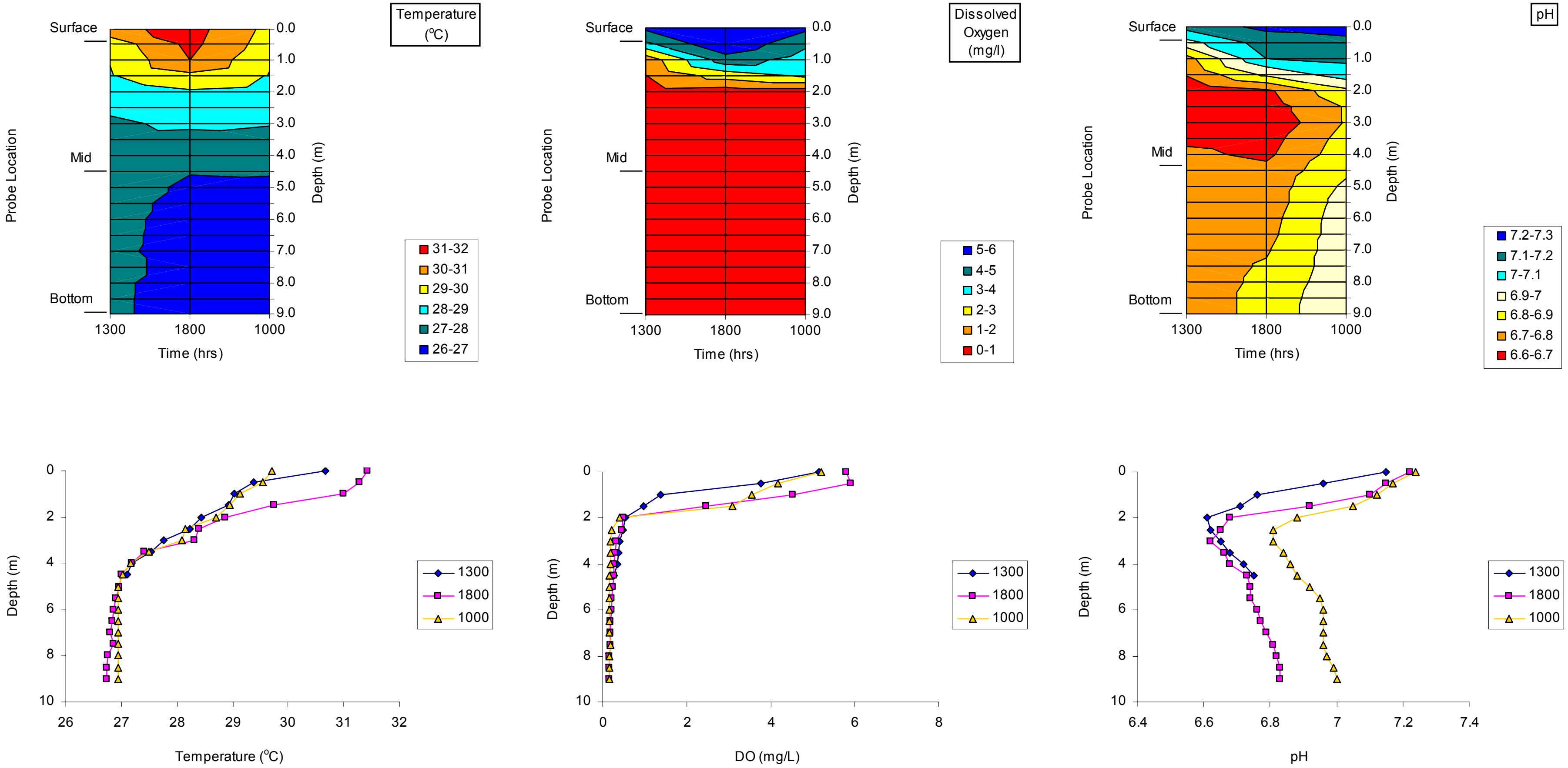

Figure 21. Changes in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Erekta (Oxb02) in February 2005.

3.1.1.3.3 Kwem (OXB06)

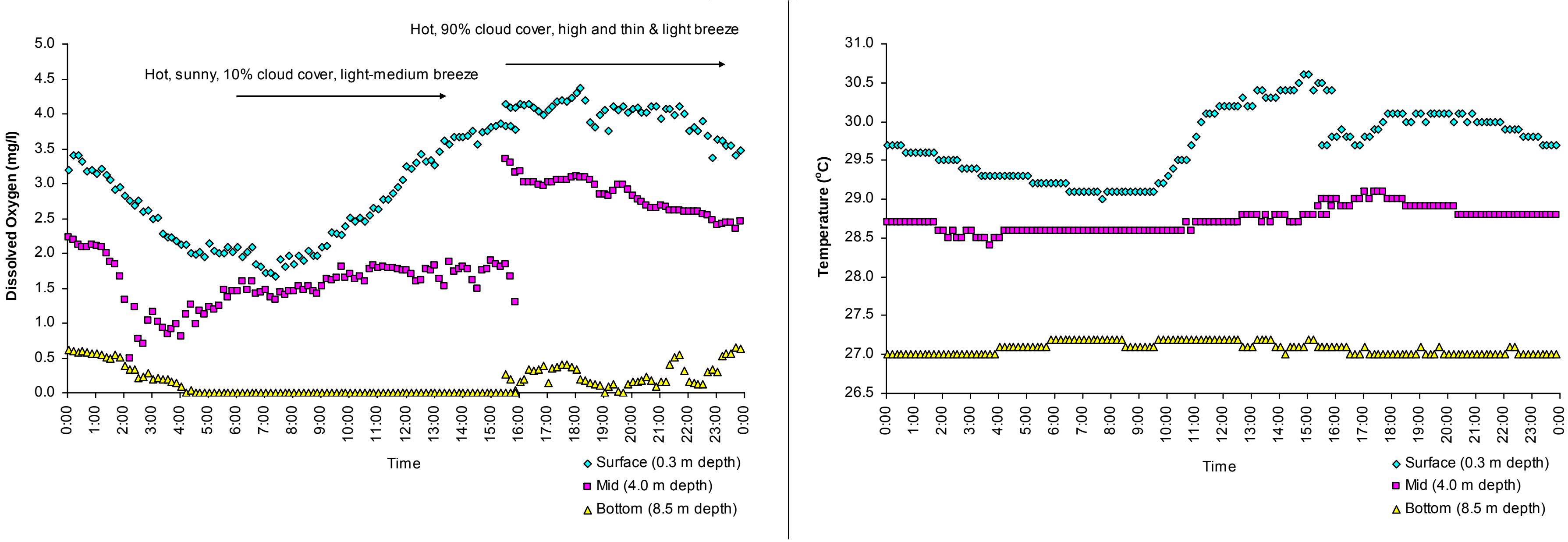

Figure 22. Diel curves for dissolved oxygen (left) and temperature (right) at Kwem (Oxb06) in February 2005. Probes were deployed at 1530 hrs and removed at 1600 hrs.

Kwem surface dissolved oxygen data displays a fairly typical diel pattern of concentration, with the peak during the middle of the day, and the lowest point occurring in the early morning after gradual depletion overnight (Figure 22). As with the other deep oxbows, Kwem had permanent anoxic conditions at the bottom depths. The overall DO values for this site were the lowest of the deep oxbows. Extensive forest dieback has occurred along the banks of Kwem oxbow, and a 20 metre belt of floating grass has developed around the perimeter. This has potential to increase the amount of decaying organic matter within the water column, and thus decrease the available oxygen. It was also noted that there was more zooplankton in the water column, during night sampling, than at any other site. The belt of grass was believed to provide good habitat (shelter) for the zooplankton, and may explain the increased numbers at this site. With increased numbers of zooplankton in the water column, you also get greater oxygen consumption and therefore decreased dissolved oxygen values, especially at night.

Temperature profiles showed a steep gradient in temperature over the surface 4 m, there was then a rapid drop of 2 - 3^{o}C in temperature over a 1 - 1.5 m depth range, indicating some stratification (Figure 23). DO showed a similar pattern, with a steady decline from surface waters to ~4 m depth, by which depth DO had declined to close to zero. As shown by the diel curves, the bottom waters were continually close to anoxic (Figure 23).

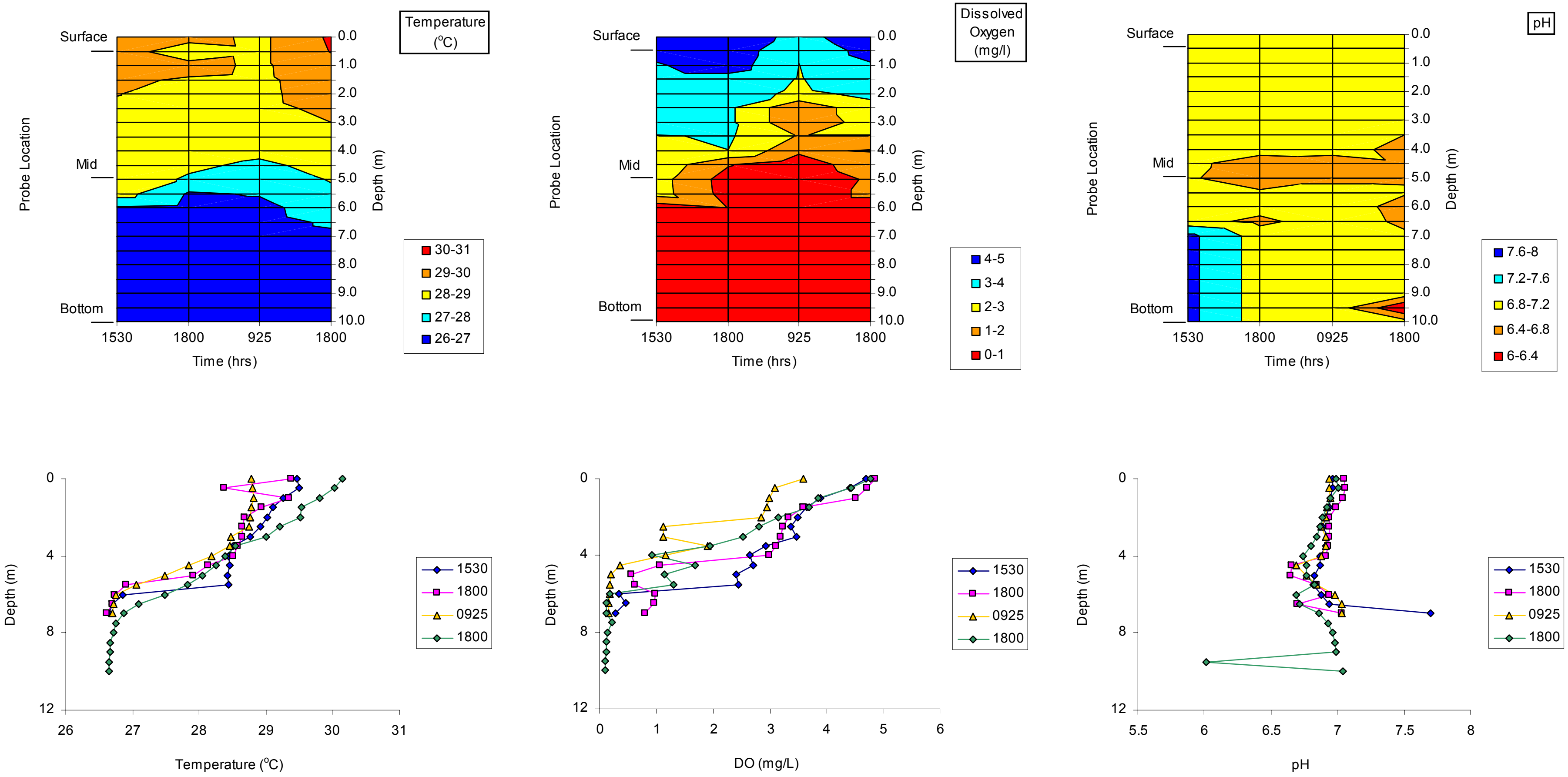

Figure 23. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Kwem (Oxb06) in February 2005.

3.1.2 July 2005 Data

3.1.2.1 *Blocked Valley Lakes*

3.1.2.1.1 Bosset Lagoon

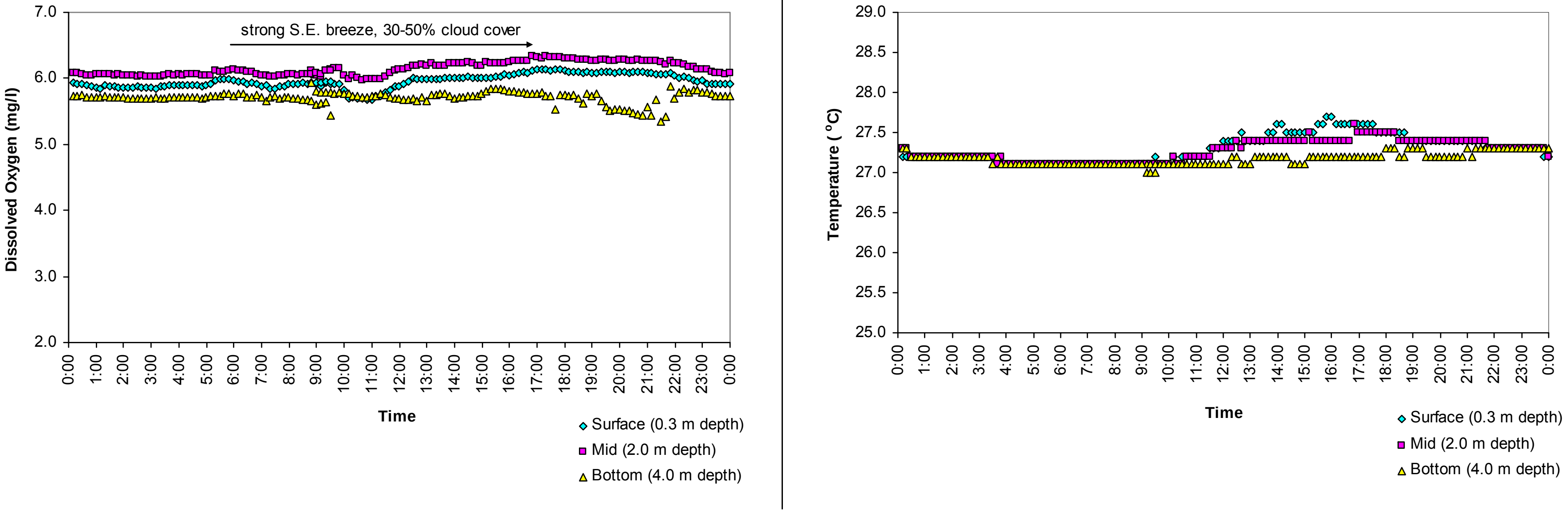

Figure 24. Diel curves for dissolved oxygen (left) and temperature (right) at Bosset Lagoon (BOS10) in July 2005. Probes were deployed at 0840 hrs and retrieved at 1030 hrs.

At the time of sampling, Bosset Lagoon was predominantly open water, with grass cover only around the edges and embayments. DO values were relatively high (5.5 - 6.5 mg L^{-1}) for surface, mid and bottom probes throughout the 24 hrs, and were above the critical level for fauna and ecological process (4 mg L^{-1}) (Figure 24). From the time of deployment Bosset Lagoon was subjected to strong and persistent south-easterly winds which appear to have kept the water body well mixed in terms of temperature and DO profiles. There was a slight reversal in DO concentrations between the surface and mid-water locations, with lowest DO levels in the bottom, but still well oxygenated. There was a slight increase in water temperature in the surface and mid-water locations, but this increase was not evident in the bottom location.

Bosset Lagoon was relatively shallow (~4 m deepest), and this combined with the SE winds appears to have caused mixing of the water column, as can been seen in the vertical profiles, whereby there is little change in temperature, DO or pH with depth (Figure 25). There was a slight drop in temperature at 2400 hrs, probably reflecting slightly lower night time temperatures (Figure 25).

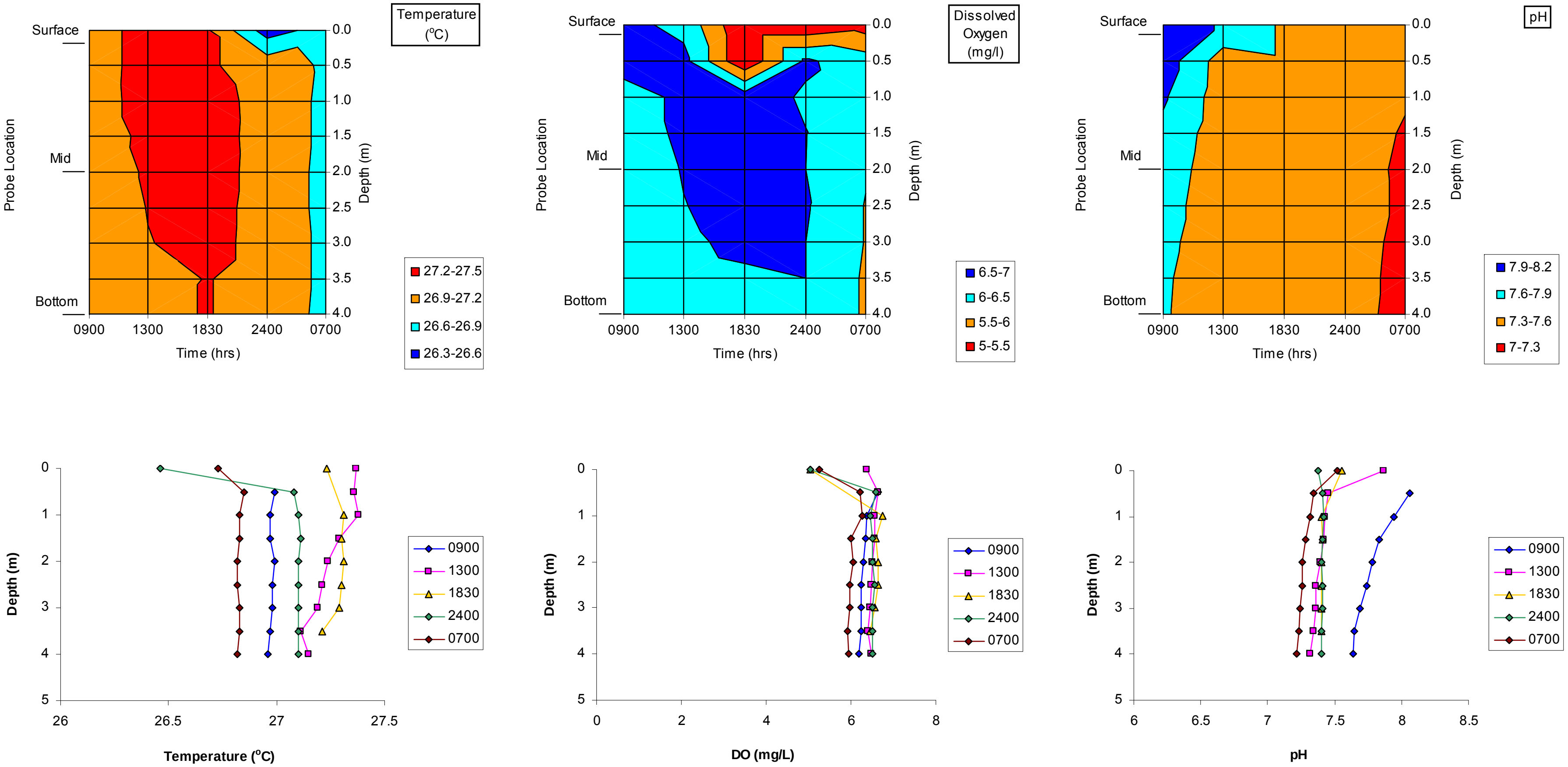

Figure 25. Changes in water chemistry variables (temperature, dissolved oxygen and pH over depth and time for Bosset Lagoon (BOS10) in July 2005.

