Seasonal river flow-through as a pit lake closure strategy: is it a sustainable option in a drying climate?

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Abstract

River flow-through has been used to effectively close pit lakes, however much of the evidence for this comes from permanent rather than seasonal rivers. Lake Kepwari (a former open-cut coal mine in Western Australia) was connected to the seasonal Collie River for closure. River water improved lake water quality but the lake caused varying downstream hydrological and chemical changes. Consecutive years of low rainfall resulting in low lake water levels could delay or reduce downstream flows and increase lake acidity. Using seasonal rivers as sources of flow-through presents a riskier scenario than using permanent rivers, particularly in a drying climate.

Keywords: AMD, ecology, salinity, mine water

Introduction

River flow-through – where a river is directed through a pit lake to improve lake water quality – has been successfully used in Germany and Austria to close pit lakes (see McCullough and Schultze 2015). Blanchette and Lund (2016) and Lund et al. (2013) proposed that pit lake catchments could be an important source of carbon for pit lakes, driving natural ecological succession, but that catchments were typically too small to be effective. River flow-through is a way to significantly increase the catchment area of a pit lake, resulting in potentially greater access to carbon, alkalinity, sediment and biological propagules.

River flow into pit lakes can be either 'controlled' (through inlet/outlet structures or pumps) or 'uncontrolled' (where the river flows through the lake unrestricted). However, this closure technique can also result in excessive nutrients, contaminants (e.g., organic pollutants), and unwanted taxa in the lake (McCullough and Schultze 2015). Downstream, the river water may be contaminated by lake decant. Of particular concern in more arid parts of the world, the river's natural hydrological regime below the pit lake may be altered by reductions in peak and base flows, and altered timing of flows (McCullough and Schultze 2015).

Unlike the above examples in Germany and Austria, many Australian rivers are characterised by highly variable flows, with seasonal drying followed by intense flows for short periods during the rainy season (Blanchette and Pearson 2012). Therefore, unlike permanent rivers, we contend that seasonally-flowing/intermittent rivers pose greater challenges for closure based around river flow-through, especially in light of current and projected climate change-related drying (driven by a combination of anthropogenic activities, variations in El Niňo-southern oscillations, tropical Atlantic sea surface temperatures, and Asian monsoons; (Dai 2011)). Further, the spatial extent of intermittent rivers is expected to rise with global increases in drying (Jaeger et al. 2014), suggesting that even current 'permanent' river flow-throughs may be under future threat.

The aim of this paper is to investigate the impacts of seasonal river flow-through on a former acidic coal pit lake in Western Australia on downstream environments, focusing on the hydrological and water quality changes to the river water entering and leaving the lake. We also consider future implications of this technique in the context of an unpredictable future climate.

Methods

Study Site

The Collie pit lake district (Lund et al. 2012) in Western Australia contains over 10 pit lakes formed from open-cut coal mining. Dating back to the 1960s, the water qualities of these pit lakes have remained largely unchanged since filling (e.g., pH mostly 3-4.5, Al-buffered, (Lund and McCullough 2008)). The largest of the Collie pit lakes is Lake Kepwari, around which the Collie River South Branch (CRSB) had been diverted to allow mining to occur. The initial mine closure concept was for Lake Kepwari to become a water ski park, but did not include connection to the seasonally-flowing CRSB. Instead, 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. In 2011 the CRSB breached the wall separating the lake from the diversion channel after a large rainfall event, adding river water to the lake (McCullough et al. 2012)Western Australia</pub-location><publisher>IMWA</publisher><urls></urls></record></Cite></EndNote>. A more limited previous study noted few consequences of the breach on the river downstream (McCullough et al. 2013) resulting in government approval to connect the river to the lake, initially as a 3-year trial. The final 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.

