Water Column Profiles And Instrument Chains Provide Complementary Understanding Of Stratification In Pit Lakes

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Abstract

In pit lakes, stratification is normally investigated using 'spot' water column profiles, whereas continuous monitoring of stratification using instrument chains (ICs) is uncommon. This research evaluated the benefits of using ICs in conjunction with spot profiles.

We collected temperature and conductivity profiles through spot measurements and ICs from 3 pit lakes in 2019-2021 from the major Australian coalfields in New South Wales and Queensland.

ICs revealed temporary mixing and rain-driven turnover in the lakes that were missed with spot profiles. However, ICs required regular maintenance, instrument failures limited the data, and sensor fouling was problematic. Combining water column profiles and IC data improved insights into the limnology of these lakes.

Keywords: Limnology, rain events, mixing, thermal stratification

Introduction

Thermal stratification results in pit lakes being divided into layers with minimal interaction between those layers, allowing different chemistries to develop (Boehrer and Schultze 2008). Salinity stratification has been of particular interest to pit lake scientists as the monimolimnion potentially will never mix with the rest of the lake and so is a stable place to store waste materials (Schultze et al. 2011). From a biological perspective, one aspect of stratification is that the hypolimnion or monimolimnion can become hypoxic to anoxic due to either chemical or biological oxygen demand. These low-oxygen environments are 'out-of-bounds' to most freshwater organisms, other than bacteria, limiting total habitat availability and therefore populations.

Stratification is typically measured using a multi-parameter instrument lowered vertically through the profile (e.g.Balistrieri et al. 2006; Kennedy and Johnstone 2018). The use of multiparameter probes can also highlight other important physico-chemical changes with depth such as in pH, ORP, dissolved oxygen and chlorophyll a. Deep chlorophyll a maxima occur in pit lakes (Tittel et al. 2003) and are missed with simple surface sampling but with a suitable probe can be detected in spot profiles (Lund and Blanchette 2018). Spot measurements can be collected at multiple sites across the lake and may record internal waves and seiches (Boehrer and Stevens 2005). In Lake Kepwari (Collie, Western Australia) we found that spot profiles revealed likely discharges of groundwater at particular depths through slight declines (100-200 µS cm-1) in electrical conductivity (hereafter called conductivity) (Lund and Blanchette 2018).

Monitoring water quality in pit lakes is rarely a priority unless they are discharging, and due to the work health and safety challenges of boating, monitoring is often restricted to one site at the lake's edge (but see Castendyk et al. 2020). Water quality models are widely used in closure planning and need to be calibrated against real data for the lake (Imberger 2004), and the absence of profiles or bottom samples limits that ability. Therefore, using a variety of sampling techniques that cover the area of the lake over time are likely to yield a more complete picture of the lake's water quality. Imberger (2004) proposed the use of an instrument chain designed specifically to provide data for modelling of stratification, that captured specific weather and water column parameters and supplied these in real time. Designing environmental sampling to improve water quality modelling is covered in detail by Oldham (2014). Despite advances in technology, the cost of instrumentation for water quality remains high and is still relatively complex to maintain and install. In active lease areas where pit lakes are many years from closure, it is hard to justify installation of complex real-time monitoring stations for measuring stratification, therefore the opportunity is lost for companies to build up data that could ultimately inform their closure planning, and capture events that would otherwise be missed.

We have approached the challenge of monitoring pit lakes by developing instrument chains that are relatively inexpensive (≈AUD$10,000 each) and relatively low maintenance (Lund and Blanchette 2018). Our chains focus on in-lake parameters and contain sensors for temperature, light, conductivity, dissolved oxygen, and depth that are off-the-shelf, and self-contained with logging capability. Removing real-time reporting and use of independent battery powered loggers simplifies the chain design. The use of independent loggers allows as many sensors to be used as needed and allows sensors to be easily relocated along the chain if the lake depth changes substantially or to target specific depths. Our chains can be typically serviced at 3–6 monthly intervals and are recommended to be accompanied by at least one spot profile near the chain for calibration purposes. Limited regular calibration of the sensors is required. These independent loggers are typically lower in precision and accuracy compared to the system designed by Imberger (2004) but is sufficient to still provide valuable insights across more sites for lower cost.