3.1.2.2 Control Forested Oxbows

3.1.2.2.1 Drimdenasuk

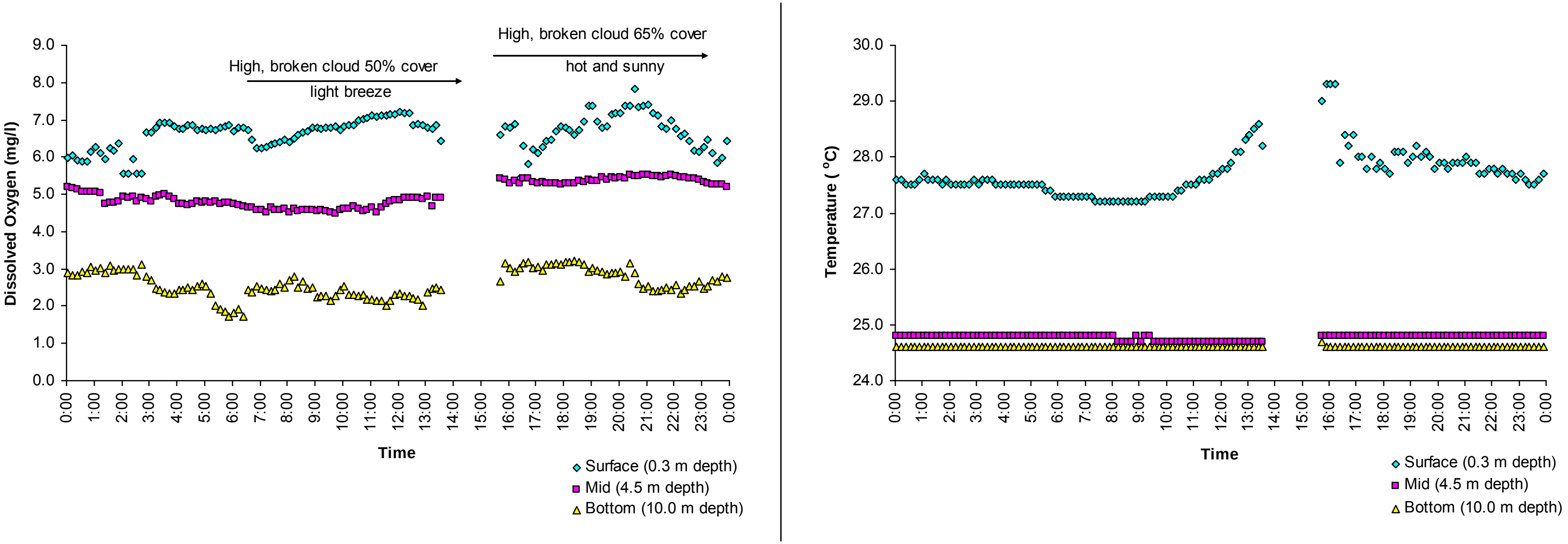

Figure 26. Diel curves for dissolved oxygen (left) and temperature (right) at Drimdenasuk (FLY02oxb) in July 2005. Probes were deployed at 1535 hrs and retrieved at 1340 hrs.

Drimdenasuk displayed a strong vertical profile in DO and temperature, with declining concentrations with depth (Figure 26). Surface and mid-water levels were consistently above 4 mg L^{-1}, however bottom waters never rose above this threshold. Water temperature showed strong stratification, with both mid and bottom waters similar to each other, and approximately 2 - 3°C below surface waters. Diel curves showed a slight decline in DO at night and a strong temperature peak for surface waters in the afternoon.

Drimdenasuk displayed the same unusual result as seen in February, with the middle layer having lower dissolved oxygen than both the upper and bottom layers. This phenomenon was noted for the hydrolab data (Figure 27), but not for the loggers, presumably because the logging probes set at 4.5 m depth missed the narrow zone of depletion. It is likely that the decrease in DO in the middle of the water column was the result of a layer of zooplankton sitting at this position in the water column, likely feeding on bacteria. This pattern was seen in February, suggesting a very stable system over time.

Vertical profiles in temperature showed strong stratification, with a thermocline at ~1 m depth, with temperatures declining from ~28°C on the surface to ~24°C at 1 - 2 m depth. This temperature stratification was constant throughout the 24 hr period. As noted above, DO showed an inversion at ~1 m. This equates to the position of the thermocline, and may reflect the level at which zooplankton accumulate above the thermocline.

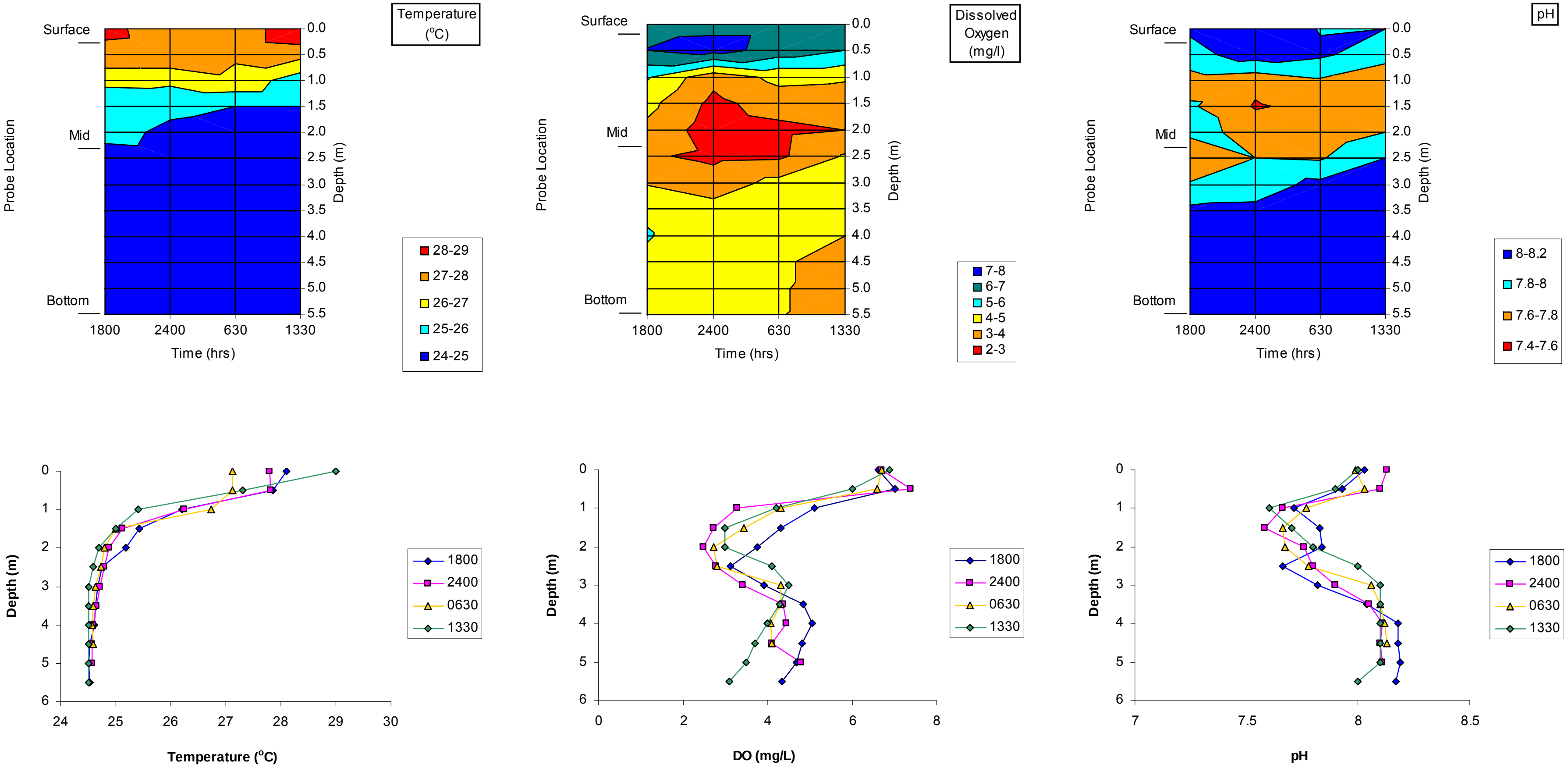

Figure 27. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Drimdenasuk (FLY02oxb) in July 2005.

3.1.2.2.2 Moian Oxbow

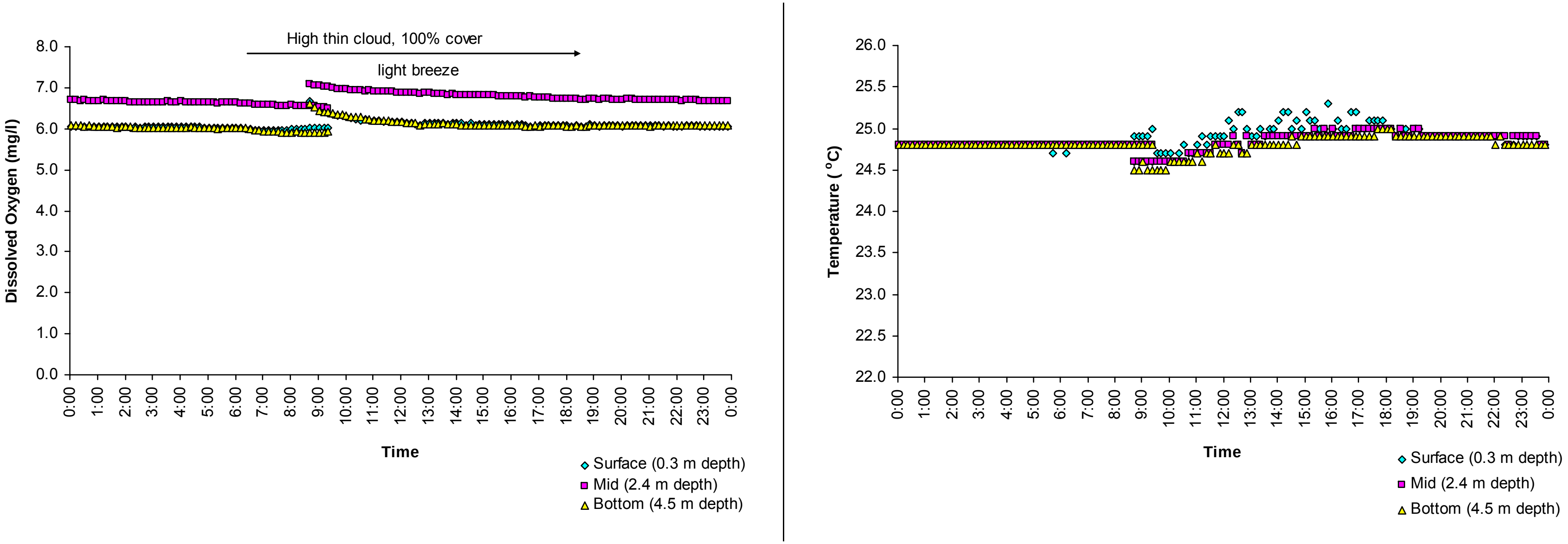

Figure 28. Diel curves for dissolved oxygen (left) and temperature (right) at Moian Oxbow in July 2005. Probes were deployed at 0835 hrs and removed at 0930 hrs.

DO values in Moian were relatively high ($\geq \sim 6.0$ mg L^{-1}) for surface, mid and bottom probes throughout the 24 hrs, and were above the critical level for fauna and ecological process (4 mg L^{-1}) (Figure 28). From the time of deployment the Fly River was flowing strongly into Moian Oxbow, and the waterbody was turbid from inflows. This strong inflow appears to have kept the water body well mixed in terms of temperature and DO profiles. There was a slight reversal in DO concentrations between the surface and mid-water locations, with lowest DO levels in the bottom, but still well oxygenated. There was a slight increase in water temperature in the surface waters, but this was not obvious in the mid or bottom locations.

As for the loggers, the Hydrolab data shows the water column to have been well mixed as can been seen in the vertical profiles, whereby there is little change in temperature, DO or pH with depth (Figure 29).

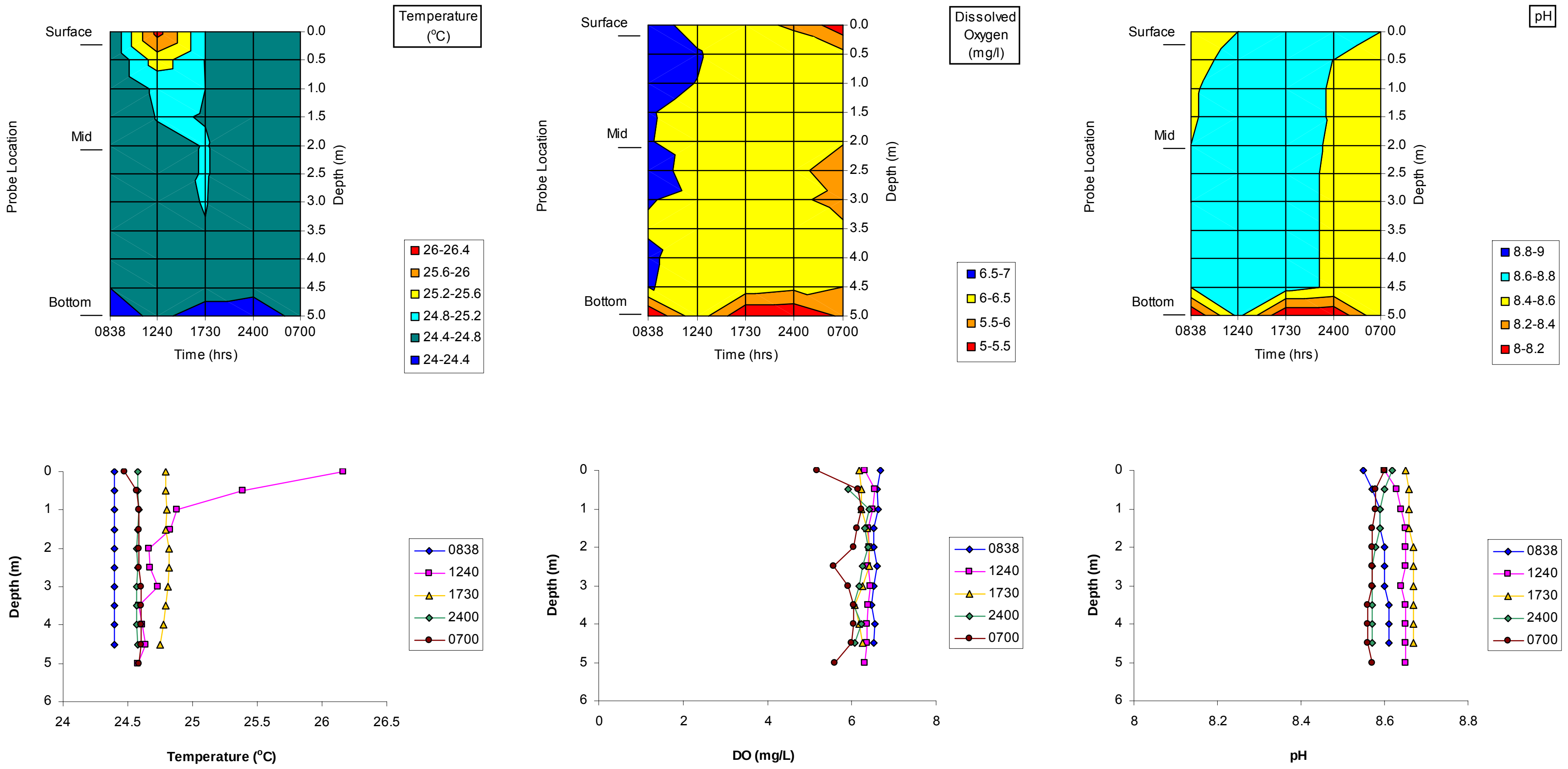

Figure 29. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Moian Oxbow in July 2005.

3.1.2.3 Exposed Forested Oxbows

3.1.2.3.1 Erekta (OXB02)

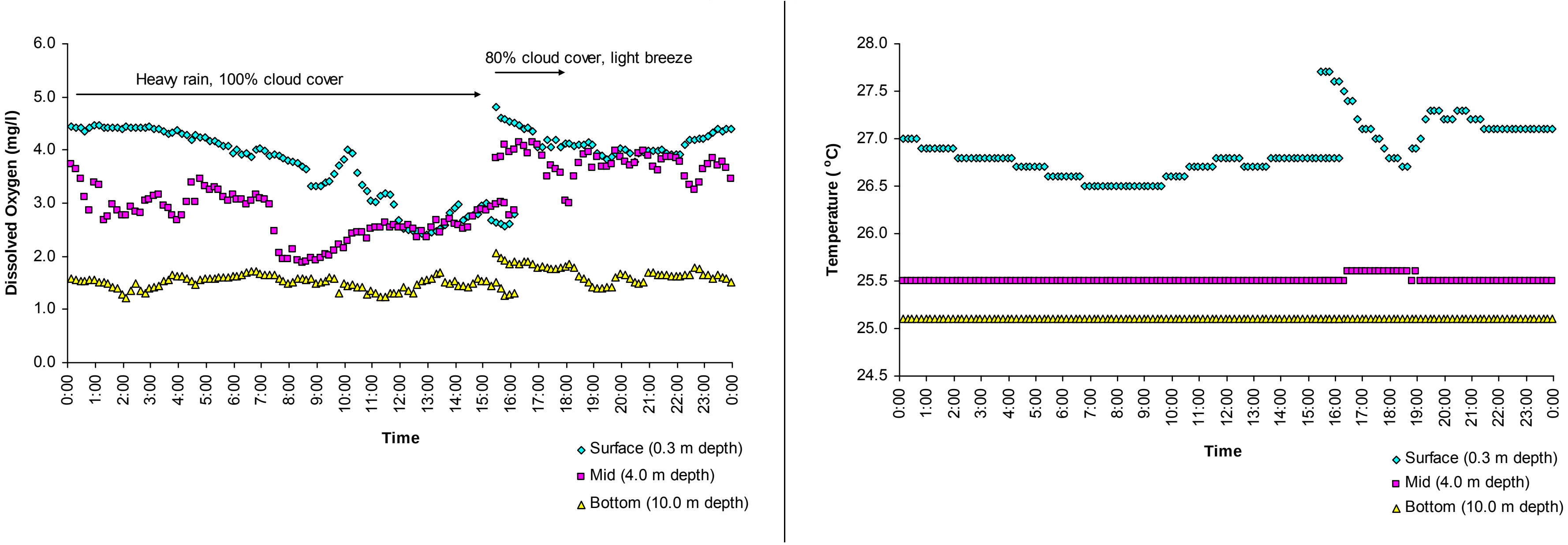

Figure 30. Diel curves for dissolved oxygen (left) and temperature (right) at Erekta (Oxb02) in July 2005. Probes were deployed at 1520 hrs and removed at 1730 hrs.