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 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 2003 and 2016 ranged between 390 mm (2010) and 902.2 mm (2005) (Figure 1). During this study, rainfall was low in 2015 (475.4 mm), while both 2014 and 2016 had average or above average rainfall. The CRSB has a catchment area of 66 047 ha, which is primarily native forest with 24% cleared for farmland and <5% disturbed by mining (Harper et al. 2005). Groundwater is generally lower than river bed, with the exception of a few pools which are groundwater discharge areas. Since 2002 (when Lake Kepwari began filling), the

a) b)

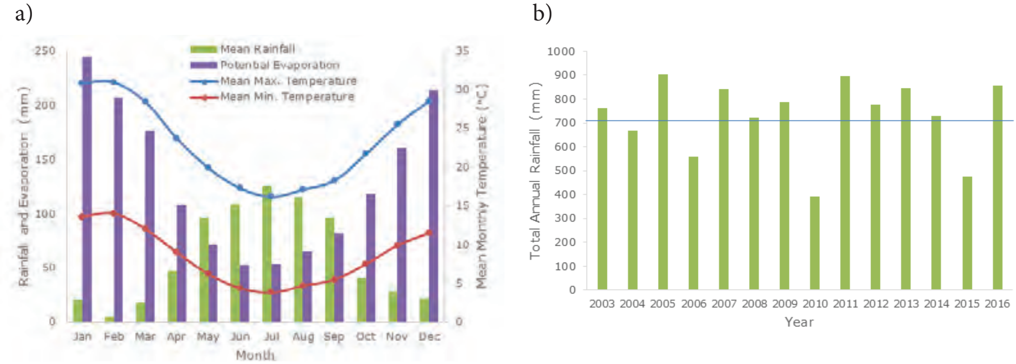

Figure 1. *a) Mean monthly minimum and maximum air temperatures, and mean monthly total rainfall and potential pan evaporation, (Collie East Station, 2002-2016 and Evaporation Atlas) and b) total annual rainfall 2003 to 2016, with average shown (blue line; Collie East, except for 2013 which comes from Collie) Data supplied by the Commonwealth of Australia Bureau of Meteorology.*

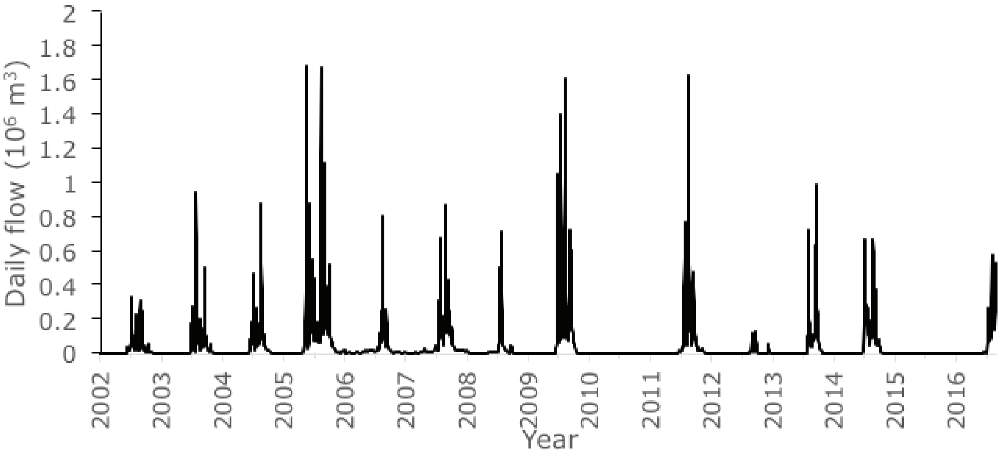

Figure 2 *Total daily flows in the Collie River South Branch 2002 to October 2016 (Shultz Weir Gauging Station, Department of Water (WA)).*

maximum flow at the gauging station downstream of the lake was recorded on 20 May 2005 at 1.69 x 10^6 m3 Figure 1). Total annual flow ranged from zero flow in 1969, 1970 and 2015 to 217.5 x 106 m3 in 1964 (median 20.7 x 106 m3). Average annual flows for each decade (1952-2000) exceeded 28.1 x 106 m3, which has declined over time (2000s; 15.1 x 106 m3 and 2010s currently 10.7 x 106 m3) possibly reflecting declining rainfall (Varma 2002).

