# Sedimentation Rates In Two Pit Lakes: Implications For Riverine Flow-Through As A Closure Strategy.

Mark Lund, Jonas Polifka, Marilyn Quintero Vasquez, Ravish Ramesseur, Ryan Bignell, and Denchen Yangzom

*Mine Water and Environment Research Centre (MiWER), Edith Cowan University, 270 Joondalup Drive, Joondalup WA 6027, m.lund@ecu.edu.au*

## Abstract

Lack of organic matter inputs into a pit lake inhibits ecological development. Connecting a river to a pit lake should add organic matter to the lake. Sedimentation traps and sediment sampling was undertaken in two co-occurring pit lakes: one with river flow-through (Lake Kepwari) and one without (WO5H) in Collie, Western Australia.

Carbon in the sediment did not vary between lakes or depths. Sedimentation rates did not vary between lakes during low/no river inflow periods. River inflow did increase sedimentation but without increasing allochthonous inputs of C. Even with river inflow C accumulation in the lakes remains very low.

**Keywords:** carbon, organic matter, succession, AMD

## Introduction

Blanchette and Lund (2016) proposed that natural evolution of pit lakes towards becoming lake ecosystems was dependent on carbon accumulating in the lake faster than it was being lost. When natural lakes form through asteroid strike, flooding of craters or from glacial action, the initial sediment at the bottom of the lake is largely devoid of organic matter, similar to the material at the bottom of pit lakes. As newly created natural lakes evolve they accumulate organic materials from external (allochthonous) or internal sources (autochthonous) that as it settles out at the bottom creates sediment. The organic materials in the sediment provide food sources for microbial activity, binding and release sites for nutrients and alter the phyisco-chemical properties of the sediment. In pit lakes, the development of sediment is similarly important, however low nutrient concentrations, potentially toxic waters, and low pH can all individually or together limit primary production within the lake. Further, small catchments and poorly developed riparian zones reduce external sources of organic matter (Lund and McCullough 2015). Despite studies examining carbon accumulation in sediment of pit lakes such as Laskov et al. (2002), the effect of increased catchment size on allochthonous inputs of carbon into pit lakes has not been measured. This study aimed to test whether river flow through a pit lake, which can effectively dramatically increase the lakes catchment, results in increased carbon input into the sediments – which were examined through sediment sampling and measurement of sedimentation rates.

## Methods

### *Study Sites*

The Collie coal basin in Western Australia contains over 10 pit lakes formed from prior open-cut coal mining (Lund et al. 2012). The largest of the Collie pit lakes is Lake Kepwari (98 ha, 65 m deep), it is circumneutral and slightly saline (≈2.4 mS $cm^{-1}$) (Lund and Blanchette 2018b). The Collie River South Branch had been diverted to allow mining to occur. The lake water level was established under a rapid fill programme whereby river water was diverted to the mine void during periods of high flow. This had the added advantage of managing acidification of the lake by preventing further oxidation of sulphides in the exposed coal seams. The lake water level was then to be maintained by seasonal top-up of the lake under high river flow conditions, with no discharge from the lake. Following an accidental river inflow (McCullough et al. 2012) government approval was given to connect the river to the lake, initially as a 3-year trial. A key conclusion of the trial was that flow through is the preferred closure strategy for Lake Kepwari. A revised closure plan includes backfilling of the diversion channel and permanent uncontrolled inlet and outlet structures to allow the river to flow unimpeded through the lake. WO5H is the second largest Collie pit lake and the deepest (44 ha, 85 m deep). WO5H is used to manage water runoff from the mine site and is used as third party water supply; discharge is prevented by use of lake water by a nearby power station for cooling. Water levels within WO5H can vary by 1 m over short periods. WO5H is acidic (pH 2.6-3.5), and slightly saline (≈2.4 mS $cm^{-1}$). Both lakes have had their catchments revegetated and contoured. Neither lake has riparian vegetation (although some is starting to grow in Lake Kepwari), although in WO5H planting of upland vegetation below the final water level (now dead) probably improves bank stability.