Erekta surface dissolved oxygen data displays a fairly typical diel pattern of concentration, with the peak during the middle of the day, and the lowest point occurring in the early morning after gradual depletion overnight (Figure 30). As with the other deep oxbows, Erekta had permanent low oxygen conditions at the bottom depths. The establishment of heavy cloud cover and then the onset of heavy rain in the afternoon seem to have reduced surface DO levels, and possibly mixed with mid-level waters to result in similar DO levels at surface and mid-water levels. However, surface water temperatures remained higher than mid and bottom temperatures throughout.

Temperature profiles showed little change over the surface ~2 m, and then a steep gradient in temperature from 3 to 7 m, over which there was a drop of 2 - 3°C, indicating some stratification (Figure 31). DO showed a similar pattern, with a steady decline from surface to deep waters, by which depth DO had declined to < 2 mg L^{-1}.

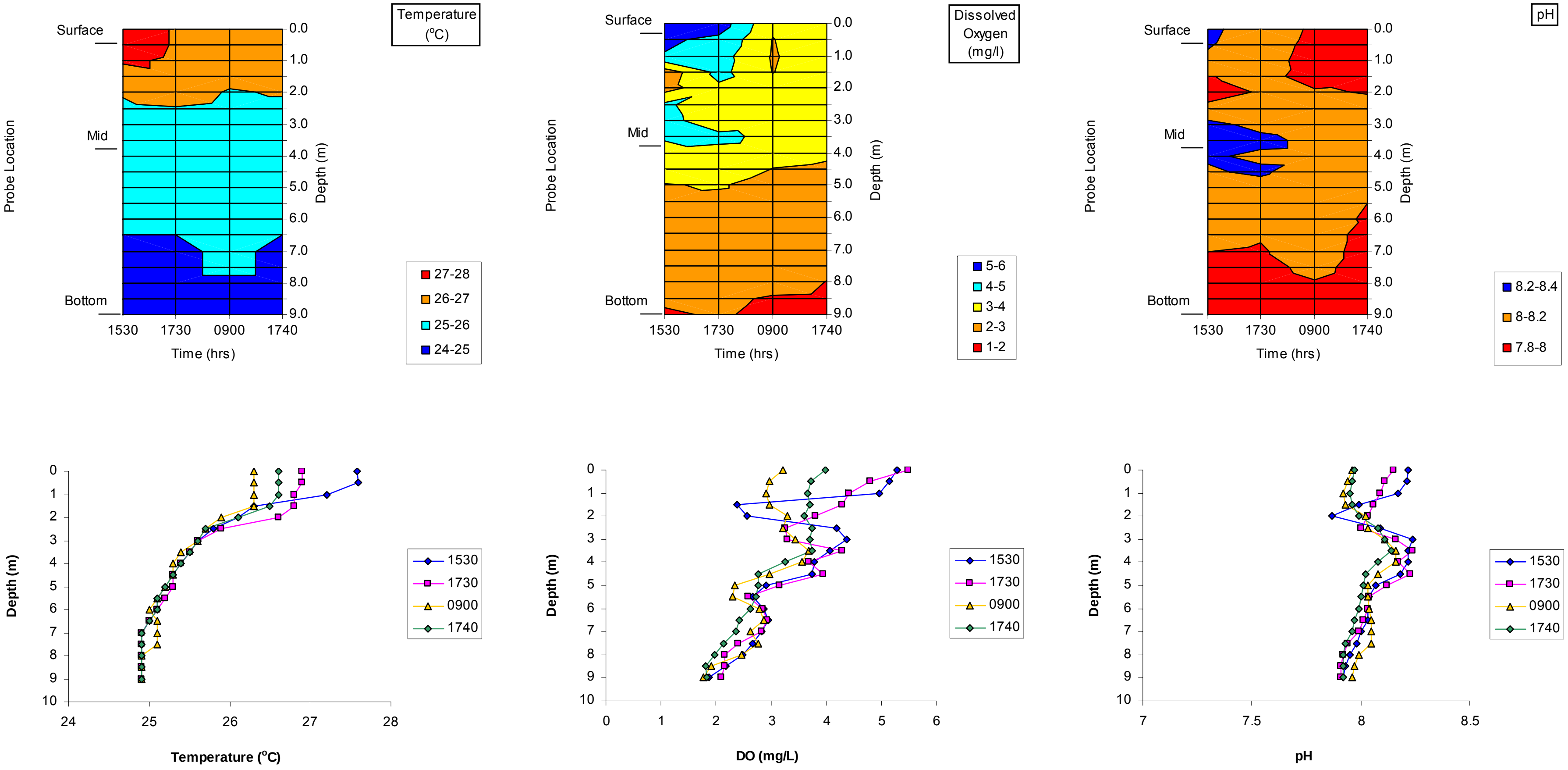

Figure 31. Changes in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Erekta (Oxb02) in July 2005.

3.1.2.3.2 Kwem (OXB06)

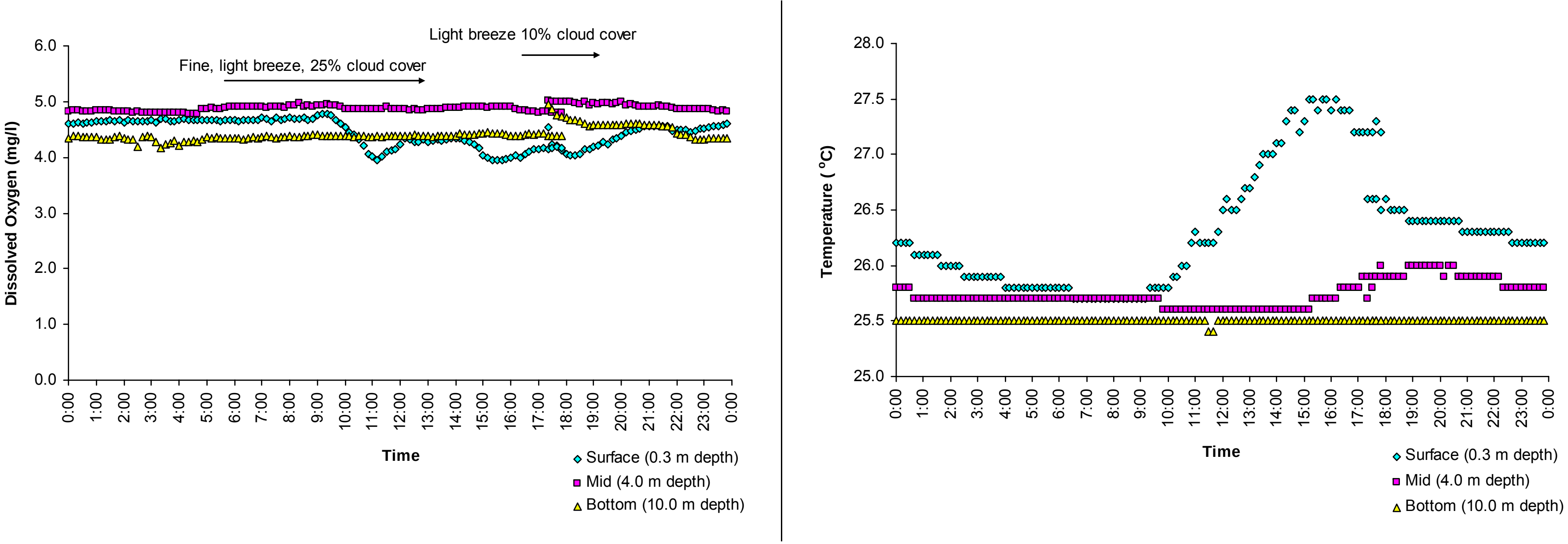

Figure 32. Diel curves for dissolved oxygen (left) and temperature (right) at Kwem (Oxb06) in July 2005. Probes were deployed at 1710 hrs and removed at 1800 hrs.

DO values in OXB06 were relatively constant (4.0 - 5.0 mg L^{-1}) for surface, mid and bottom probes throughout the 24 hrs, but were close to the critical level for fauna and ecological process (4 mg L^{-1}) (Figure 27). From the time of deployment the Fly River was flowing strongly into Kwem Oxbow, and the waterbody was turbid from inflows. This strong inflow appears to have kept the water body well mixed in terms of temperature and DO profiles. There was a slight reversal in DO concentrations between the surface and mid-water locations, with lowest DO levels in the bottom, but still well oxygenated. There was an increase in water temperature in the surface waters in the middle of the day, but this was not obvious in the mid or bottom locations (Figure 32).

As for the loggers, the Hydrolab data shows the water column to have been well mixed as can been seen in the vertical profiles, whereby there is little change in temperature, DO or pH with depth, except midday and afternoon temperature which was elevated on the surface (Figure 33).

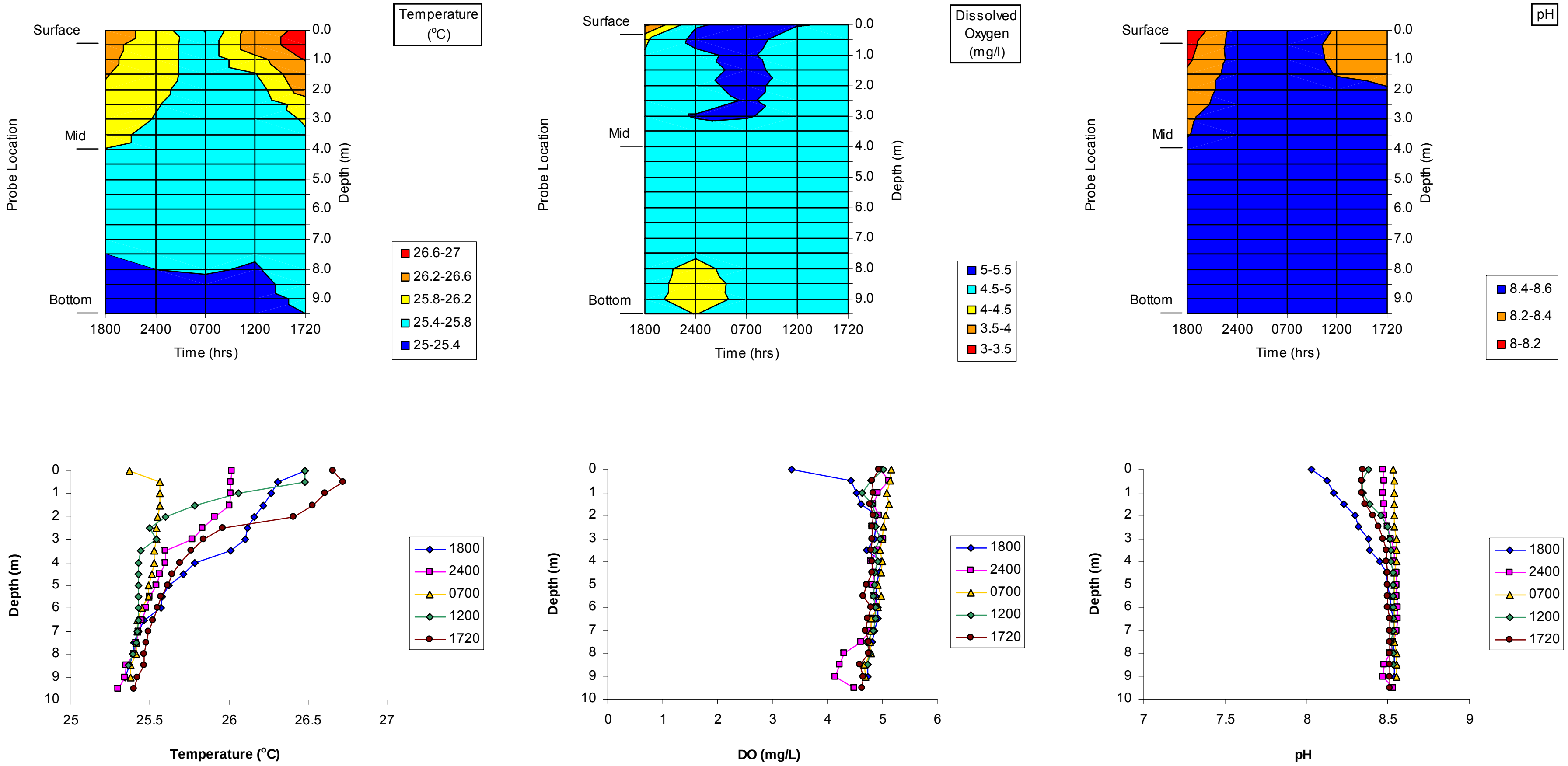

Figure 33. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Kwem (OXB06) in July 2005.

3.1.2.4 Impact Grassed Oxbows

3.1.2.4.1 Lake Pangua

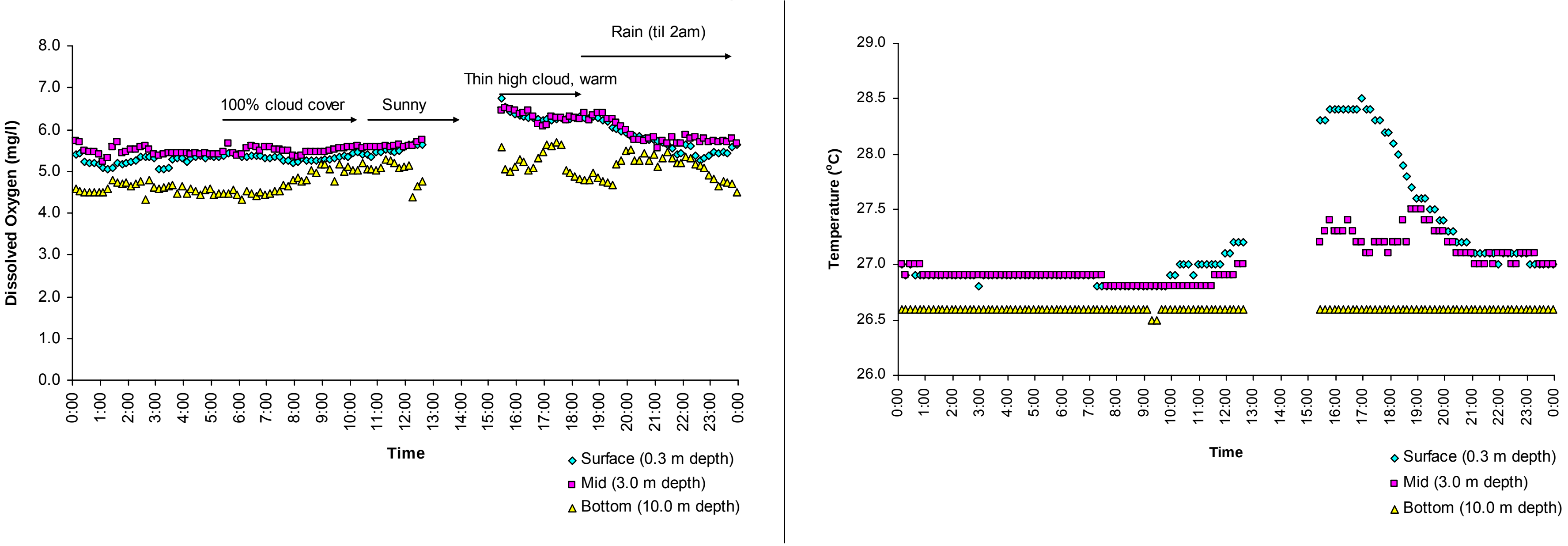

Figure 34. Diel curves for dissolved oxygen (left) and temperature (right) at Lake Pangua in July 2005. Probes were deployed at 1530 hrs and removed at 1245 hrs.

DO values in Pangua (OXB05) were relatively constant (4.0 - 5.0 mgL^{-1}) for surface, mid and bottom probes throughout the 24 hrs, but were close to the critical level for fauna and ecological process (4 mg L^{-1}) (Figure 34). From the time of deployment the Fly River was flowing strongly into the north end of Pangua Oxbow, and the waterbody was turbid from inflows at the north end, however, turbidity was much reduced around the probes which were positioned towards the southeast end of the system. This strong inflow may have kept the water body well mixed in terms of temperature and DO profiles. The lake was also subject to constant south-easterly winds, which may have assisted mixing. There was a slightly lower DO concentration in the bottom waters compared with the surface and mid-water locations, but still well oxygenated. There was an increase in water temperature in the surface and mid-water in the middle/latter half of the day, but this was not detectable in the bottom locations. However, it should be noted that this is a very deep oxbow, and maximum depth exceeded probe depth by 5 - 10 m.

Due to distances involved in entering the oxbow and accessing the monitoring location, the Hydrolab was only deployed three times, and therefore data are limited. However, data show the water column to have been well mixed as can been seen in the vertical profiles, whereby there is little change in temperature, DO or pH with depth (Figure 35).