In this paper, we show how data collected from both spot profiles and low-cost instrument chains provides complementary and valuable insights into pit lake limnology.

Methods

Study area

Three Australian coal mine pit lakes were selected for this study, one (HL1) from the Hunter Basin (21, 500 km2) in New South Wales, and two (BL1, BL2) from the Bowen Basin (60, 000 km2) in Queensland (see Blanchette and Lund 2021, for more details). The Hunter Basin is in Köppen climate type Cfa (humid subtropical, mild with no true dry season and hot summers), with rains typically occurring during summer (Peel et al. 2007). The Bowen Basin is within Köppen climate type BSa (arid steppe, with hot summer) with predominantly summer rainfall (Peel et al. 2007).

None of these lakes had been rehabilitated at the time of sampling 2019-2021. HL1 was actively used for water storage and the other lakes used occasionally for water management. HL1 was approximately 20 years old at the time of sampling, BL1 was still filling, and BL2 was 10 years old. Aspects of the data for this paper were originally published in Blanchette and Lund (2021) and are re-written with an emphasis on practical application.

Sampling

An instrument chain was installed in each of the three lakes in early 2019 to investigate stratification (chains described in Blanchette and Lund (2021)). Each chain collected data on surface and bottom electrical conductivity, and temperature at a variety of depths. The instrument chain was serviced and downloaded during sampling trips (see below).

The lakes were sampled quarterly (February, May, August and December) in 2019, at three sites approximately equidistant across each lake which included the deepest location. On each occasion, an in situ spot physico-chemical profile was collected through the entire water column using a Hydrolab Datasonde DS5 multiparameter instrument (Hach, Austin, USA). Water column profile data were: temperature, pH, dissolved oxygen (mg L-1 and % saturation; luminescent), conductivity standardized at 25 ˚C and oxidation-reduction potential (ORP, platinum electrode).

Results and Discussion

Spot profiles

All three lakes were thermally stratified yet not salinity stratified during summer with winter mixing (Figure 1). Only HL1 developed anoxia in the hypolimnion, with the other lakes showing no substantive decrease in hypolimnetic dissolved oxygen concentrations. pH varied by <1 in all lakes down the profile. All profiles showed positive ORP values across all lakes and times. In HL1, the high ORP might be linked to the presence of NOx (mean 65 µ g L^{-1}) in the bottom waters. Hypolimnetic anoxia in HL1 resulted in a moderate increase in conductivity, whereas in the other lakes high evaporation rates resulted in small (100-200 µS cm-1) increases in surface waters that had insufficient impact on water density to overcome the thermal gradient (Figure 1).

Instrument Chains

Heat maps showing the stratification in all the lakes can be seen in Blanchette and Lund (2021). In summary from Blanchette and Lund (2021) HL1 was thermally stratified between February and early March 2019, was 'mixed' from April-September, and re-stratified in early October to November. BL1 was thermally stratified over the spring/summer (late September to March), completely mixed from late March-June, and then weakly thermally stratified (19–21°C) in July and August. The hypolimnion started at 17m. BL2 was thermally stratified for most of the study except between late April and late May when the lake mixed. The hypolimnion formed at about 4 m. During winter, thermal stratification was weak with only 1–2°C difference between top and bottom.

Temperatures during both stratification events in HL1 ranged from a high of 27°C at the surface to a low of 12°C at the bottom, with bottom waters increasing briefly to a