Collie is situated in an area of Mediterranean climate, with hot, dry summers (range 11.7–30.5°C) and cool, wet winters (range 4.2–16.3°C) (Commonwealth of Australia, Bureau of Meteorology (BOM) 18/5/2018). Seventy-five percent of the rainfall occurs during the five months from May to September (Figure 1). The 100-year mean annual rainfall for the Collie Basin is 933.1 mm, (BOM) 18/5/2018), although this has decreased to an average of 731 mm over the last 15 years. Evaporation rates for the

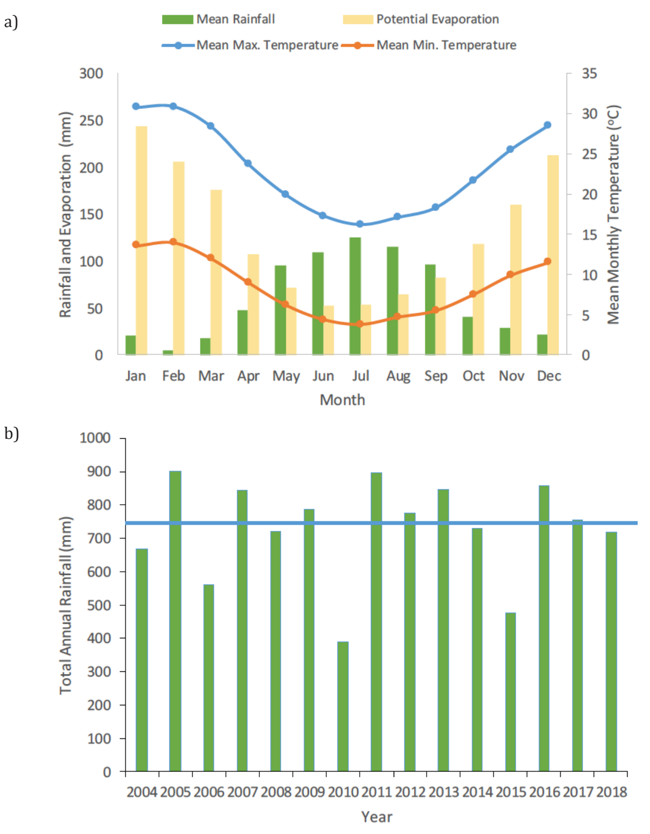


*Figure 1. a) Mean monthly minimum and maximum air temperatures, and mean monthly total rainfall and potential pan evaporation, (Collie East Station, 2002-2018 and Evaporation Atlas) and b) total annual rainfall 2004 to 2018, with average shown (blue line; Collie East, except for 2013 which comes from Collie) Data supplied by the Commonwealth of Australia Bureau of Meteorology.*

area are not routinely measured by the BOM weather stations in the region, but it supplies an atlas of potential evaporation rates.

Total annual rainfall in Collie between 2004 and 2018 ranged between 390 mm (2010) and 902.2 mm (2005) (fig 1).

## *Sampling*

A single set of sediment traps made of plastic cylinders were deployed in centers of WO5H and Lake Kepwari for 30 days in September 2016, 42 days in September/October 2017, and 23 days in September/October 2018. Groups of 3 duplicate cylinders (0.98 m long, 80 mm dia.) sealed at the bottom were attached to a 50 m rope, at depths of 10 m, 25 m and 40 m representing top, middle and bottom of the water column (Bloesch and Burns 1980). The vertical cylinders were attached so as to maintain a distance of approximately 0.2 m from each other thereby minimising contamination from any algal growth that might occur on the rope. The rope was anchored to the sediment with approximately 15 kg of weights, and a buoy was mounted about 2 m from the water surface to hold the cylinders vertically in the water column. A second free-floating buoy on the surface allowed the traps to be located (fig 2). Additionally in 2018, at 3 approximately equidistant sites around the edge of each lake, a set of 3 duplicate sediment traps were set at a 5 m depth in a water depth of 10 m – they were treated and designed as per the central tubes. At the end of the experiment, the entire set of traps was removed from the lake and each cylinder was immediately capped upon collection.

After collection, each cylinder was shaken for 10 seconds in order to homogenise any captured sediment and then a subsample of 0.5 L was filtered through 0.5 µm pre-weighed glass fibre filter paper (Pall Metrigard, USA) for later determination of dry weight (DW) according to methods described by APHA (1998). Once dry the filter papers were burnt for 1h at 550 °C to allow for determination of loss on ignition (LOI). Carbon content was estimated from LOI by dividing by 2 as per Pribyl (2010).