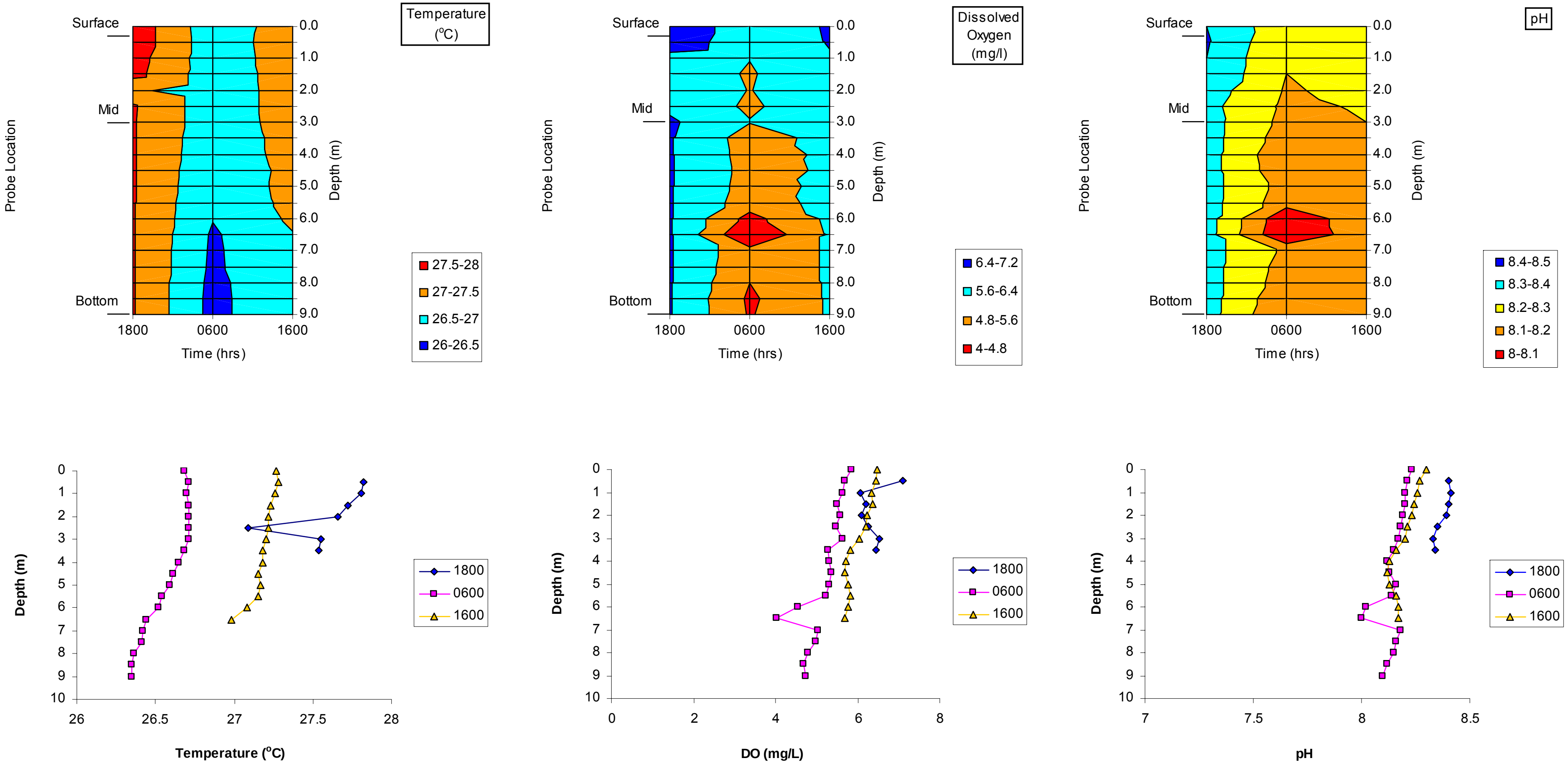

Figure 35. Change in water chemistry variables (temperature, dissolved oxygen and pH) over depth and time for Lake Pangua in July 2005.

3.2 Heavy and Alkali Metals

3.2.1 Aluminium (Al)

Aluminium concentrations were for the most part highly variable, with no clear patterns to suggest differences between any of the factors under investigation (Table 3). Nevertheless, marginal trends (Table 3) were evident at exposure level oxbows in February, when the concentration of aluminium tended to increase with depth (Figure 36). However, despite these trends, there was little additional evidence supporting this notion, with most sites exhibiting highly variable aluminium concentrations (both at the level of Depth (D) and Season (Sn)). Of some concern, however, was the fact that concentrations of aluminium were in some instances found to exceed the ANZECC/ARMCANZ (2000) trigger value expected to maintain 99% of aquatic biodiversity (Figure 36). This was particularly the case at Moian and Oxbow 6 in July, when aluminium concentrations exceeded the trigger value at each of the Depth (D) levels (Surface, Middle and Bottom). In these instances, the uniformity of Al concentrations with depth effectively limits opportunity for fauna to seek refuge; hence, those species (~1%) adversely affected at this level of aluminium concentration are likely to be adversely affected, or where possible, migrate out of the oxbow (provided concentrations are not also elevated in the main river channel).

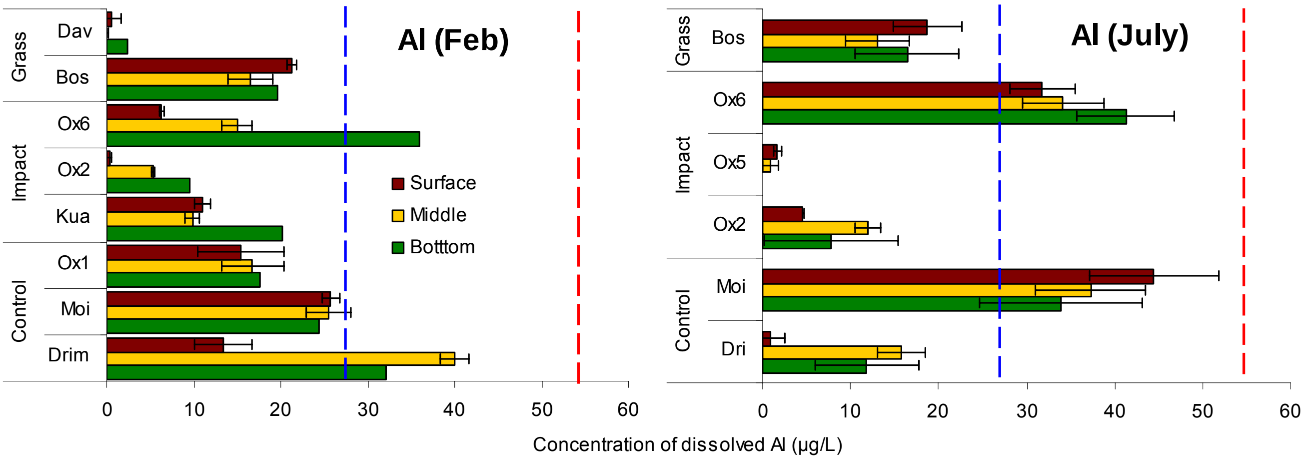

Figure 36. Seasonal comparison of dissolved aluminium concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grassland, Impact and Control). Blue and red vertical broken lines depict ANZECC/ARMCANZ (2000) trigger values for the protection of 99% and 95% of aquatic species respectively.

Table 3. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Al concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→				High	Low	→	High
Al				Bos	Dav	Kiu	Kua	Ox2	Ox5	Dri	Ox6	Moi	Mid	Sur	Bot
Site (S)	8	0.516	0.841												
Depth (D)	2	1.442	0.243												
Season (Sn)	1	0.028	0.867												
S*D	15	0.651	0.824												
S*Sn	4	1.714	0.155												
D*Sn	2	0.105	0.901												
S*D*Sn	8	1.692	0.113												

3.2.2 Copper (Cu)

Clear trends were apparent with regard to copper, with most sites exceeding ANZECC/ARMCANZ trigger values for the protection of aquatic fauna (Figure 37). This was the case particularly at impact sites, all of which exceeded the trigger value expected to protect 80% of aquatic biodiversity (based on Australian tropical rivers). Contrasting results were obtained at control oxbows, where concentrations of Cu were significantly lower (Table 4), but, nevertheless sufficient to exceed the 99% and 95% trigger values during February. Significant differences were also apparent between seasons, with Cu concentrations tending to decrease slightly in July. However, this was not a trend observed consistently across oxbows, but a reflection of the substantial reduction observed at control sites alone (Figure 37). Concentrations of copper within other exposure levels maintained similar levels between seasons, with the possible exception of Bosset Lagoon where dCu appeared to increase significantly in July. There were no clear trends with respect to copper concentration with depth (Table 4).

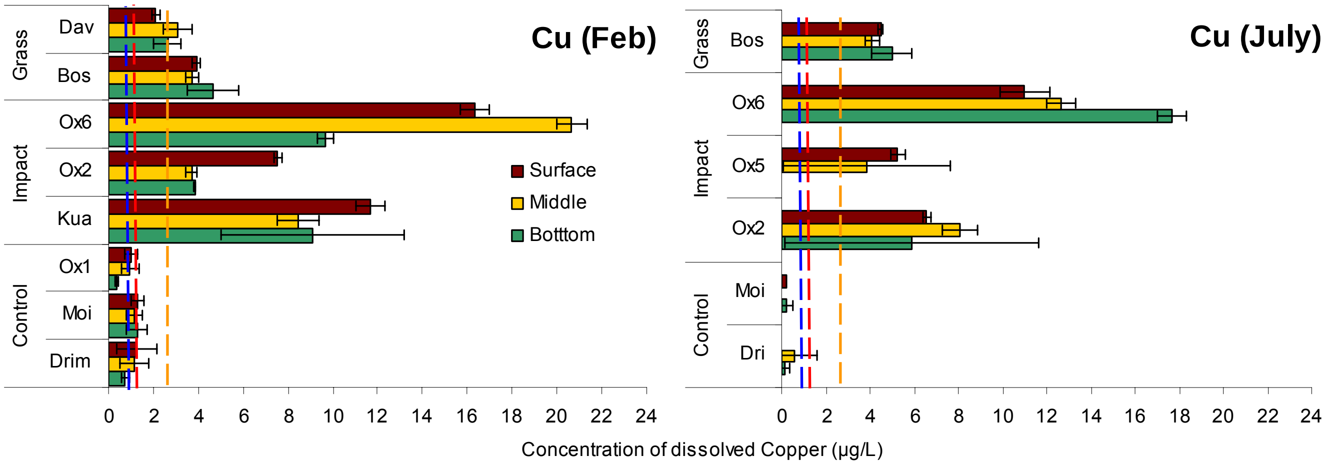

Figure 37. Seasonal comparison of dissolved Copper concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grassland, Impact and Control). Blue, red and orange vertical broken lines depict ANZECC/ARMCANZ (2000) trigger values for the protection of 99%, 95% and 80% of aquatic species, respectively.

Table 4. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Cu concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Cu				Dri	Moi	Kiu	Dav	Ox5	Bos	Ox2	Kua	Ox6	Bot	Mid	Sur
Site (S)	8	153.68	0.000												
Depth (D)	2	0.987	0.377												
Season (Sn)	1	4.600	0.035												
S*D	15	1.819	0.046												
S*Sn	4	5.367	0.001												
D*Sn	2	4.458	0.015												
S*D*Sn	18	5.024	0.000												

3.2.3 Lead (Pb)

In similar vein to the results obtained for dCu, trends were apparent with regard to dissolved lead (Pb) (Figure 38). The standout feature in this instance was once again the marked differences in lead concentrations between control and impact sites, particularly during the February study, when concentrations appeared to exceed those obtained in July. However, despite the apparent shift in the concentration of Pb between study periods, no significant differences were detected between February and July overall. Nonetheless, a significant S*Sn interaction term suggested that the effect of Season (Sn) on the concentration of Pb depended on Site (S); hence, despite the non-significant ANOVA result obtained for the factor of season (Sn), significant seasonal differences are likely to be apparent, though, differences are limited presumably to selected sites only (*i.e.* Oxbows 2 and 6) (Table 5).

Highly significant differences in the concentration of Pb were detected also between the surface, middle and bottom of oxbow lakes (Table 5). This trend was most pronounced at impact sites, all of which displayed increasing concentrations with depth. Although a strong feature of impact sites in February, the apparent stratification of dissolved Pb concentrations had diminished substantially by the beginning of the second study period (July) - a trend reflected in the non-significant Tukey's post hoc test (which takes into account the data obtained in both of the study periods). The highly stratified or increasing gradient of dissolved Pb with depth resulted in some cases in elevated hypolimnetic (bottom) concentrations, some of which exceeded ANZECC/ARMCANZ (2000) guidelines for the protection of aquatic fauna. Although of some concern, this is unlikely to affect fish species given that the majority of sites affected maintained hypolimnetic dissolved oxygen levels well below that required for successful respiration (NB: Bosset Lagoon was a notable exception to this).

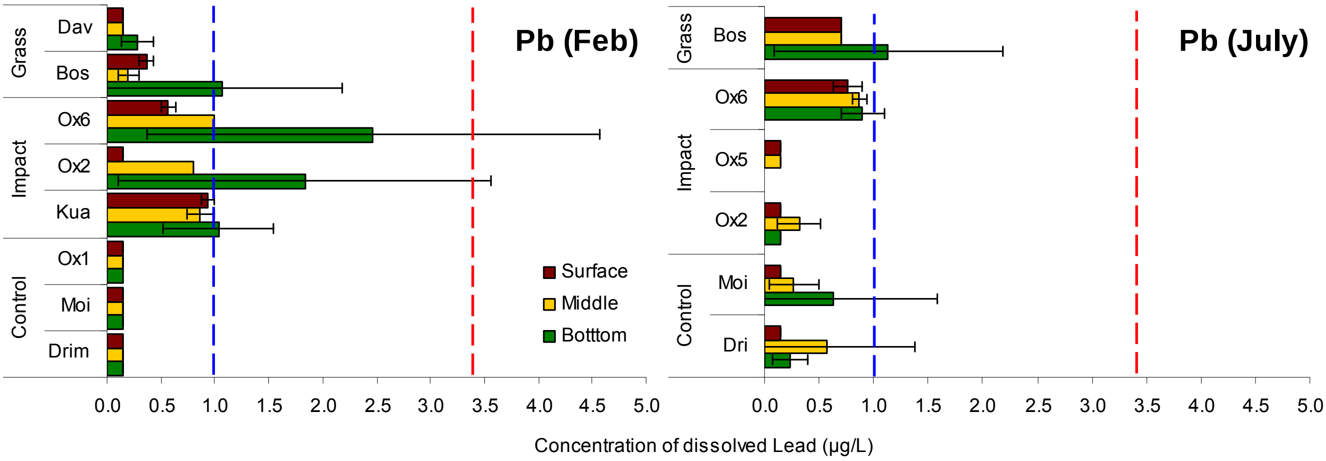

Figure 38. Seasonal comparison of dissolved Lead concentrations (mean ± 95% CI; µg L^{-1}) at the surface (■), middle (■) and bottom (■) of oxbow lakes. Sites are presented within their respective exposure level (Grassland, Impact and Control). Blue and red vertical broken lines depict ANZECC/ARMCANZ (2000) trigger values for the protection of 99% and 95% of aquatic species respectively.

Table 5. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Pb concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Pb				Kiu	Ox5	Dav	Dri	Moi	Ox2	Bos	Kua	Ox6	Mid	Bot	Sur
Site (S)	8	13.47	0.000												
Depth (D)	2	5.397	0.006												
Season (Sn)	1	0.552	0.460												
S*D	15	1.497	0.126												
S*Sn	4	6.203	0.000												
D*Sn	2	4.473	0.014												
S*D*Sn	8	2.190	0.037												

3.2.4 Cadmium (Cd)

Concentrations of dissolved cadmium (Cd) differed significantly between site, depth and season (Fig 39 and Table 6). Differences were particularly pronounced with respect to season, with concentrations appearing greater during February relative to those obtained in July - a trend reflected in the highly significant ANOVA result (Table 6). At the level of site, highly significant differences were detected also between Kuambit / Oxbow 1 (Kiunga) and all other sites (irrespective of exposure level), whilst at the level of depth, marginally significant differences only (*p* = 0.038) were detected between the surface, middle and bottom levels of oxbow lakes (Table 6). In the case of depth, a slight trend toward elevated hypolimnetic concentrations was detected, once again reflecting a Cd gradient with increasing depth.

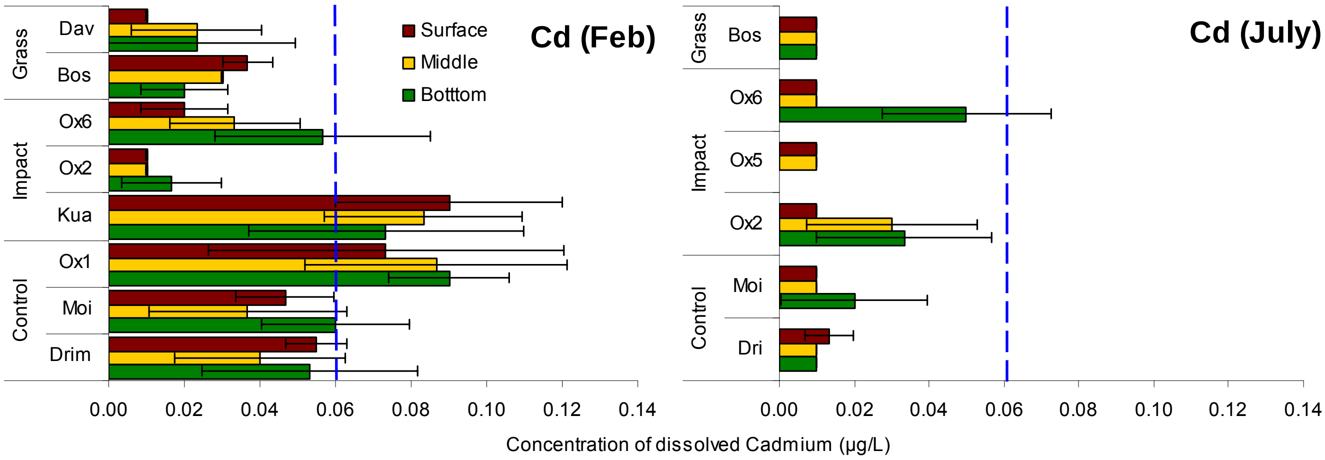

Figure 39. Seasonal comparison of dissolved cadmium concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grassland, Impact and Control). Blue vertical broken lines depict ANZECC/ARMCANZ (2000) trigger values for the protection of 99% of aquatic species.

Table 6. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Cd concentrations. Additional results are presented for Tukey’s post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey’s homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Cd				Ox5	Ox2	Dav	Bos	Dri	Ox6	Moi	Kua	Kiu	Sur	Mid	Bot
Site (S)	8	17.64	0.000												
Depth (D)	2	3.41	0.038												
Season (Sn)	1	30.21	0.000												
S*D	15	1.619	0.087												
S*Sn	4	7.06	0.000												
D*Sn	2	0.438	0.647												
S*D*Sn	8	0.428	0.901												

3.2.5 Calcium (Ca)

Dissolved calcium concentrations differed significantly between site ($p < 0.001$), depth ($p < 0.01$) and season ($p < 0.000$) (Figure 40). Despite the high level of significance obtained for each of the factors, trends in the data were difficult to elucidate due to the high degree of data variability (Table 7). Further complicating data interpretation was the fact that many of the interaction terms yielded highly significant results, suggesting that differences were restricted to selected sites only. For example, it is highly likely that the significant result obtained for depth is a reflection of results obtained at Drimdenasuk and Bosset Lagoon, and not a trend observed consistently. In similar vein, the significant result obtained for Site (S) is likely also to be a reflection of values obtained at certain sites only *i.e.* both Bosset Lagoon and Moian were found to contain particularly low concentrations of Ca, especially during February. Seasonal differences, on the other hand, were easier to discern, with most sites undergoing a significant decrease in the concentration of Ca between February and July. Of some interest, was the slight trend toward higher Ca concentrations in the hypolimnetic waters, reflecting once again a Ca gradient with increasing depth.