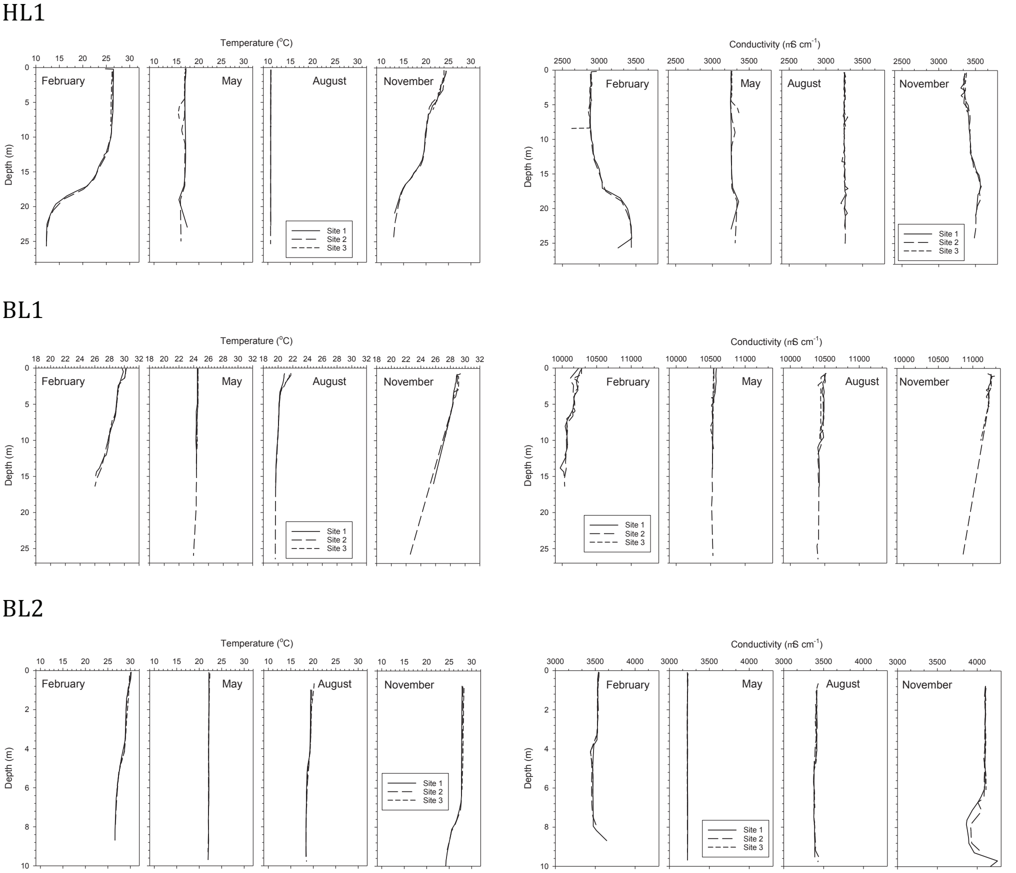

***Figure 1** Water profiles for temperature (left) and conductivity (right) for HL1, BL1 and BL2 lakes measured at three sites (1 to 3) in 2019 (n.b., in November, equipment issues meant that profiles in BL1 were measured at approximately 0.5 m intervals to 5 m and then a single bottom sample was collected using the Kemmerer bottle which may mask trends between 5 m and the bottom).*

high of 18°C due to mixing. To investigate the phenomenon of warm surface water moving to the bottom of the lake prior to complete mixing, first we compared rainfall events to lake temperatures from February to April (Figure 2). Sporadic small rainfall events followed by one large rain event in March (40mm on 30/3/2019, Ulan Water, Australian Bureau of Meteorology (BOM) 2020) coincided with a rise in temperature in water at the bottom of the lake. However, surface water temperature declined at the same time bottom water temperature was rising (Figure 2) and therefore rainfall did not appear responsible for the observed increase in bottom water temperatures. Secondly, comparing minimum air temperature between March and April 2019 was difficult due to missing data in April, although April did have a few substantially cooler days than March. As air temperature cooled, the top 1 m layer of the lake cooled, but did not reach the same temperature as the bottom water which would have triggered full mixing. During stratification, bottom conductivities were ~500 µS cm-1 higher than surface waters indicating that weak salinity and strong thermal stratification occurred simultaneously (Figure 2). The rainfall in late March resulted in a temporary increase in conductivity of surface waters, presumably from surface runoff (Figure 2). Although the rainfall did not directly result in any obvious mixing, variability in both bottom temperatures and conductivity increased indicating small amounts of mixing. This mixing was probably caused by overnight cooling of surface waters plunging through the water column, pulling lower conductivity and warmer waters down with them. This small scale mixing increased bottom temperatures and reduced conductivity over time allowing the lake to mix completely by start of May. The salinity stratification was not sufficient to prevent mixing.