Five random (approximately equidistant) sediment samples were collected from <10 (shallow), 10-20 m (intermediate) and >20 m (deep) water depths in each lake. Sediment was collected in 2016 using an Ekman dredge and Peterson sampler (Wildco, Fl, USA) and in 2018 using a Standard Ponar sampler (Wildco, Fl, USA). Sediment samples consisted of ≈0.5 L of the top 100 mm of sediment. In the laboratory, the sediment sample was manually homogenised and then ≈25 ml of sediment (3 duplicates) was taken and dried to constant weight at 60 °C and then burnt for 1 h at 550 °C for determination of LOI.

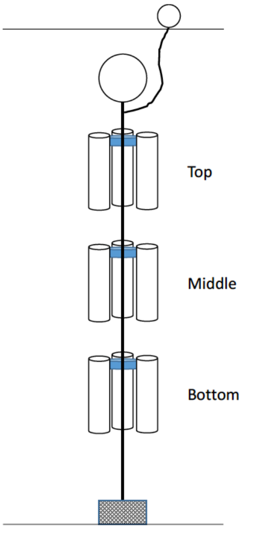


***Figure 2*** *Diagram of the arrangement of the sediment traps used in the lakes*

## *Data Analysis*

Groups of three cylinders were averaged (where data for a cylinder varied by >50% from the other cylinders for dry weight or LOI that data was excluded from the average as an outlier). There was no replication of the central cylinders so no statistics were undertaken, however edge samples were replicated and tested for difference using Oneway ANOVA (SPSS v24, IBM). Three way ANOVA (fixed factors) was used to compare sediment C between depths, lakes and years. Data was transformed as required to achieve homoscedasticity as determined by the Levenes Test (for the sediment C, homoscedasticity was not demonstrated, but $\log_{10}$ transformation reduced heteroscedasticity and given the low sample size, the test was undertaken, however caution should be used in interpretation.

## Results and Discussion

The carbon content of sediments from Lake Kepwari and WO5H were measured in 2016, and 2018, there was a significant difference ($P<0.05$) between years and depths, but not between lakes and the interaction (years x depth) was also significant. The estimated marginal means for depth and lake show that the interaction occurred as C content in deep sediment decreased slightly between 2016 and 2018 (respectively for WO5H and Lake Kepwari %C was in 2016, 6.8±0.5 and 5±0.9 and in 2018, 6.4±0.5 and 3.8±0.9), while increasing in the shallow (0.5-0.7 to 3.4-3.8 %C 2016 to 2018) and no real change in the intermediate zone (3.4-4.6 %C in 2016 to 3.7-4.1 %C in 2018). In 2012, the shallow zone of Lake Kepwari had a mean of 1.1%C, which was the lowest of another 4 Collie pit lakes sampled (2.0 -12.0%C)(Lund et al. 2014). The 2012 sediment samples were collected by diving and focused on the surface layer, therefore provide a more accurate assessment of C content, as compared to the bulk collections used in 2016 and 2018 where surficial organic matter can get washed out of the sampler as it is being hauled to the surface and the top 100 mm was homogenised together potentially lowering the %C measured. Therefore the difference in shallow sediment %C from 2012 to 2018 probably represents an important increase in organic matter accumulating. Since partial river flow through Lake Kepwari commenced in 2013, submerged plants (predominantly *Chara* spp) were observed in the shallows and are likely to be contributing to C accumulation in the sediment (Lund pers. Obs.).

The similarity between lakes, in %C in the sediments did not appear to reflect the observed organic layer visible on the surface of Lake Kepwari sediments. WO5H sediments were also found to contain coal