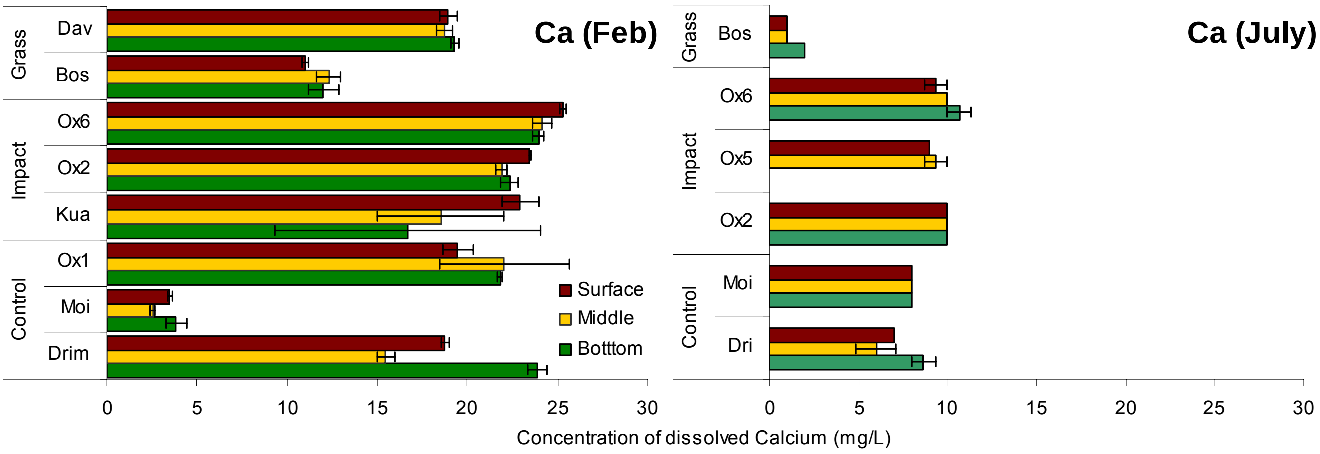

Figure 40. Seasonal comparison of dissolved Calcium concentrations (mean ± 95% CI; mg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no specific trigger value for [Ca] for the protection of aquatic ecosystems.

Table 7. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Ca concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Element	df	F	*p*	Low				→		High			Low	→	High
Ca				Bos	Moi	Ox5	Dri	Ox2	Ox6	Dav	Kua	Kiu	Mid	Sur	Bot
Site (S)	8	299.12	0.000												
Depth (D)	2	5.99	0.004												
Season (Sn)	1	1420.70	0.000												
S*D	15	6.52	0.000												
S*Sn	4	298.25	0.000												
D*Sn	2	1.303	0.277												
S*D*Sn	8	2.214	0.035												

3.2.6 Magnesium (Mg)

Despite the significant results obtained for each of the factors, site, depth and season, specific trends in concentrations of Magnesium were difficult to elucidate (Table 8). Trends were particularly difficult to discern at the level of Site (S), with most oxbows yielding similar results (Figure 41). Exceptions to this were obtained at Moian and Oxbow 1 (Kiunga), both of which yielded very low and highly elevated concentrations of Mg, respectively. Differences between surface, middle and bottom levels of the water column were also difficult to establish with certainty. For example, the concentration of dissolved Mg appeared to fluctuate between sites, resulting, in some instances, in both negative and positive Mg gradients with depth (*e.g.* February data for Oxbow 6 and Oxbow 1 (Figure 41)).

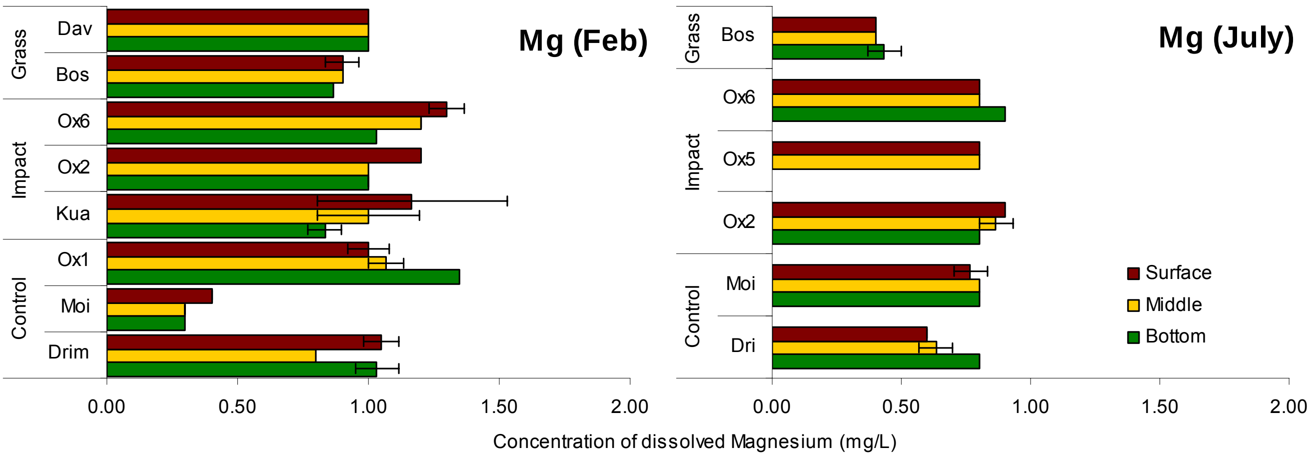

Figure 41. Seasonal comparison of dissolved magnesium concentrations (mean ± 95% CI; mg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no specific trigger value for [Mg] for the protection of aquatic ecosystems.

Table 8. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Mg concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Mg				Moi	Bos	Ox5	Dri	Ox2	Kua	Ox6	Dav	Kiu	Mid	Bot	Sur
Site (S)	8	111.21	0.000												
Depth (D)	2	4.116	0.020												
Season (Sn)	1	147.66	0.000												
S*D	15	7.87	0.000												
S*Sn	4	177.85	0.000												
D*Sn	2	15.59	0.000												
S*D*Sn	8	2.43	0.021												

3.2.7 Sodium (Na)

Despite a significant ANOVA result for Site (S) (Table 9), Na concentrations varied markedly, with no evidence to suggest that the variation was related to exposure level (*i.e.* impact, control or grassland) (Figure 42). Hence, the significant variation in [Na] between sites is likely a reflection of natural variability. In contrast to results obtained for site, it was possible to discern meaningful trends for both Depth (D) and Season (Sn). In the case of depth, there was tendency for oxbows (particularly, Oxbow 2, Kuambit, Moian and Drimdenasuk) to maintain a decreasing Na gradient between the surface and middle / bottom layers of the water column (see Tukey's post hoc test result in Table 9). The strength and consistency of this trend, however, did appear to diminish during the later sampling period (July). Results for Sn also suggest a significant difference in [Na] between February and July. This appeared to be a consistent trend, with most sites recording a net decrease in [Na] between the study periods (Figure 42).

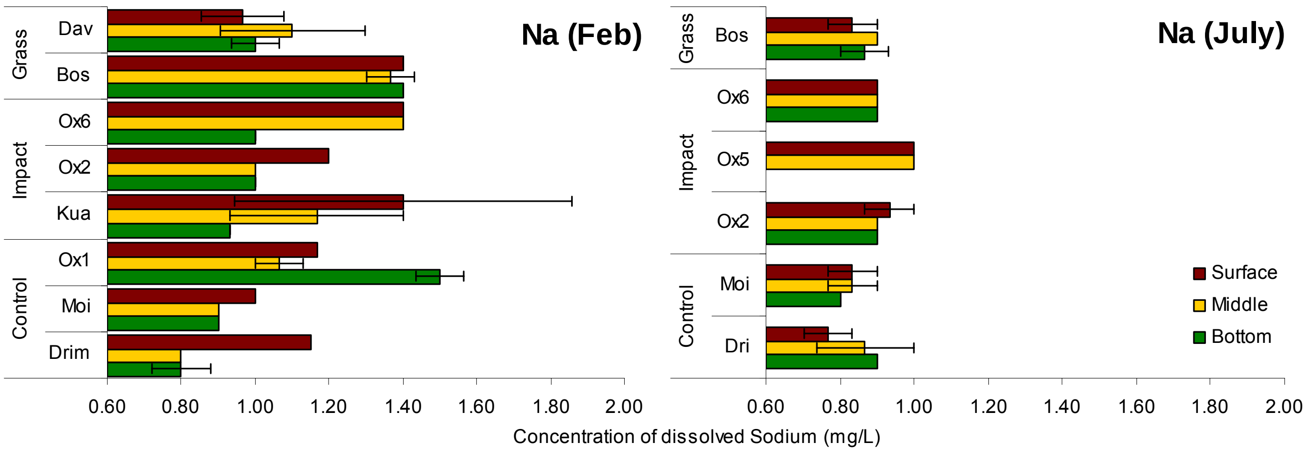

Figure 42. Seasonal comparison of dissolved Sodium concentrations (mean ± 95% CI; mg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no specific trigger value for [Na] for the protection of aquatic ecosystems.

Table 9. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake K concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Element	df	F	*p*	Low				→		High			Low	→	High
Na	8	20.40	0.000	Dri	Moi	Ox2	Ox5	Dav	Ox6	Bos	Kua	Kiu	Bot	Mid	Sur
Site (S)	2	3.77	0.027												
Depth (D)	1	177.34	0.000												
Season (Sn)	15	6.484	0.000												
S*D	4	20.507	0.000												
S*Sn	2	19.90	0.000												
D*Sn	8	3.387	0.000												
S*D*Sn	80														

3.2.8 Potassium (K)

In contrast to results obtained for other alkali metals (Na and Mg), potassium concentrations appeared to differ between exposure levels, with both grassland and impacts sites maintaining higher concentrations than those observed at control sites (Figure 43) (see also Tukey's post hoc test results). This trend was particularly strong in February but appeared to diminish consistently in July, with all sites recording a significant reduction in [K]. Despite a significant ANOVA result for Depth (D), potassium concentrations varied markedly between surface, middle and bottom levels of the water column. In several instances (Bosset Lagoon, Oxbow 6, Kuambit and Moian), [K] appeared to decrease with depth (a trend reflected in the Tukey's post hoc test) (Table 10), however this was not a trend observed consistently. For example, opposite trends (increasing [K] with depth) were apparent at Daviumbu and Oxbow 1.

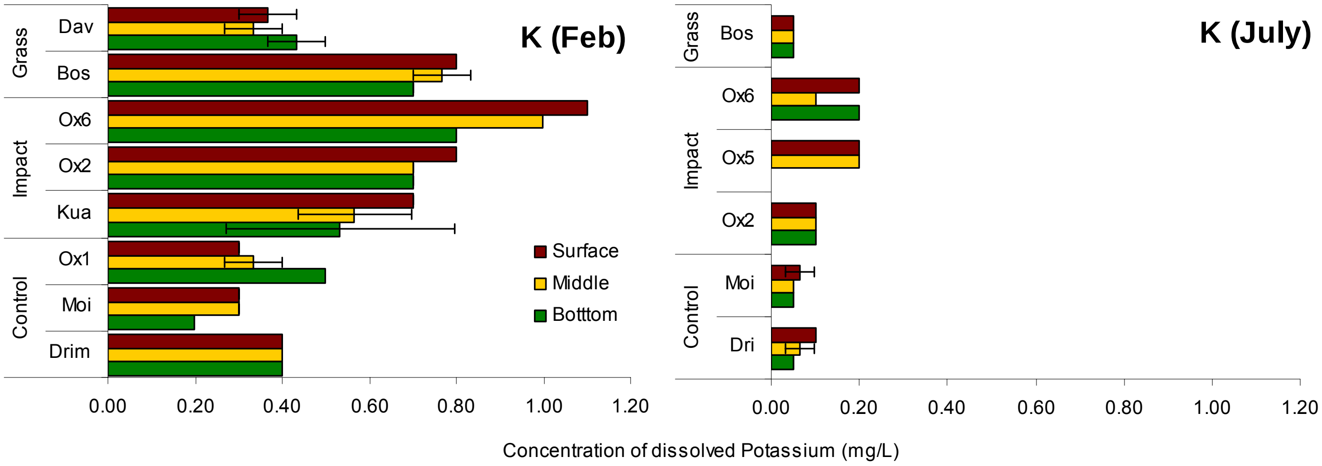

Figure 43. Seasonal comparison of dissolved Potassium concentrations (mean ± 95% CI; mg L^{-1}) at the surface (■), middle (■) and bottom (■) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no specific trigger value for [K] for the protection of aquatic ecosystems.

Table 10. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake K concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Element	df	F	*p*	Low				→		High			Low	→	High
K				Moi	Ox5	Dri	Kiu	Bos	Dav	Ox2	Ox6	Kua	Mid	Bot	Sur
Site (S)	8	160.044	0.000												
Depth (D)	2	6.207	0.003												
Season (Sn)	1	3540.27	0.000												
S*D	15	6.319	0.000												
S*Sn	4	121.257	0.000												
D*Sn	2	9.863	0.000												
S*D*Sn	8	3.769	0.001												

3.2.9 Cobalt (Co)

Six of the eight sites under investigation maintained relatively consistent Cobalt concentrations. This was particularly the case in February, when [Co] appeared substantially inflated relative to results obtained in July. Despite the relatively consistent trends observed at most sites, exceptions were apparent at Oxbow 1 and Oxbow 2, both of which maintained significantly elevated [Co] within the middle and bottom hypolimnetic water column levels (Table 11 and Figure 44). Increasing [Co] gradients with depth were observed also at several other sites (Bosset Lagoon, Moian and Drimdenasuk), suggesting a trend toward increasing [Co] with depth, and particularly within the bottom hypolimetic waters. The somewhat ambiguous results obtained in July were more difficult to explain. Although results for many metals are indicative of a temporal decrease in concentration (a trend also observed here), the negative values presented here are likely the result of erroneous analytical techniques and / or instrument readings.

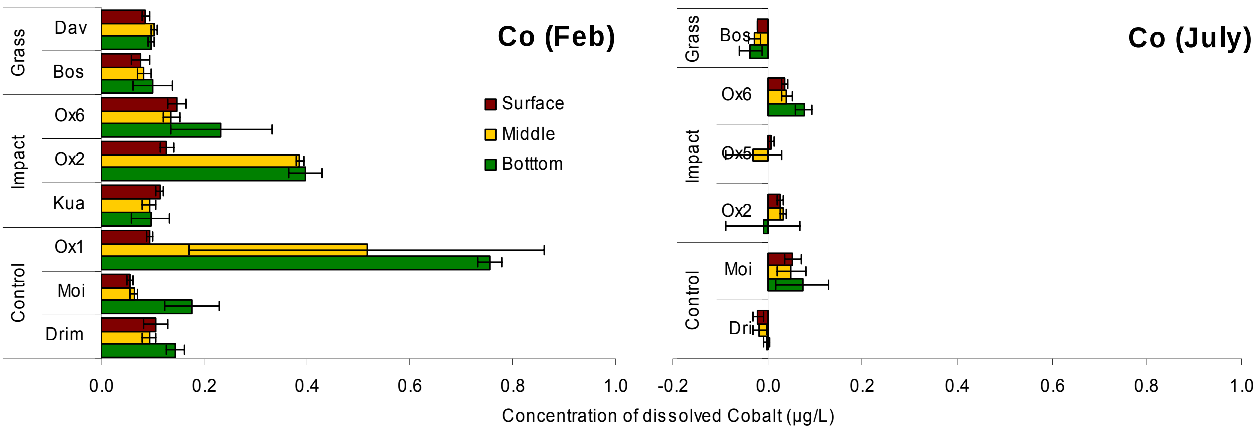

Figure 44. Seasonal comparison of dissolved Cobalt concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no trigger value for [Co] for the protection of aquatic ecosystems.

Table 11. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Co concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Co				Ox5	Bos	Dri	Moi	Dav	Kua	Ox6	Ox2	Kiu	Sur	Mid	Bot
Site (S)	8	40.78	0.000	—	—								—		
Depth (D)	2	23.56	0.000		—	—	—							—	
Season (Sn)	1	203.623	0.000			—	—	—	—						—
S*D	15	11.111	0.000				—	—	—	—					
S*Sn	4	15.478	0.000					—	—	—	—				
D*Sn	2	8.279	0.001									—			
S*D*Sn	18	2.738	0.010												

3.2.10 Manganese (Mn)

Manganese concentrations, although highly variable within exposure levels (Table 12), maintained several clear trends. In general, [Mn] displayed a strong increasing gradient with depth. This was particularly so at impact sites, Oxbows 2, Oxbow 6 and Kuambit, where the concentration of Mn also appeared elevated relative to other exposure levels (Figure 45). As with many other metals, [Mn] appeared to decrease considerably in July.

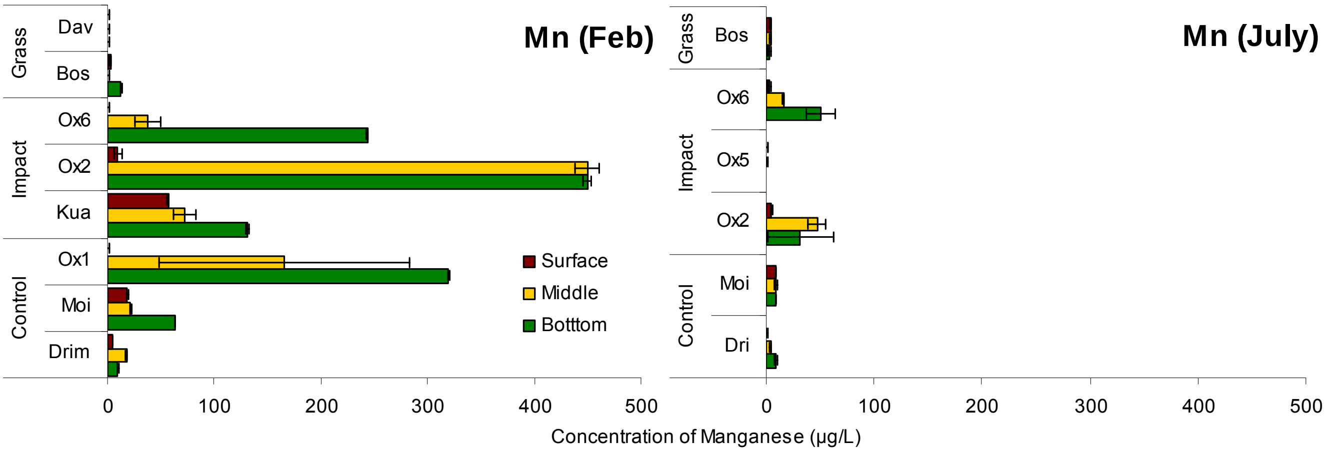

Figure 45. Seasonal comparison of dissolved Manganese concentrations (mean ± 95% CI; μg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: the ANZECC/ARMCANZ (2000) trigger value for [Mn] for the protection of 95% of aquatic species is 1900 μg L^{-1}.

Table 12. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Mn concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest).