Instrument chain surface conductivity loggers generally reflected the spot profile observations (Figures 1 & 2). However, after the May 2019 sampling, there were substantial increases in conductivity at 33 m in BL1 to approx. 15,000 µS cm^{-1} that returned to baseline (approx. 10,500 µS cm^{-1}) in the August sampling before increasing again to approx. 15,000 µS cm^{-1} (Figure 3). A similar pattern in conductivity was observed in surface conductivity in HL1 which appeared to reflect instrument drift correction from using spot profile data. High drift appeared to be due to observed biofouling on the sensors, which in HL1 was due to algae and in BL1 was a deposition of a hard precipitate (believed to be a carbonate, as it dissolves readily in acid with odourless gas evolution potentially CO_2). Biofouling in some lakes limited reliable data collection times.

The effect of a 100-mm rain event in March 2019 at lakes BL1 and BL2 likely influenced surface and bottom water temperatures and conductivity (Figure 3). In BL1, the rain event resulted in a ~2,000 µS cm^{-1} drop in

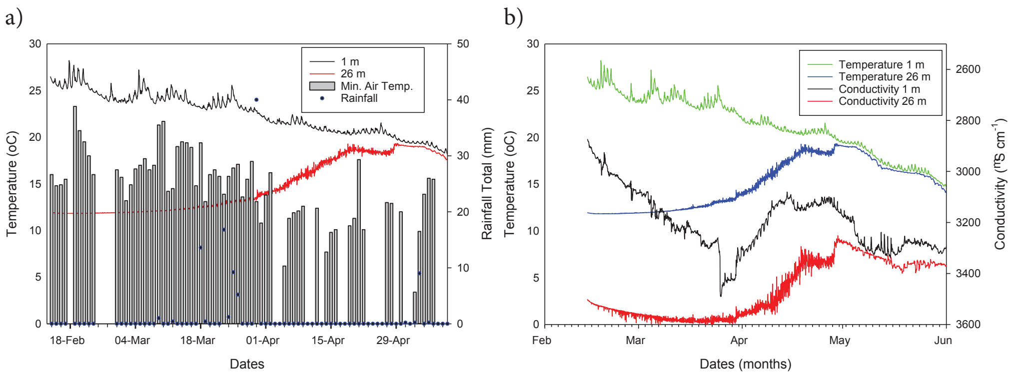

__Figure 2__ In 2019 for HL1, a) water temperatures at surface (1 m) and bottom (26 m), with minimum daily air temperatures (Gulgong Post Office, BOM 2020) and daily rainfall (Ulan Water, BOM 2020) between February and May and b) water temperature (1 and 26 m) and conductivity (surface and bottom; inverted axis – to reflect increasing water density) for the winter mixing event

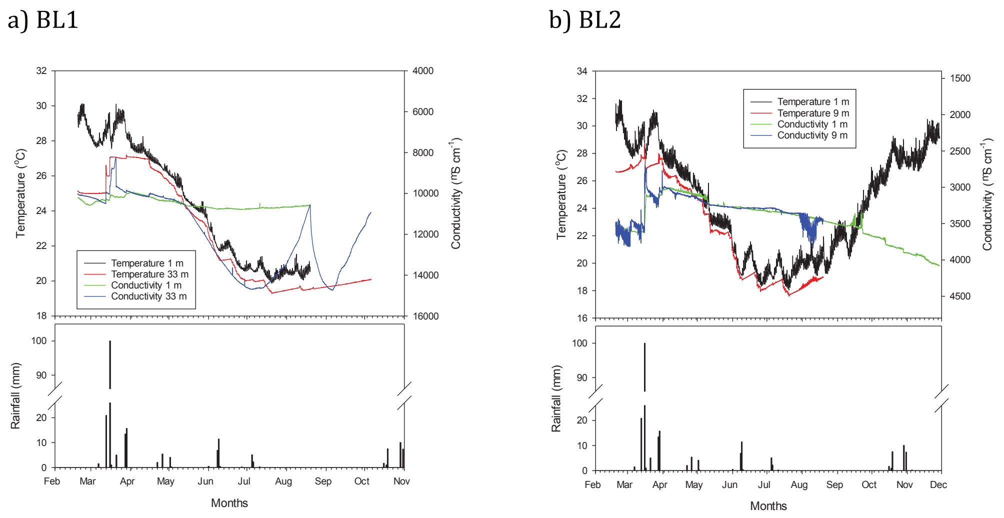

Figure 3 Daily rainfall, and surface (1 m) and bottom (33 m, 9 m respectively) conductivity and temperature in a) BL1 and b) BL2 in 2019 (Note the inverse conductivity scale to reflect density).