Data collection

A water budget was estimated for Lake Kepwari between 2010 and 2016. After the commencement of river flow through in 2013, river inflows and outflows were measured every 15 minutes (2013-2016) using automatic gauging stations, as were select physicochemical data (pH, turbidity, conductivity). Additional measures of water quality (e.g., zinc, net alkalinity, DOC) were sampled monthly by hand (2013-2016; n=35 inlet and n=42 outlet). As the 2011 breach was an unexpected event, inflows and outflows for this breach event were estimated based on McCullough et al. (2012)Western Australia</pub-location><publisher>IMWA</publisher><urls></urls></record></Cite></EndNote>.

Rainfall data for Collie during the study period were sourced from the BOM. There was no pan evaporation data available for Collie or surrounds, however the BOM Climatic Atlas of Australia provided potential evaporation data at Collie as a monthly average. To generate evaporation data for each month of the study period, the potential evaporation data for Collie was adjusted for each month using the ratio of Perth actual monthly evaporation to the Perth long term average monthly evaporation (n.b., Collie is approximately 200 km south of Perth). The lake height data (Australian height datum; AHD) was taken as the value closest to the start of each month (where multiple measurements were available), and linear interpolation was used for missing data. Lake height to lake area and volume was taken from Salmon et al. (2017) and used to develop a hypsographic curve. Polynomial lines of best fit were then applied to calculate the volume and area for any lake water height. Groundwater input and output was estimated from data in Varma (2002). Surface runoff was based on a total catchment area of 150 ha (Lund et al. 2013), and a runoff coefficient estimated at 0.25 (approximating those estimated for the lake by Varma (2002)).

Results and Discussion

Overall, the water budget (Table 1) indicated that *excluding river inflows the lake existed in a slight water deficit, where [(groundwater* *in) + (surface inflow) + (direct rainfall)] < [(evaporation) + (groundwater out)], which has been previously estimated as 0.8 GL per annum* (Platt et al. 2012). Therefore, under most circumstances (c.f., extraordinary scenarios such as extreme direct rainfall over the pit lake or geological or engineering faults – causing the lake to decant without river water inflow), when seasonal river flows commence, the lake will fill first, then an equal or lesser amount of the inflow water volume will flow downstream – either with or without substantial delay after inflows.

There was an error (up to 2.2 GL) associated with the water budget (Table 1), with the greatest error (difference between water inputs and outputs) occurring in years with river inflow, suggesting gauging station error. This error was likely due to unmeasured overtopping of the former breach point in September 2013, 2014 and again in 2016 (increasing river outflow volumes).

Outflows from Lake Kepwari were generally similar in timing and magnitude to inflows, and discharge often continued after inflows ceased (Figure 3). The downstream impact of the lake was most obvious in 2015 when antecedent conditions (low rainfall, high evaporation rates) resulted in low water levels within the lake, delaying outflows by three months as the lake was filled first. In the same way, high lake water levels facilitated outflow from the lake, as small amounts of rainfall across the lake catchment resulted in outflows even when there was no inflow. Future research will examine the impacts of the lake on downstream hydrology in more detail, although these results suggest that if there were several years of low rainfall that resulted in low lake water levels, downstream flows could be substantially delayed.

Changes in water chemistry can occur between inflows and outflows due to chemical interactions and precipitation in the lake (McCullough and Schultze 2015). The pH in the lake was generally lower than the river water flowing in, although lake water did not drop below pH 6 (Figure 4). Conductivity of river water inflows was highly temporally variable (1-6 mS cm^{-1}), although moderated by lake water, and, upon release at outflow, was of similar conductivity (2-3 mS cm-1) throughout the year. Particulates in the river could be expected to settle out in the lake as the river water moved through the larger water body (McCullough and Schultze 2015). However, in Lake Kepwari, the data indicates that turbidity at outflows was not consistently lower than at inflows, although the nature of the turbidity may have changed (e.g., became more algal-dominated). During the study period, acidity was either being produced in or entering the lake via aquifers before being neutralised by river inflows. Therefore, several years of poor rainfall could result in the lake becoming increasingly acidic due to a lack of river water input. Lake Kepwari is a sink for dissolved organic C (DOC), which