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Mn				Ox5	Dav	Bos	Dri	Moi	Ox6	Kua	Kiu	Ox2	Sur	Mid	Bot
Site (S)	8	111.6	0.000												
Depth (D)	2	147.95	0.000												
Season (Sn)	1	213.60	0.000												
S*D	15	32.74	0.000												
S*Sn	4	57.09	0.000												
D*Sn	2	45.73	0.000												
S*D*Sn	8	16.11	0.000												

3.2.11 Molybdenum (Mo)

In similar vein to the trends observed with Cu and Pb, Molybdenum (Mo) concentrations also appeared to maintain significantly higher concentrations at exposure level oxbows (Figure 46). Once again, this was a trend observed particularly in February, when the Mo concentrations obtained at control sites were in stark contrast to those observed at both grassland and impact level exposures. Less striking trends were apparent in July, when Mo concentrations appeared to decrease overall - a trend reflected by the significant ANOVA result for Season (Sn) (Table 13). Despite the tendency for increasing concentration gradients with depth, especially at higher Mo concentrations (*i.e.* Oxbow 6 and Oxbow 2), no significant differences were detected between water column levels (D) (Table 13).

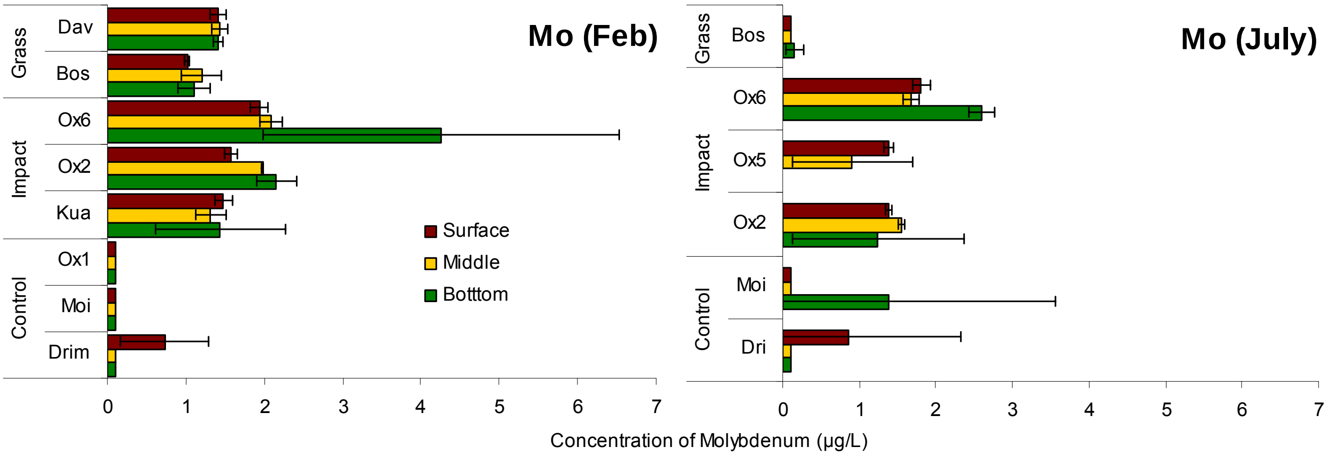

Figure 46. Seasonal comparison of dissolved Molybdenum concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: ANZECC/ARMCANZ (2000) provide no trigger value for [Mo] for the protection of aquatic ecosystems.

Table 13. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Mo concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Mo				Kiu	Moi	Dri	Boss	Ox5	Kua	Dav	Ox2	Ox6	Mid	Sur	Bot
Site (S)	8	43.89	0.000												
Depth (D)	2	2.573	0.083												
Season (Sn)	1	12.949	0.001												
S*D	15	2.238	0.011												
S*Sn	4	7.563	0.000												
D*Sn	2	0.105	0.901												
S*D*Sn	8	1.452	0.188												

3.2.12 Nickel (Ni)

Analysis of Nickel (Ni) concentrations revealed significant differences at the level of site and season (Table 14). However, the significant result for site is most likely a reflection of the relatively low concentrations obtained at two sites, namely Moian and Bosset Lagoon (February data), and not a reflection of exposure level differences (Figure 47). As observed consistently throughout the study, Ni concentration decrease significantly between seasons, with most sites recording a net reduction in [Ni]. In contrast no significant differences were detected between depths (Table 14).

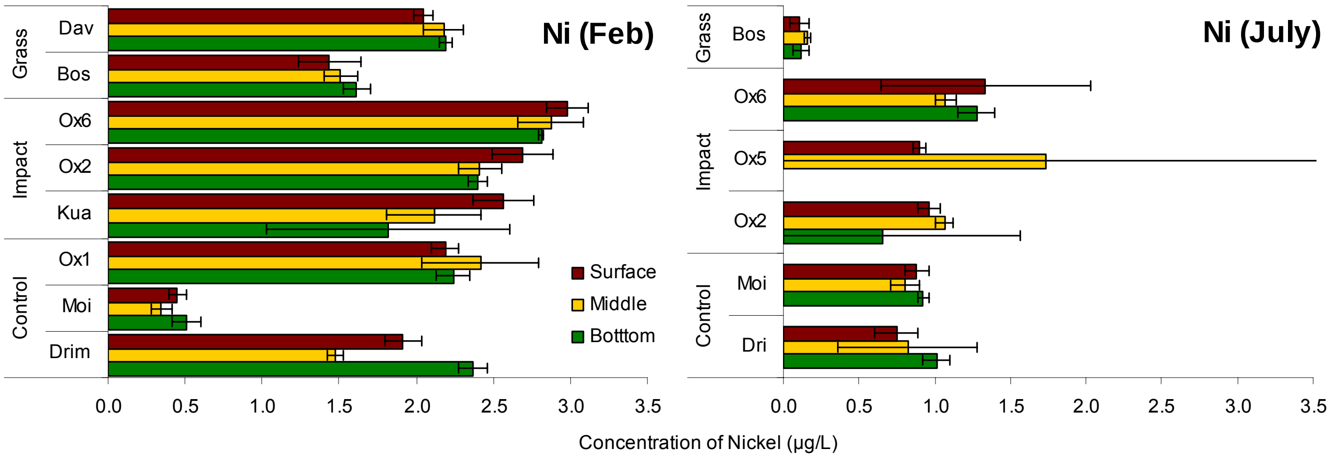

Figure 47. Seasonal comparison of dissolved Nickel concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Note: the ANZECC/ARMCANZ (2000) trigger value for Mn for the protection of 95% of aquatic species is 1900 µg L^{-1}.Note: the ANZECC/ARMCANZ (2000) trigger value for [Ni] for the protection of 99% of aquatic species is 8 µg L^{-1} and 11 µg L^{-1} for 95%.

Table 14. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Ni concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Ni				Moi	Bos	Ox5	Dri	Ox2	Ox6	Dav	Kua	Kiu	Mid	Sur	Bot
Site (S)	8	18.265	0.000												
Depth (D)	2	0.050	0.951												
Season (Sn)	11	124.873	0.000												
S*D	15	0.893	0.574												
S*Sn	4	19.922	0.000												
D*Sn	2	0.573	0.566												
S*D*Sn	8	0.296	0.965												

3.2.13 Zinc (Zn)

Zinc (Zn) was unique given that it was the only metal to record a significant net increase in concentration between February and July (Table 15 and Figure 48). This trend, depicted clearly in Figure 48, also illustrates the level of dissolved Zinc in relation to ANZECC/ARMCANZ (2000) trigger values. Although Zn concentrations at both impact and grassland sites encroach upon the 99% trigger value in February, the net increase in concentration in July also saw values reaching the 95% confidence interval in some instances (Oxbow 6, Oxbow 2 and Drindenasuk). In addition, the marked temporal shift in the concentration of Zn, also resulted in each of the oxbows exceeding the 99% trigger value in all cases. It must be emphasised however, that trigger values represented here were formulated with Australian and New Zealand tropical systems in mind. Hence, trigger values presented here in conjunction with data obtained in New Guinea are intended as a guide only.

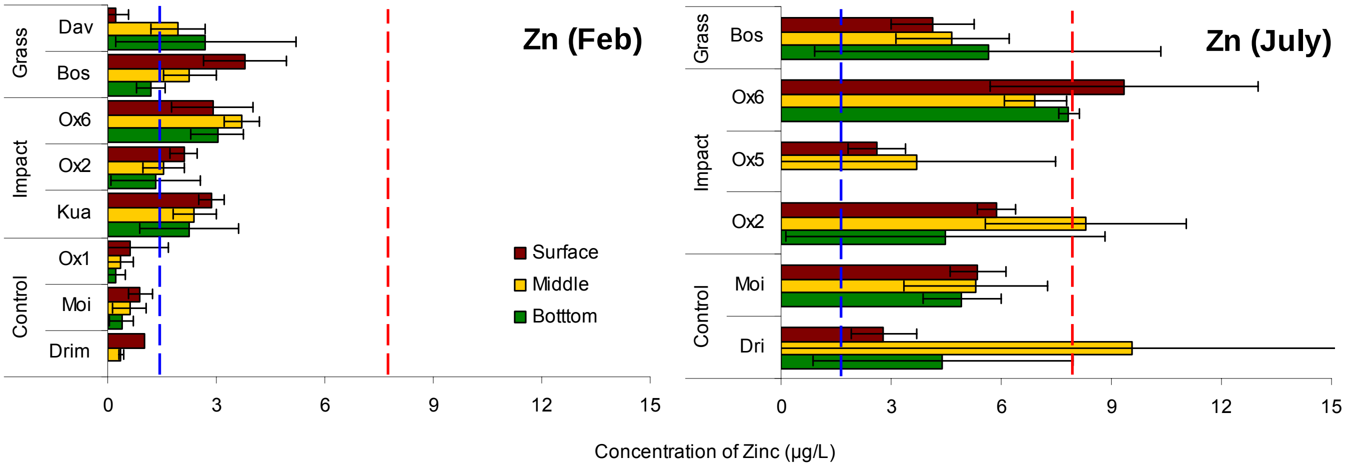

Figure 48. Seasonal comparison of dissolved Zinc concentrations (mean ± 95% CI; µg L^{-1}) at the surface (🟥), middle (🟨) and bottom (🟩) of oxbow lakes. Sites are presented within their respective exposure level (Grass land, Impact and Control). Blue and red vertical broken lines depict ANZECC/ARMCANZ (2000) trigger values for the protection of 99% and 95% of aquatic species, respectively.

Table 15. Results of 3 factor analysis of variance procedure examining the effect of Site (S), Depth (D) and Season (Sn) on oxbow lake Zn concentrations. Additional results are presented for Tukey's post hoc tests elucidating relative differences at the level of site and depth. In both cases, concentrations are presented from left to right in order of increasing concentration (lowest to highest), and levels not significantly different are underlined by a common line.

Three factor ANOVA				(Post-hoc analyses) Tukey's homogenous subsets											
Between group effects				Between sites									Between depths		
Metal	df	F	*p*	Low				→		High			Low	→	High
Zn				Kiu	Dav	Dri	Moi	Kua	Ox5	Bos	Ox2	Ox6	Bot	Sur	Mid
Site (S)	8	6.65	0.000												
Depth (D)	2	1.30	0.277												
Season (Sn)	1	111.97	0.000												
S*D	15	0.901	0.566												
S*Sn	4	1.909	0.117												
D*Sn	2	1.152	0.240												
S*D*Sn	8	1.239	0.288												

3.3 Regression Analysis: Heavy metal *v* Dissolved Oxygen Concentration

Given the highly significant differences in some cases between surface, middle and bottom levels of the water column, regression analyses were conducted to determine the influence of dissolved oxygen on heavy metal concentrations. To determine trends specific to exposure levels, regression analyses were conducted for each metal using data obtained from impact and control sites separately. Data presented below are restricted to those metals displaying specific trends in the data; *i.e.* those in which there appears to be a correlation between DO and heavy metal concentration. Although the strength of the individual regression analyses varied substantially, there were still instances where strong relationships could be derived. However, of the analyses yielding r^2 values of 0.2 and greater, results are suggestive of a negative relationship, whereby concentrations of heavy metals decrease with increasing oxygen concentration. This was particularly the case at impact sites, which, in most cases, maintained r^2 values in the range 0.22 – 0.48. Analysis of the significance of these results, however, found that the slope of the trend line deviated significantly from zero in 3 out of 7 cases only (see results for Co, Mn and Mo in Figures 49 and 50), suggesting that the data were either insufficient, or too widely spread to derive meaningful trends. It should be acknowledged however, that the value of the regression for determining relationships in this instance was diminished due to large scale variation in metal and DO concentration between sites. Much stronger relationships are likely to be obtained if sites are considered independently.

At impact sites particularly, the striking dissolved oxygen gradient between surface and hypolimnetic waters is likely to have significant implications for chemical /oxidation processes, including, but not limited to changes in the valency of heavy metals. For example, under anoxic conditions iron exists as Fe^{2+} (II), but converts to Fe^{3+} (III) when exposed to oxygen; a species of iron visible as an orange coloured flocculent in waters released from the hypolimnion of certain reservoirs (Shiell 1998). In similar vein, lead (Pb) and cadmium (Cd) undergo chemical changes related to the availability of dissolved oxygen. In both cases, anoxia in the lower hypolimentic waters facilitates the release of these metals from sediments (Shine *et al.* 1998). Such a process may very well have been occurring at impact sites during February), particularly with regard to Mo, Mn, Cd (Oxbows 2 and 6 in particular), Pb and Al.

In contrast to the process of heavy metal release observed under anoxic conditions, copper (Cu) appeared to decrease with depth. This may be an artefact of fundamental differences in the way Cu reacts to changing dissolved oxygen concentrations. Specifically, hypolimnetic waters devoid of oxygen may act as a net sink for copper, or expressed simply, the concentration of dissolved copper has the potential to decrease with depth; in direct contrast to the fate of other heavy metals (Simon Apte, CSIRO, unpublished data). Such a process has been shown previously in oxbow lakes of the Fly River where sediment act as a net sink for dCu, and perhaps again in the current study, as indicated by the results presented in Figure 37. Despite these results, the regression analysis of Cu against DO revealed a negative relationship with an r^2 value of +0.0921 (Figure 49). This result serves to highlight the difficulty in obtaining meaningful regression trends when considering sites with highly variable limnological characteristics. Future regression analyses may be improved by increasing the level of replication (at a number of depths) within individual oxbow lakes.

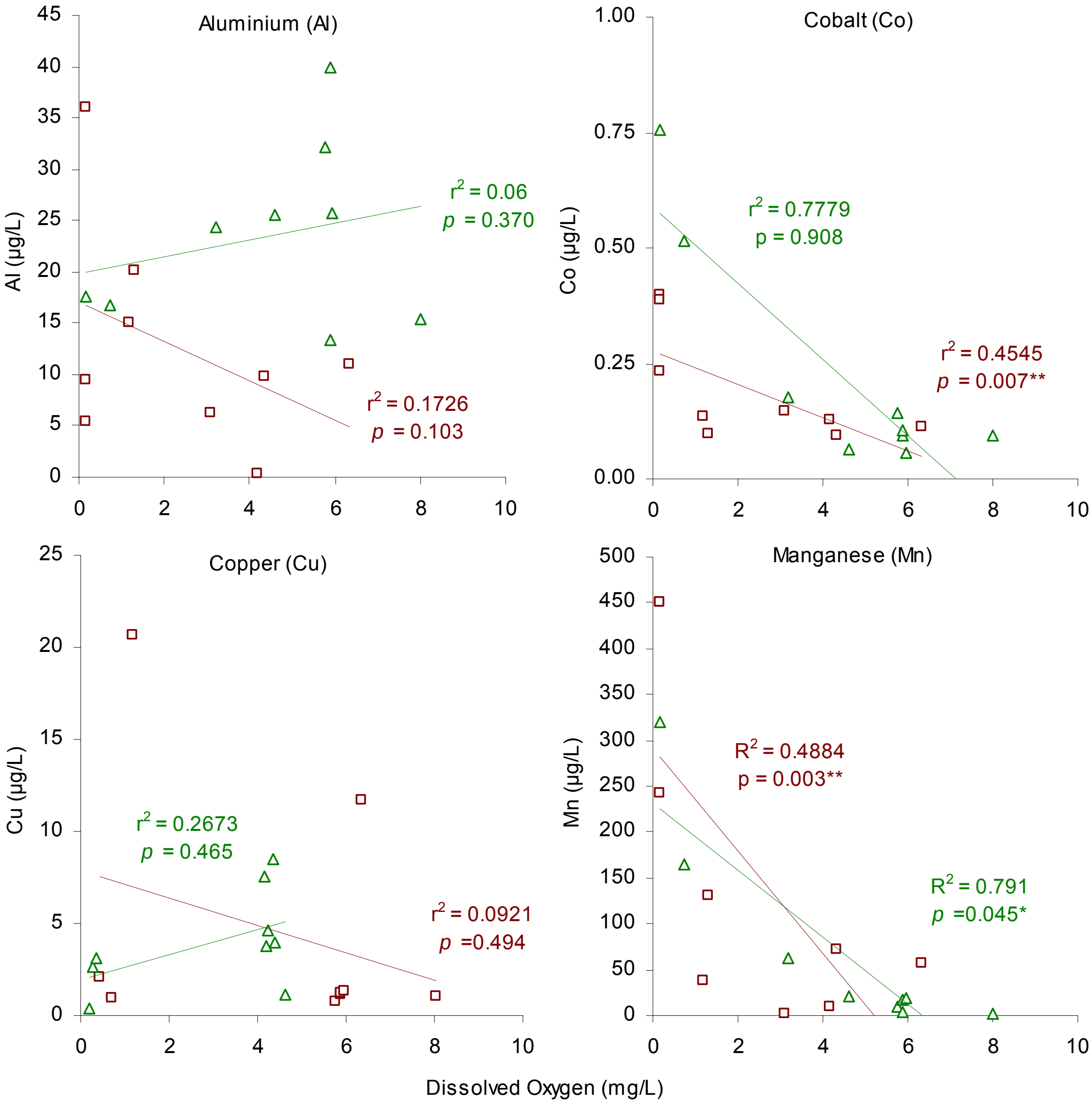

Figure 49. Regression analysis of heavy metal (Al, Co, Cu, Mn) versus dissolved oxygen concentration (△ control sites; □ impacts sites). Regression lines/equations for impact and control sites are represented by the colours red and green, respectively.