conductivity at 33 m. The lowest conductivity reading at 33 m (approx. 8,000 µS cm 1) was reached 5 days after the rainfall event, although this pattern was not replicated in the surface waters. By day 6 conductivity rose by ~1,000 µS cm^{-1} and then slowly reached surface conductivity levels 11 days after the rain event (Figure 3). Examining individual sensor data in Figure 4, temperatures increased in the hypolimnion (23 and 33 m) but declined in the metalimnion and epilimnion (12, 9, 6 and 3 m). Rain and lake water interaction likely occurred when 1) rainwater (about 27°C) cooled the surface waters and 2) water washing down the steep highwalls plunged to the lake bottom, diluting the hypolimnion, reducing conductivity, and increasing temperature causing mixing. Essentially, warm rainwater pushed the bottom water upwards (thermal contour map – Figure 4). Although the high air temperature subsequently does re-establish a slight thermal gradient, it is short-lived. Lake BL2 was shallower, and the temperature gradient was re-established more quickly than at BL1, partially as bottom waters only briefly increased in temperature before dropping to temperatures lower than before the event. The steep walls and larger catchment of BL1 probably resulted in a larger inflow of rainwater than in BL2 which might explain the longer-term effects of the rain event at BL1 than BL2.

Conclusions

Spot profiles of physico-chemical properties provide reference values for calibration of instrument chain sensors and can include a broader range of sensors at lower cost (e.g. ORP, Chlorophyll a) than instrument chains. We found that instrument chains need to be serviced at 3–6 monthly intervals due to biofouling of both conductivity and oxygen sensors, although temperature sensors appeared unaffected and could survive up to 1 year depending on the battery. For relatively low cost and minimal intervention, instrument chains provide insights into mixing processes that would otherwise be missed with spot profiles alone. For example, instrument chains revealed he importance of intense rainfall events to mixing, how weak stratification was maintained most of the year in BL1 and BL2, and how bottom temperatures can rise prior to mixing. Therefore, the use of both spot profiles and instrument chains complements our understanding of basic limnological processes in pit lakes with benefits for improved models and closure outcomes.

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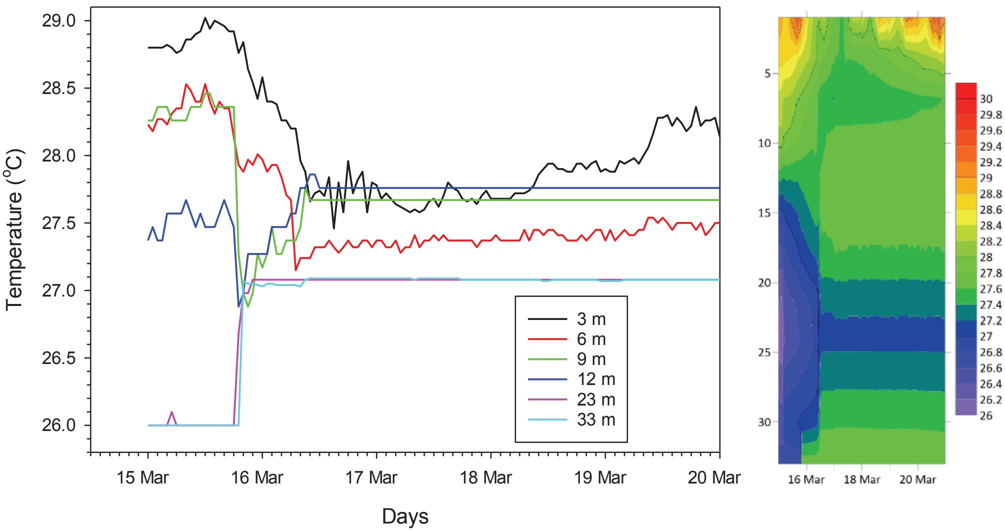

Figure 4 *Water temperatures with depth at BL1 before and after the 100 mm rain event (on 15 March 2019).*

examined the microbial dynamics of the study lakes and water quality as cited in text.

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