Table 1. *Water budget for Lake Kepwari 2010 to 2016 showing inputs, outputs and the error associated with the calculation*

	Inputs				Outputs			Summary		
Years	Rainfall Direct (ML)	Groundwater In (ML)	Surface Runoff (ML)	River Inflow (ML)	Evaporation (ML)	River Outflow (ML)	Groundwater Out (ML)	Total Inputs – Outputs (ML)	Change in Lake Volume (ML)	Error (ML)
2010	396.5	292.0	57.9		1111.1		224.9	-589.6	-538.2	-51
2011	1011.0	292.0	132.5	1900.0	1163.1	600.0	273.8	1298.5	1261.8	37
2012	857.5	292.8	111.5		1125.7		256.2	-120.0	-375.5	255
2013	822.2	292.0	112.0	9473.5	1091.5	8754.1	255.5	598.6	-342.0	941
2014	761.0	292.0	99.5	8682.5	1124.6	10852.9	255.5	-2398.0	-154.2	-2244
2015	511.0	225.2	72.9	28.3	1129.9	3.7	255.5	-551.6	67.9	-620
2016	964.8	219.6	128.9	10793.4	1075.6	12078.1	390.2	-1437.1	68.0	-1505

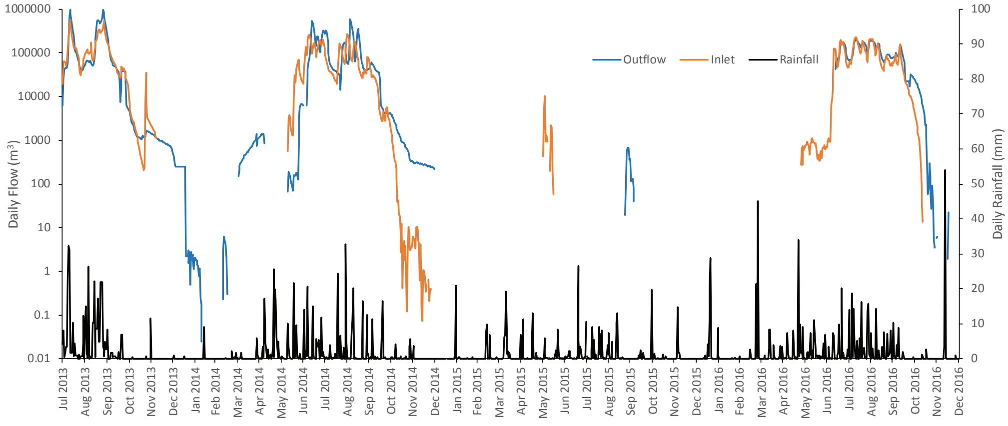

Figure 3 *Collie River inflows and outflows through Lake Kepwari compared with rainfall (2013-2016). Rainfall for 2013 provided by BOM (for Collie), other years use rainfall data provided by PCL as fewer missing dates.*