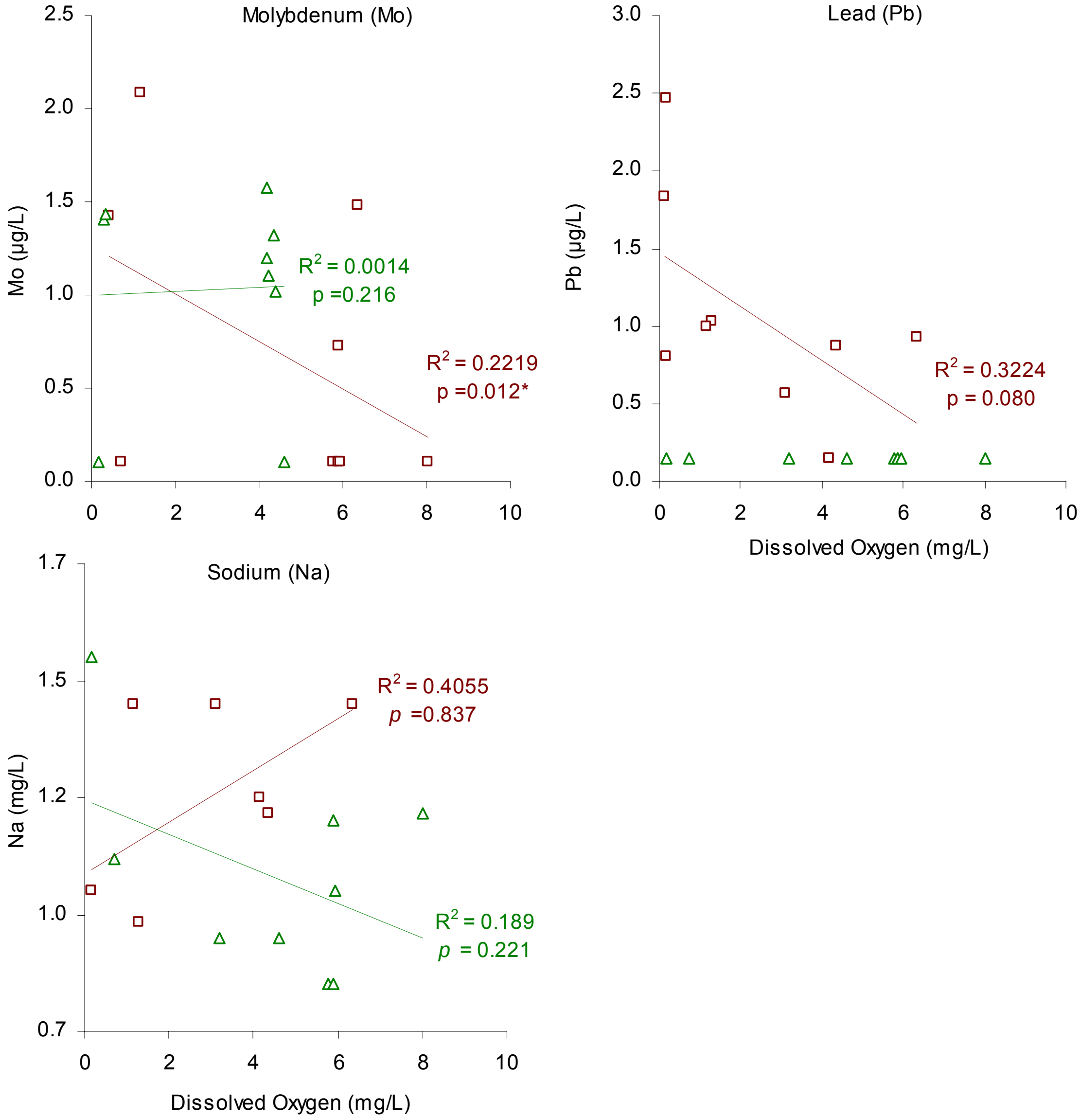

Figure 50. Regression analysis of heavy metal (Mo, Pb, Na) versus dissolved oxygen concentration (△ control sites; □ impacts sites). Regression lines/equations for impact and control sites are represented by the colours red and green, respectively.

4 SYNTHESIS

4.1 Thermal Stratification of Oxbow Lakes

Limnological studies of oxbow lakes within the Fly River catchment indicate significant differences in water quality parameters on both a temporal and geographic scale. Although data collected on two occasions (representing wet and dry seasons) suggested potential for temporal and geographic variation in water quality, the most striking outcome of the study was the persistence of heavy thermal stratification during the wet season (February) relative to the dry season (July/August). This was particularly the case at control and impact sites, all of which maintained distinct thermoclines in February. There also appeared to be a greater reduction in DO at lower depths in impact sites compared with control sites, particularly in the wet season sampling. Grass land sites (Bosset and Daviumbu), in contrast, maintained isothermal temperature profiles, and appeared resistant to the process of stratification (*i.e.* there was no evidence of thermal and or chemical stratification at Bosset Lagoon in either of the February or July studies). This was an unusual phenomenon considering the lack of surrounding riparian vegetation, and the exposure of these oxbows to direct sunlight. Of interest also, was the near-anoxic dissolved oxygen (DO) levels measured throughout the water column at Lake Daviumbu during February. It was hypothesised that the low DO concentration in this case may be attributable to a combination of several factors. In the first instance, Lake Daviumbu is a shallow water body covered almost entirely with floating grass. The presence of grass may effectively act as a 'lid' impeding physical re-aeration. This, combined with respiration associated with decomposition of grasses (and associated organic debris) may result in a net loss of oxygen from the system resulting in the close to anoxic conditions observed at this site.

Thermally stratified water bodies theoretically can be divided into three layers of water: the upper epilimnion, containing warm water and relatively high dissolved oxygen concentrations; the metalimnion, containing the thermocline (the plane representing the point of greatest temperature change); and the hypolimnion, typically containing cooler, poorly oxygenated water. Although the majority of impact and control sites could reasonably be classified according to this description, there appeared to be distinct inter exposure differences in ambient dissolved oxygen concentrations (particularly within the hypolimnion). The mechanisms contributing to this trend were difficult to elucidate; however, it is possible that higher DO concentrations at control sites were a result of frequent mixing events, whilst the near-anoxic conditions observed at impact sites were a result of persistent thermal stratification (and thus, less frequent mixing events). Whilst the current study limited data collection to two relatively short studies of water column profiles, the potential for persistent thermal stratification at impact sites was inferred from observations of site characteristics, combined with interpretation of diel water quality trends. For example, it was reasonable to assume that relative to control sites, each of the impacts sites receive substantial inputs of sediments, and in the case of Oxbows 2 and 6, large inputs of decaying vegetation (*i.e.* debris associated with extensive forest dieback). These factors are likely to contribute large volumes of organic matter (fine organics and rotting vegetation) to the oxbows, thus creating potential for strong solute derived density gradients between upper and lower levels of the water column (referred to as biogenic stratification). Biogenically derived stratification is typically indicated by increasing conductivity with depth. Although this was not always a feature of stratified oxbows, a strong conductivity gradient was observed in February at Kuambit suggesting the stability of stratification at this site may be enhanced by a solute derived gradient. Biogenically derived density differences between the epilimnion and the hypolimnion lead to a magnitude of stability far greater than that produced under standard thermally stratified conditions alone (Wetzel 1975). Under these conditions, forces such as high winds and density currents (strong temperature directed inflows) may be ineffectual in breaking down the thermocline. It is therefore likely that the very low DO concentrations at impact sites may be the result of infrequent mixing events. The exceedingly low values obtained for redox potential particularly at Kuambit and Oxbow 2 during February, were also considered a function of thermal stratification.

In contrast to the effects of density currents at impact sites, the intrusion of such inflows to control oxbows could be expected to be more destabilising. Density inflows are particularly disruptive when the temperature of inflowing water equates to that maintained in the metalimnion (the strata of the water column also containing the thermocline). The greater density of the cooler inflowing water means that it immediately sinks and penetrates beneath the epilimnion, thus entering the water column at the level of the thermocline. The disruptive nature of this process is often sufficient to break down the density gradient, causing the complete turn over of the water column. This was observed on one occasion in February, when rising river levels resulted in cooler water entering Oxbow 1 (Kiunga) effectively reducing both the temperature and dissolved oxygen gradient. However, it was noted that the thermal and chemical gradients re-established quickly, suggesting that the biological oxygen demand of the sediments and / or hypolimnion, were sufficient to rapidly exhaust the supply of oxygen. Lake Pangua, OXB06 and Moian oxbows were also relatively well mixed in July/August, and were all experiencing strong riverine inflows.

4.2 Temporal Variation in Water Quality Characteristics

Results of the present study revealed variation in the limnological characteristics of ORWBs on a number of scales. The propensity for ORWBs to experience rapid change (and their ability to recover) appeared dependent on several factors, including the depth of the waterbody and the relative input of organic matter. Rapid diel fluctuations were also likely influenced by other abiotic factors such as the proportion of cloud cover, thunderstorms and inflows from the main river channel. The effect of cloud cover and thunderstorms were particularly apparent at oxbows Drimdenasuk, Moian and Kuambit, where such events typically resulted in a decrease in surface water DO concentrations (due to retarded primary productivity) and in some cases, a weakening of the thermocline. Of particular importance were the density currents, *i.e.* the influx of cooler river water through the tie channels connecting the oxbow lakes with the main river channel. The effects of these currents were often sufficient to cause a rapid breakdown of the thermocline and mixing of the water column (albeit part of) (*i.e.* Kiunga).

The ORWBs exhibited not only large daily fluctuations, but also significant seasonal changes in water quality in the form of reduced incidence of thermal stratification and a general increase in the concentration of dissolved oxygen at the majority of sites during the dry season (July). This was coincident with a marked decrease in heavy metal concentrations. A net decrease in heavy metal concentration was observed in nearly all cases with the possible exception of Al, Mg, Cu and Zn. Most of these metals maintained similar levels of concentration with the exception of Zn, which exhibited a dry season increase. The reduction in thermal stratification may be the result of strong river inflows following significant rainfall events in the mountains. As mentioned previously, the effects of riverine inflows may be sufficiently disruptive to alter thermal profiles, particularly where inflows contain cooler water. In contrast, warm rainfall runoff, although contributing large volumes of water to oxbows during the wet season, may only penetrate the upper epilimnion and may therefore be less disruptive.

Hypotheses to account for the seasonal decrease in heavy metal concentration are perhaps more difficult to establish. It is likely however, that the increase in riverine flows may have acted to increase both a) turbidity and b) dissolved oxygen, two factors that in combination may act to reduce dissolved heavy metal concentrations (*i.e.* in the presence of oxygen, heavy metal cations are likely to bind (adsorb) to sediment particles, thus making them undetectable to analytical processes).

4.3 Chemical and Biological Ramifications of Thermal Stratification

Thermal stratification of a water body has both biological and chemical ramifications. As already discussed in some detail, persistent thermal stratification may eventually lead to the hypolimnetic deoxygenation, particularly where detrital inputs are high. However, physical and chemical gradients resulting from differences in water temperature and dissolved oxygen may also have biological implications. At higher trophic levels, the distribution of aquatic organisms such as fish and macro-invertebrates is dictated by the minimum DO level required to maintain effective respiration. Under conditions of anoxia or DO of less than 4 mg L^{-1}, these organisms are forced to migrate to the upper levels of the water column where DO levels are typically greatest. This may have flow-on effects for feeding and predation, particularly if fauna are required to move out of their preferred habitat. Other problems arise as increasing temperatures approach thermal tolerance limits of the fauna. For example, some species of temperate cladocerans show high mortality at temperatures above 23°C and as a result are forced to inhabit very small niches within the epilimnion, 'sandwiched' between a layer of water above which is too warm, and a layer below that is too poorly oxygenated (Moore *et al.* 1996). At lower trophic levels, density differences between the upper and lower sections of the water body can affect the distribution of microalgae and the feeding behaviour of zooplankton. Due to the sharp decrease in water temperature at the thermocline, the resulting density differential acts as a barrier to phytoplankton, which in the absence of water turbulence sink out of suspension. In some instances (particularly where diatoms are abundant), this can lead to a build up (or layer) of phytoplankton at the thermocline, where the density difference acts as a buffer to further downward movement. This also has flow on effects for the distribution of zooplankton, which migrate to the thermocline to graze on the phytoplankton. Given sufficient numbers, the gathering of zooplankton at the thermocline has the potential to reduce the overall DO concentration on a relatively small micro-habitat scale. This was perhaps reflected at Drimdenasuk, where DO levels were consistently lower within the metalimnion.

Apart from the biological effects of oxbow stratification, the resulting dissolved oxygen chemocline may have significant consequences for certain chemical processes, not least of which may act to change the valency and thus bio-availability of certain metals. This is of major concern for water bodies located down steam of the mine, which have the potential to receive large volumes of mine derived sediment with metals adsorbed to sediment particles. Although under conditions of sufficient oxygenation most heavy metals remain adsorbed to sediment particles, anoxic conditions result in the liberation of metals to the water column, leading to an increase in the concentration of dissolved contaminants during periods of prolonged stratification. Heavy metals affected by this process include Cd, Co, Ni, Pb and Pb. Under heavily stratified conditions, impacts sites recorded elevated concentrations of Pb, Mo, Mn, Co, Cd and Al in their hypolimentic waters. Similar results were obtained at control and grassland sites where relatively high concentrations of Cd, Al, Co, Mn and Pb were measured in the hypolimnion relative to the upper levels of the water column. It is likely that the increase in hypolimnetic concentrations of Co, Ni, Cd and Pb, was due to the net flux of these contaminants out of the sediments during periods of stratification. The exact rate of metal flux from the sediments is unknown, but there is potential for rates of disassociation to vary with both the level of sediment contamination and, presumably, the period of anoxia. In addition, different rates of sediment flux are reported for certain metals. For example studies of marine sediments report a strong regression between rates of benthic oxygen demand and the flux of Cd and Zn (Shine *et al.* 1998). Although Zn is reported to be liberated under anoxic conditions, this did not appear to be the case in the current study. In contrast, there appeared to be little relationship between the concentration of Zn and the depth of the water body, despite impact sites maintaining elevated concentrations overall.

4.4 Implications of Water Column Turn-over (Meromixis)

Given the relatively high level of sediment inputs to impact sites in particular, there is some potential for periodic release of metal contaminants to the water column. However, this would require the complete breakdown of thermal stratification at these sites, a process which may, as already discussed, have the potential to occur infrequently at impact sites. Hence prolonged periods of anoxia (as observed in February) followed by water column turn over may have deleterious effects on resident fauna. This is of particular concern for metals such as Pb and Al, which in some instances were observed to exceed the indicative ANZECC/ARMCANZ/ARMCANZ (2000) trigger values for aquatic ecosystems. However, it should be noted that the trigger value guidelines were developed for general application to Australian tropical wetlands, and system-specific guidelines should be developed to determine the toxicity potential of these metal concentrations in New Guinean water bodies. The 9th Supplemental Agreement in December 2001, introducing the Regime and granting approval to mine for the next 10 yrs, was predicated on the State acknowledging / accepting that significant ecological impact had already occurred, and that this would continue to occur as the mine proceeds. Consequently, as aquatic ecology guidelines had already been exceeded in some parts of the system, potability guidelines (NHMRC & ARMCANZ 1996) were adopted for future reporting of water quality. However, for the current study, the more conservative ANZECC/ARMCANZ (2000) water quality guidelines for the protection of aquatic ecosystems are indicated, as these were more relevant for estimating potential ecological harm in parts of the river system where mine-related impacts had not previously been detected. Guideline limits for potability are often far in excess of known tolerances of aquatic fauna.

4.5 Copper (Cu)

One metal of major concern yet to be discussed is the effect of Cu. Although Cu is reported to exhibit a net flux out of marine sediments during periods of elevated biological oxygen demand (Shine *et al.* 1998), opposite trends were observed here. In February in particular, the concentration of Cu appeared to correlate positively with increasing dissolved oxygen. It appears therefore, that under thermally stratified conditions, oxbow lakes may act as a net sink for dissolved copper. A similar phenomenon has been reported for Fly River oxbow lakes (CSIRO 1995). Even allowing for net flux of dCu into sediments, oxbow lakes downstream of the mine had elevated concentrations of dCu, with OXB06 particularly high (~20 µg L^{-1}). Without knowing the complexing capacity of these sites, nor the actual concentrations of labile copper, it is likely that the observed concentrations of Cu at impact sites in particular, are detrimental to the resident aquatic fauna either through acute or chronic effects. In April 2006, CSIRO Chelex columns were installed in the Environmental Chemistry Laboratory at Tabubil in order that labile Cu concentrations could be routinely determined on site. This approach should be used to test for labile Cu levels in the oxbow lake sites being studied, particularly those with elevated dCu levels (*i.e.* OXB06).

5 Conclusions

Results of the present study indicate temporal variation in ORWB water quality parameters. Of particular note was the propensity of ORWBs to experience rapid fluctuation in both water temperature and dissolved oxygen characteristics. Factors contributing to these changes included episodic thunderstorm events and inflow events, both of which appeared to affect predominantly surface and metalimnion water characteristics. The incidence of changes relating to short term environmental perturbations however, were seemingly greater in shallow ORWBs such as Daviumbu, Kuambit and Moian. In contrast, deeper oxbow lakes appeared more resistant to change, with most maintaining a bottom layer of water characterised by lower water temperatures and lower ambient dissolved oxygen concentrations (*i.e.* Oxbow 6). This was particularly the case at impact sites during the wet (February), where it was proposed that inputs of organic debris have lead to the formation of a solute derived gradient between the surface and bottom of the oxbow (as indicated by increasing conductivity with depth). The relationship is likely a balance between depth and biological/chemical oxygen demand, with Kuambit oxbow, for instance, which is relatively shallow, maintaining stratification, likely due to high oxygen demand. Referred to as biogenic stratification, this form of stratification is extremely resistant to turn over and it was proposed that ORWBs affected by this phenomenon rarely experience complete mixing. Hence, it is also likely that this ‘infrequency’ of mixing in these cases has lead to lower than average dissolved oxygen concentrations, particularly in the hypolimnion, or bottom layer of these water bodies.

Although thermal stratification was a common feature of ORWBs, exceptions to this trend included the blocked valley lakes, Bosset and Daviumbu, both of which displayed isothermal temperature properties throughout the water column (though see result for Daviumbu in July). However, despite maintaining very similar temperature profiles, these sites maintained striking differences in DO oxygen concentration. For example, although Bosset Lagoon maintained relatively high DO concentrations between the surface and bottom layers of the water column, Daviumbu maintained typically anoxic water conditions. This was an unusual finding relative to other oxbows, which typically maintained anoxic conditions in the hypolimnion exclusively. The striking results obtained at Daviumbu were therefore attributed to dense floating mats of slowly decomposing terrestrial grasses which may have acted as a) a physical barrier to reoxygenation and b) a major consumer of oxygen (through their decomposition). Through time, these factors in combination are likely to have contributed to the exceedingly low DO values recorded at this site. In comparison, the floating grasses in Bosset Lagoon had dispersed and broken-down, and the open nature of the waterbody allowed wind and wave action to promote mixing of the relatively shallow water body.

Despite the supposed barriers to mixing inferred from the current study, it is unlikely that any of the sites maintain permanent thermal stratification. This is reflected in the distinct seasonal change in DO profiles between the wet and dry seasons. Although, both thermal and oxygen gradients were found to persist at some sites throughout the study regime, levels of dissolved oxygen appeared to increase substantially in July, indicating that each of the water bodies had experienced mixing at some point. However, the potential for differences in the frequency with which ORWBs experience complete mixing may have ramifications for metal toxicity. Results of the present study indicated elevated hypolimnetic concentrations of Pb, Mo, Mn, Co, Cd and Al, that in some cases exceeded indicative trigger values. The incidence of elevated metal concentrations within the hypolimnion, suggests potential for a net flux of metals out of the sediment under anoxic conditions. We propose that the supposed infrequency of water column mixing events, particularly at impact sites (where heavy metal concentrations were in many cases found to be significantly greater), may provide scope for the liberation of substantial volumes of bioavailable heavy metals. Although limited to the bottom of ORWBs during periods of thermal stratification, the exposure of these metals to fauna following water column turnover/mixing has the potential to impact some species of aquatic fauna, particularly those most susceptible to metal toxicity. Interstingly, in many instances there was a reduction in metal concentrations in July compared with February. It is hypothesized that this relates to inflow of riverine water with increased pH and also increased sediment which binds the metals into a particulate state.