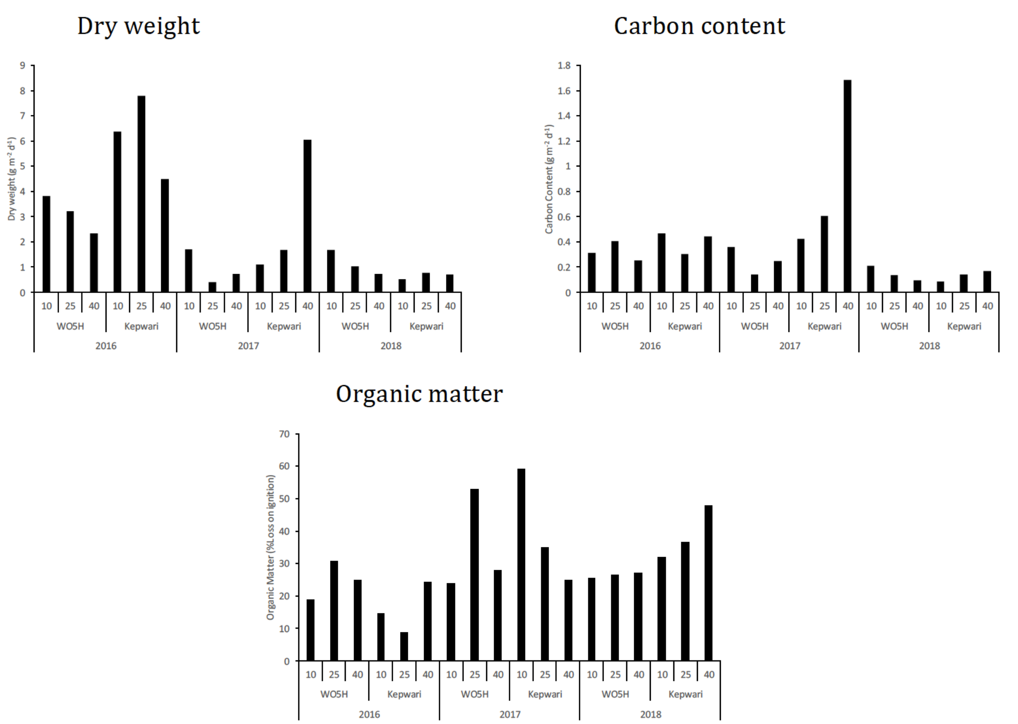


*Figure 3 Sedimentation in WO5H and Lake Kepwari pit lakes in September/October of 2016 - 2018, as mean (based on 3 duplicates) a) dry weight (g $m^{-2}$ $d^{-1}$), b) carbon content (g $m^{-2}$ $d^{-1}$) and c) organic matter (%LOI) at three depths.*

fines (which were removed when possible) but this may also have increased the %C in these sediments. Estimating from the accumulations of sediment in the sediment traps at 40 m deep, there appears to be a depositional rate of approximately 0.5 mm per month in both lakes. Therefore the depth of sediment that is likely to have accumulated since river inflow started is 20 to 30 mm. The sediment collection methodology integrated at least the top 100 mm together effectively diluted the organic accumulation by a third which may explain why no significant difference was found between lakes. Further investigation of the pit lake sediments identifying sources and lability of the carbon such as the approach of Laskov et al. (2002) may be useful in separating the lakes.

In a study of 40 natural wetlands in Perth (Western Australia), %C as determined from LOI ranged between 0.8 to 40.8% with a mean of 16% suggesting that the pit lakes while at the lower end of %C range were within the range of natural lakes (Davis et al. 1993). The lack of anoxia in the bottom of both lakes during stratification (Lund, unpublished data) may also limit C accumulation in the sediment as the carbon may be consumed by oxidative processes (see Radbourne et al. 2017).

The lakes were stratified at the time of sampling, however it was just re-establishing after the annual mixing (warm monomictic) and the epilimnion extended to about 7 m with the hypolimnion starting at 10 m in both lakes (unpublished data; Lund and Blanchette 2018a). Sedimentation rates (DW) were generally lower with water depth in both lakes and years, indicating little re-suspension of bottom sediments (fig 3). Low re-suspension is not surprising given the substantial water depth (Bloesch, 1995). Rainfall during deployment of the sediment traps could be responsible for differences between years as suggested by Axler et al. (1998). In 2016, there was 94 mm (daily maximum of 11.8 mm) of rainfall, in 2017, 104.8 mm (max. 34 mm) and in 2018, 44.4 mm (max. 17.6 mm). Aside from the direct effect of rainfall on surface runoff, additionally in Lake Kepwari this would also increase river inflow (which was minimal in 2018 during the sampling period). River flow through in 2016 and 2017 does appear to generally result in higher rates of sedimentation in Lake Kepwari compared to WO5H (fig 3a). In 2018, there was no apparent difference between the two lakes and overall sedimentation was lower than previous years. The intense rainfall event of 2017 were associated with lower rates of DW sedimentation compared to 2016, and in WO5H there was no difference apparent between DW sedimentation rates in 2017 and 2018 suggesting that rainfall was not directly responsible for altering sedimentation rates assuming that particles settle quickly so that antecedent conditions are not important.