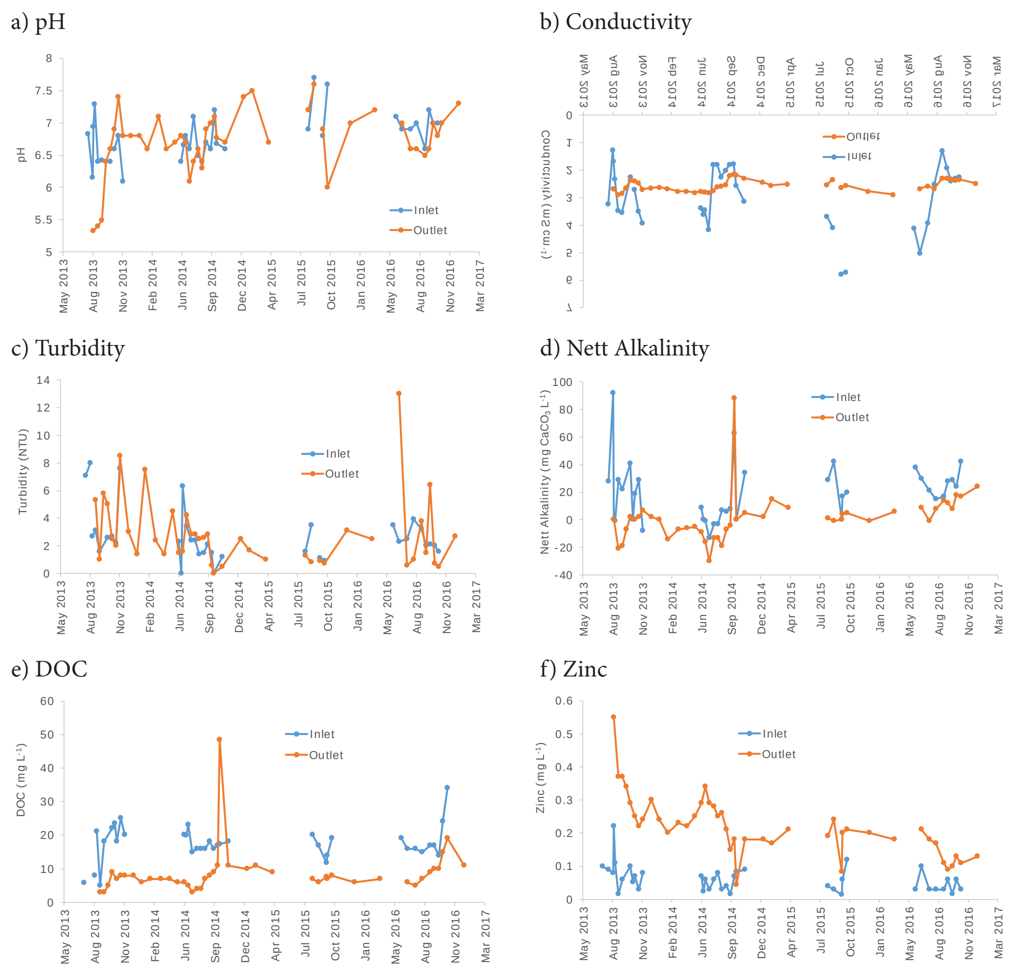

Figure 4 *Physico-chemical parameters for the river inflow and outflow from Lake Kepwari (2013-2016).*

likely benefits ongoing ecological evolution of the lake (Blanchette and Lund 2016). Zinc concentrations (initially high in the river) increased approximately three fold in the outflow, although the high hardness of the waters ameliorated exceedances of trigger values (>0.28 mg L-1 for the outflow) for the protection of aquatic ecosystems (moderately disturbed, 80%)(ANZECC/ARMCANZ 2000).

River flow-through has improved the water quality in Lake Kepwari (e.g., C storage, neutralised pH, increased net alkalinity) to the extent that permanent flow-through has been accepted and agreed by government as an appropriate mine closure strategy. However, flow-through has had a statistically significant effect on the downstream environment by: changing the hydrology of the river, increasing zinc, reducing EC variability, and reducing overall DOC. The Collie River downstream of Lake Kepwari is relatively short (≈15 km) and already highly modified. Therefore, the downstream impacts from the flow-through may be an acceptable trade-off compared to the social and economic benefits associated with the lake's proposed future use for recreation. Our research suggests that using seasonal rivers as sources of flow-through to close acidic pit lakes presents a riskier scenario than using permanent rivers, particularly in light of climate change projections (Dai 2011). However, given the predictions that even permanently flowing rivers may become intermittent (Jaeger et al. 2014), the application of this strategy may be limited. Clearly, careful planning based on projected water volume and acceptance of any downstream impacts is required before river flow-through is used to close pit lakes.

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