In contrast to the apparent negative correlation between metal concentration and decreasing dissolved oxygen obtained for most metals, Cu was found to maintain opposite trends. In this case, Cu concentrations increased with increasing DO, thus maintaining higher concentrations in surface waters. We propose that this is cause for concern on two levels:

1. The highest concentrations of Cu occur at the level of the water column most frequently containing the greatest diversity of aquatic fauna (*i.e.* above the thermocline);
2. Cu concentrations exceeded indicative trigger levels by a relatively high margin. Concentrations recorded from downstream sites, and OXB06 in particular, unless substantially complexed and therefore unavailable, would likely invoke chronic and even acute responses in biota.

The current study is based upon two short term investigations of ORWBs, and not all sites were sampled twice. Additional data have been collected from the original (February 2005) eight sites in February 2006 as part of sampling for plankton and aquatic invertebrate studies. However, this is still only a very limited view of oxbow limnology. Hence, the temporal dynamics of temperature and dissolved oxygen gradients can only be inferred from observations of oxbow characteristics (*i.e.* water depth, health of riparian vegetation and the level of conductivity) together with the perceived differences in water quality characteristics between February and July. In most cases, this appears to be sufficient to derive meaningful conclusions about the limnology of ORWBs; however, the sampling regime did not allow for a thorough investigation of processes such as the incidence of mixing events. Further studies of limnology incorporating longer term deployment of data loggers may be useful for determining temporal trends in water column characteristics, including average diurnal processes and long term qualities, such as the length of time between significant turn over events. An understanding of these processes, in conjunction with more frequent measures of metal concentrations may also help to elucidate episodic events of metal toxicity to resident fauna under different scenarios and at different points in time (*e.g.* between wet and dry seasons).

6 Recommendations

As a recommendation, frequent re-sampling of the same suit of wetlands may be beneficial in establishing a more comprehensive overview of spatial and temporal patterns in ORWB limnology, dissolved metal concentrations, and episodic mixing events. Collection of replicate (x3) water samples for determination of metals data from surface, mid and bottom levels, in conjunction with 6-hourly vertical profiles with a multi-probe meter should be considered the minimum data requirement. Logging 24 hr changes in temperature and dissolved oxygen is logistically more demanding and, although providing valuable information, is not required on as regular a basis.

Elevated levels of metals in downstream oxbows are of concern, especially dCu in surficial waters at OXB06. The labile proportion of dCu in these sites should be determined to assess possible risk of toxicity to biota. The Chelex column installed in the Environmental Chemistry Laboratory at Tabubil should be used to test for labile Cu levels in these oxbow lakes, particularly those with elevated dCu levels (*i.e.* OXB06).

The current study examining spatial and temporal patterns in phytoplankton, zooplankton and aquatic macroinvertebrates of these ORWBs should look specifically for a mine-effect in OXB06 in response to the elevated levels of various metals.

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8 APPENDICES

8.1 Appendix 1 – Hydrolab and physical chemistry logger data for 2005.

Table 16. (February) Physico-chemistry data obtained at ORWBs. Data are presented for three different depths (Bottom, Middle and Surface of water column). Max, min and range of dissolved oxygen concentrations are derived values obtained from data loggers.

Date	Site					Dissolved Oxygen				
		Oxbow level	Temp (C^{o})	pH (H^{+})	Conduct (ms/cm)	(mg/L)	Max (mg/L)	Min (mg/L)	Range (mg/L)	Redox (mV)
05-Feb-05	Bosset	Bottom	28.96	6.62	72.6	4.22	5.37	3.71	1.66	223
05-Feb-05	Bosset	Middle	28.96	6.65	72.6	4.19	5.32	4.34	0.98	221
05-Feb-05	Bosset	Surface	28.95	6.71	72.6	4.4	5.38	4.05	1.33	218
17-Feb-05	Drimdenasuk	Bottom	25.02	8	118	5.77	5.8	2.96	2.84	158
17-Feb-05	Drimdenasuk	Middle	25.63	7.9	122.1	5.88	5.97	2.61	3.36	160
17-Feb-05	Drimdenasuk	Surface	28.23	7.4	105.2	5.88	6.34	3.98	2.36	162
11-Feb-05	Kuambit	Bottom	28.48	7.09	136	1.3	5.61	0.91	4.7	157
11-Feb-05	Kuambit	Middle	29.47	7.25	138	4.34	6.46	2.39	4.07	151
11-Feb-05	Kuambit	Surface	31.66	7.53	133	6.34	6.82	2.65	4.17	141
03-Feb-05	Daviumbu	Bottom	29.4	6.58	107.5	0.28	0.3	0	0.3	197
03-Feb-05	Daviumbu	Middle	29.45	6.56	107.6	0.34	0.8	0	0.8	202
03-Feb-05	Daviumbu	Surface	29.47	6.57	107.6	0.43	2.13	0	2.13	205
13-Feb-05	Moian	Bottom	27.92	6.23	26.2	3.2	4.46	2.19	2.27	305
13-Feb-05	Moian	Middle	28.51	6.39	18.3	4.61	4.95	3.26	1.69	298
13-Feb-05	Moian	Surface	29.24	6.58	24.1	5.95	5.99	3.88	2.11	289
15-Feb-05	Oxbow 1	Bottom	25.5	6.61	134.6	0.18	2.4	0	2.4	-106
15-Feb-05	Oxbow 1	Middle	27.01	7.03	106.6	0.72	5.9	0.91	4.99	254
15-Feb-05	Oxbow 1	surface	30.68	7.9	99.5	8.02	8.59	4.11	4.48	225
09-Feb-05	Oxbow 2	Bottom	26.95	7	134.4	0.15				-110
09-Feb-05	Oxbow 2	Middle	27.02	6.88	136.1	0.17				-60
09-Feb-05	Oxbow 2	Surface	29.54	7.17	132.3	4.17				136
07-Feb-05	Oxbow 6	Bottom	26.7	7.03	131.4	0.16	0.65	0	0.65	32
07-Feb-05	Oxbow 6	Middle	28.18	6.88	141	1.17	3.35	0.49	2.86	192
07-Feb-05	Oxbow 6	Surface	28.8	6.94	141	3.1	4.37	1.67	2.7	185

Table 17. (July/August) Physico-chemistry data obtained within ORWBs. Data are presented for three different depths (Bottom, Middle and Surface of water column). Max, min and range of dissolved oxygen concentrations are derived values obtained from data loggers.

Date	Site					Dissolved Oxygen				
		Oxbow level	Temp (C^o)	pH (H^+)	Conduct (ms/cm)	(mg/L)	Max (mg/L)	Min (mg/L)	Range (mg/L)	Redox (mV)
28-Jul-05	Bosset	Bottom	26.82	7.22	27.2	5.94	5.93	5.34	0.59	278
28-Jul-05	Bosset	Middle	26.82	7.26	26.9	6.04	6.33	5.97	0.36	277
28-Jul-05	Bosset	Surface	26.85	7.34	27.6	6.22	6.14	5.67	0.47	272
05-Aug-05	Drimdenasuk	Bottom	24.59	8.13	145.6	4.1	3.21	1.71	1.5	266
05-Aug-05	Drimdenasuk	Middle	24.79	7.67	112.2	2.73	5.52	4.5	1.02	278
05-Aug-05	Drimdenasuk	Surface	27.13	8.03	102.7	6.6	7.83	5.41	2.42	267
27-Jul-05	Oxbow 5	Bottom	26.35	8.1	145	4.73	5.68	4.31	1.37	275
27-Jul-05	Oxbow 5	Middle	26.61	8.13	143.6	5.36	6.52	5.24	1.28	304
27-Jul-05	Oxbow 5	Surface	26.71	8.21	141.7	5.68	6.73	5.04	1.69	301
03-Aug-05	Oxbow 2	Bottom	24.9	7.96	160	1.77	2.05	1.22	0.83	252
03-Aug-05	Oxbow 2	Middle	25.3	8.08	156	2.96	4.15	1.88	2.27	249
03-Aug-05	Oxbow 2	Surface	26.3	7.94	158	2.96	4.8	2.41	2.39	252
31-Jul-05	Oxbow 6	Bottom	25.38	8.55	152	4.69	4.95	4.16	0.79	226
31-Jul-05	Oxbow 6	Middle	25.51	8.54	154	4.98	5.02	4.78	0.24	228
31-Jul-05	Oxbow 6	Surface	25.56	8.54	153	5.14	4.78	3.94	0.84	230
04-Aug-05	Moian	Bottom	24.59	8.57	101.7	5.59	6.6	5.89	0.71	233
04-Aug-05	Moian	Middle	24.59	8.57	101.6	5.57	7.09	6.5	0.59	234
04-Aug-05	Moian	Surface	24.57	8.58	101.4	6.15	6.68	5.95	0.73	235

8.2 Appendix 2 - Oxbow lake dissolved metal concentrations recorded in 2005.

Table 18. (February) Dissolved metal concentrations obtained within surface, middle and bottom waters of oxbow lakes. Values are mean values obtained by averaging three replicate samples.

Date	Site	Level	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Ag (µg/L)	Al (µg/L)	As (µg/L)	Cd (µg/L)	Co (µg/L)	Cr (µg/L)	Cu (µg/L)	Mn (µg/L)	Mo (µg/L)	Ni (µg/L)	Pb (µg/L)	Se (µg/L)	Zn (µg/L)
05-Feb-05	Bosset	Bottom	12.00	0.87	1.40	0.70	0.10	19.66	0.50	0.02	0.10	0.50	4.67	12.60	1.11	1.61	1.07	0.50	1.20
05-Feb-05	Bosset	Middle	12.33	0.90	1.37	0.77	0.10	16.54	0.50	0.03	0.08	0.50	3.73	1.70	1.20	1.51	0.20	0.50	2.27
05-Feb-05	Bosset	Surface	11.00	0.90	1.40	0.80	0.10	21.21	0.50	0.04	0.08	0.50	3.93	2.50	1.02	1.44	0.37	0.50	3.80
17-Feb-05	Drimdenasuk	Bottom	23.87	1.03	0.80	0.40	0.10	32.07	0.50	0.05	0.14	0.50	0.73	9.57	0.10	2.37	0.15	0.50	0.05
17-Feb-05	Drimdenasuk	Middle	15.47	0.80	0.80	0.40	0.10	39.95	0.50	0.04	0.09	0.50	1.13	17.33	0.10	1.47	0.15	0.50	0.37
17-Feb-05	Drimdenasuk	Surface	18.75	1.05	1.15	0.40	0.17	13.35	0.50	0.06	0.11	0.50	1.25	4.60	0.73	1.92	0.15	0.50	1.00
11-Feb-05	Kumabit	Bottom	16.70	0.83	0.93	0.53	0.10	20.11	0.50	0.07	0.10	0.50	9.10	131.33	1.44	1.82	1.03	0.50	2.23
11-Feb-05	Kumabit	Middle	18.53	1.00	1.17	0.57	0.10	9.88	0.50	0.08	0.09	0.50	8.47	71.67	1.32	2.12	0.87	0.50	2.40
11-Feb-05	Kumabit	Surface	22.93	1.17	1.40	0.70	0.10	11.07	0.71	0.09	0.11	0.50	11.67	56.67	1.48	2.57	0.93	0.50	2.87
03-Feb-05	Daviumbu	Bottom	19.30	1.00	1.00	0.43	0.10	2.35	0.50	0.02	0.10	0.50	2.63	1.63	1.41	2.19	0.28	0.50	2.70
03-Feb-05	Daviumbu	Middle	18.73	1.00	1.10	0.33	0.10	0.09	0.50	0.02	0.10	0.50	3.07	0.93	1.43	2.18	0.15	0.50	1.93
03-Feb-05	Daviumbu	Surface	18.93	1.00	0.97	0.37	0.10	0.60	0.50	0.01	0.09	0.50	2.10	0.90	1.42	2.05	0.15	0.50	0.23
13-Feb-05	Moian	Bottom	3.83	0.30	0.90	0.20	0.10	24.40	0.50	0.06	0.18	0.50	1.27	63.33	0.10	0.51	0.15	0.50	0.38
13-Feb-05	Moian	Middle	2.53	0.30	0.90	0.30	0.10	25.47	0.50	0.04	0.06	0.50	1.17	21.67	0.10	0.35	0.15	0.50	0.60
13-Feb-05	Moian	Surface	3.50	0.40	1.00	0.30	0.10	25.78	0.50	0.05	0.06	0.50	1.30	18.33	0.10	0.45	0.15	0.50	0.90
15-Feb-05	Oxbow 1	Bottom	21.80	1.35	1.50	0.50	0.10	17.63	5.73	0.09	0.76	0.50	0.35	320.00	0.10	2.24	0.15	0.50	0.23
15-Feb-05	Oxbow 1	Middle	22.03	1.07	1.07	0.33	0.10	16.76	1.26	0.09	0.52	0.50	0.97	165.67	0.10	2.42	0.15	0.67	0.35
15-Feb-05	Oxbow 1	surface	19.47	1.00	1.17	0.30	0.10	15.44	0.50	0.07	0.09	0.50	1.00	1.83	0.10	2.19	0.15	0.50	0.62
09-Feb-05	Oxbow 2	Bottom	22.33	1.00	1.00	0.70	0.10	9.52	2.45	0.02	0.40	0.50	3.83	450.00	2.16	2.40	1.83	0.50	1.33
09-Feb-05	Oxbow 2	Middle	21.90	1.00	1.00	0.70	0.10	5.41	1.76	0.01	0.39	0.50	3.70	450.00	1.98	2.41	0.80	0.50	1.53
09-Feb-05	Oxbow 2	Surface	23.47	1.20	1.20	0.80	0.10	0.28	0.50	0.01	0.13	0.50	7.53	9.47	1.57	2.69	0.15	0.76	2.10
07-Feb-05	Oxbow 6	Bottom	23.93	1.03	1.00	0.80	0.31	35.98	0.98	0.06	0.23	0.72	9.67	243.33	4.26	2.81	2.47	0.50	3.03
07-Feb-05	Oxbow 6	Middle	24.13	1.20	1.40	1.00	0.10	15.02	0.90	0.03	0.14	0.50	20.67	37.67	2.09	2.87	1.00	0.50	3.70
07-Feb-05	Oxbow 6	Surface	25.30	1.30	1.40	1.10	0.10	6.29	0.50	0.02	0.15	0.50	16.33	2.00	1.94	2.98	0.57	0.67	2.90

Table 19. (July/August) Dissolved metal concentrations obtained within surface, middle and bottom waters of oxbow lakes. Values are mean values obtained by averaging three replicate samples

Date	Site	Level	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Ag (µg/L)	Al (µg/L)	As (µg/L)	Cd (µg/L)	Co (µg/L)	Cr (µg/L)	Cu (µg/L)	Mn (µg/L)	Mo (µg/L)	Ni (µg/L)	Pb (µg/L)	Se (µg/L)	Zn (µg/L)
28-Jul-05	Bosset	Bottom	2.00	0.43	0.87	0.05	0.10	16.43	0.50	0.01	-0.04	0.05	5.00	3.20	0.16	0.11	1.13	0.05	5.63
28-Jul-05	Bosset	Middle	1.00	0.40	0.90	0.05	0.10	13.05	0.50	0.01	-0.03	0.05	4.10	3.83	0.10	0.16	0.70	0.05	4.67
28-Jul-05	Bosset	Surface	1.00	0.40	0.83	0.05	0.10	18.70	0.50	0.01	-0.02	0.05	4.50	3.77	0.10	0.11	0.70	0.05	4.13
05-Aug-05	Drimdenasuk	Bottom	8.67	0.80	0.90	0.05	0.10	11.84	0.50	0.01	0.00	0.05	0.17	8.97	0.10	1.01	0.23	0.05	4.40
05-Aug-05	Drimdenasuk	Middle	6.00	0.63	0.87	0.07	0.10	15.76	0.50	0.01	-0.02	0.05	0.57	3.90	0.10	0.82	0.57	0.05	9.57
05-Aug-05	Drimdenasuk	Surface	7.00	0.60	0.75	0.10	0.10	0.05	0.50	0.01	-0.02	0.05	0.05	0.58	0.10	0.70	0.15	0.05	3.10
27-Jul-05	Oxbow 5	Bottom	No data due to water sampling apparatus failure																
27-Jul-05	Oxbow 5	Middle	9.33	0.80	1.00	0.20	0.10	0.94	0.50	0.01	-0.03	0.05	3.85	1.08	0.90	1.74	0.15	0.05	3.72
27-Jul-05	Oxbow 5	Surface	9.00	0.80	1.00	0.20	0.10	1.70	0.50	0.01	0.01	0.05	5.27	1.00	1.39	0.90	0.15	0.05	2.60
03-Aug-05	Oxbow 2	Bottom	10.00	0.80	0.90	0.10	0.10	7.77	0.50	0.03	-0.01	0.05	5.92	31.78	1.25	0.65	0.15	0.07	4.48
03-Aug-05	Oxbow 2	Middle	10.00	0.87	0.90	0.10	0.10	12.02	0.50	0.03	0.03	0.05	8.10	47.00	1.54	1.07	0.32	0.05	8.30
03-Aug-05	Oxbow 2	Surface	10.00	0.90	0.93	0.10	0.10	4.61	0.50	0.01	0.03	0.05	6.57	5.03	1.38	0.96	0.15	0.05	5.87
31-Jul-05	Oxbow 6	Bottom	10.67	0.90	0.90	0.20	0.10	41.30	0.50	0.05	0.08	0.05	17.67	50.67	2.60	1.28	0.90	0.05	7.83
31-Jul-05	Oxbow 6	Middle	10.00	0.80	0.90	0.10	0.10	34.15	0.50	0.01	0.04	0.05	12.67	15.67	1.68	1.07	0.87	0.05	6.93
31-Jul-05	Oxbow 6	Surface	9.33	0.80	0.90	0.20	0.10	31.78	0.50	0.01	0.04	0.05	11.00	3.27	1.81	1.33	0.77	0.05	9.33
04-Aug-05	Moian	Bottom	8.00	0.80	0.80	0.05	0.35	33.89	0.50	0.02	0.07	0.05	0.20	8.77	1.38	0.92	0.63	0.05	4.93
04-Aug-05	Moian	Middle	8.00	0.80	0.83	0.05	0.10	37.28	0.50	0.01	0.05	0.05	0.05	8.93	0.10	0.80	0.27	0.05	5.30
04-Aug-05	Moian	Surface	8.00	0.77	0.83	0.07	0.10	44.48	0.50	0.01	0.05	0.05	0.20	8.47	0.10	0.88	0.15	0.05	5.37