Sedimentation rates (DW) were low compared to Kalin and Wheeler (2013) who found DW sedimentation rates for a circumneutral uranium pit lake in Canada to be 28.7 g $m^{-2}$ $d^{-1}$ in 1992 before dropping to 2 g $m^{-2}$ $d^{-1}$ in 1999. However, in shallow Polish natural lakes, DW deposition rates of 0.521 g $m^{-2}$ $d^{-1}$ (equivalent to 2-3 mm deposition per year) were recorded (Gąsiorowski, 2008) which are similar to those noted in Collie. In a pit lake used for aquaculture (Twin City-South pit lake, MN, USA) sedimentation ranged from 0.5-6 g $m^{-2}$ $d^{-1}$ with the highest values associated with localised flooding (Axler et al. 1998). In April 2013, Lund et al. (2014) using identical sedimentation sampling methods as this study measured very similar rates of DW sedimentation between WO5H and Lake Kepwari and over depth at 0.15 – 0.45 g $m^{-2}$ $d^{-1}$. April 2013 was a very dry month in Collie with 0.4 mm rainfall during sample deployment and no river inflows into Lake Kepwari, suggesting that these DW sedimentation rates are due to wind induced erosion of the banks and pit lake side walls, airborne particulates from soil erosion, and biological production. In 2017, the 40 m deep sample in Lake Kepwari had a very high sedimentation rate at 6.1 g $m_{-2}$ $d^{-1}$ compared to other depths and WO5H, this was not matched by a high organic matter (OM) content so that algal biomass was not responsible – the cause is not known. Lund and Blanchette (2018a) noted for Lake Kepwari (2014-2016) that Total N concentrations in the river inflow compared to river outflow whilst similar differed in that the inflow was dominated by organic/particulate N and the outflow by NOx suggesting deposition of those particles within the lake. OM content of the depositional material was high variable between years and lakes, there appears to be no difference between WO5H and Lake Kepwari in terms of OM content. There is no evidence that river inflow has resulted in a substantial increase in autochthonous C production through inputs of nutrients.

The 2018 edge samples were not significantly different ($P<0.05$) between lakes for OM, %C and DW, with OM content similar to the centres of the lakes at 20.0±2.2 and 21.6±2.6 % for WO5H and Lake Kepwari respectively. Edge sedimentation as DW was similar to the centre of WO5H (10 m) at 2.1±0.6 $g\ m^{-2}\ d^{-1}$ but higher than the centre of Lake Kepwari at 1.9±0.5 $g\ m^{-2}\ d^{-1}$, with C showing the same trend at 0.2±0.1 $g\ m^{-2}\ d^{-1}$ for WO5H and Lake Kepwari. The higher surface area of Lake Kepwari increases wind fetch potentially increasing resuspension in the shallows compared to the centre of the lake.

In WO5H and Lake Kepwari, although sediment depositional rates were low, it has been previously speculated by Phillips et al. (2000) that sedimentation may be sufficient to continually bury secondary minerals reducing the chances of re-oxidation. Axler et al. (1998) found that organic matter produced by aquaculture in a pit lake was rapidly buried following localised flooding, allowing the lake to recover from the eutrophication effects of aquaculture. Sedimentation rates and accumulation of organic matter in the sediments are important drivers of aquatic processes in pit lakes and warrant further investigation.

## Conclusions

Rates of sedimentation in Collie pit lakes are similar to those identified in other pit lakes worldwide, however river flow through in Lake Kepwari resulted in higher rates. The higher rate of sedimentation during river flows appears to be predominantly associated with inorganic particulates rather than the river catchment substantially contributing to an increase in allochthonous C. Despite the neutralisation of Lake Kepwari by river flow through and the continual input of nutrients from river water this does not appear to have resulted in a substantial change in autocthanous C production, except in the littoral area. This experiment suggests that despite river flow-through it will take many years before C levels in Lake Kepwari are sufficient to substantially alter the biology of the lake.

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