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Research papers

Extreme drought causes distinct water acidification and eutrophication in the Lower Lakes (Lakes Alexandrina and Albert), Australia

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ABSTRACT

Droughts are set to increase in frequency and magnitude with climate change and water extraction, and understanding their influence on ecosystems is urgent in the Holocene. Low rainfall across the Murray-Darling Basin (MDB) of Australia resulted in an unprecedented water level decline in the Lower Lakes (Lakes Alexandrina and Albert) at the downstream end of the river system. A comprehensive data covering pre-drought (2004–2006), drought (2007–2010) and post-drought (2010–2013) was firstly used to unravel drought effects on water quality in the contrasting main parts and margins of the two Lakes, particularly following water acidification resulting from acid sulfate soil oxidation. Salinity, nutrients and Chl-*a* significantly increased during the drought in the Lake main waterbody, while pH remained stable or showed minor shifts. In contrast to the Lake Alexandrina, total dissolved solid (TDS) and electrical conductivity (EC) during the post-drought more than doubled the pre-drought period in the Lake Albert as being a terminal lake system with narrow and shallow entrance. Rewetting of the exposed pyrite-containing sediment resulted in very low pH (below 3) in Lake margins, which positively contributed to salinity increases *via* SO_4^{2-} release and limestone dissolution. Very acidic water (pH 2–3) was neutralised naturally by lake refill, but aerial limestone dosing was required for neutralisation of water acidity during the drought period. The Lower Lakes are characterized as hypereutrophic with much higher salinity, nutrient and algae concentrations than guideline levels for aquatic ecosystem. These results suggest that, in the Lower Lakes, drought could cause water quality deterioration through water acidification and increased nutrient and Chl-*a* concentrations, more effective water management in the lake catchment is thus crucial to prevent the similar water quality deterioration since the projected intensification of droughts. A comparative assessment on lake resilience and recovering processes should be undertaken with a post-drought monitoring program.

1. Introduction

Anthropogenic climate change has contributed to the increasing likelihood of extreme weather related events such as floods and droughts, i.e., intensification of heavy precipitation or less frequent (or little) rainfall events (Karl and Trenberth, 2003; Qiu, 2010; Min et al., 2011). In many land areas, large increases in frequency and severity of droughts are projected over the next 30–90 years with respect to the historical records (Dai, 2013). Moreover, increased and increasing water extraction could further enhance the risk of hydrological droughts. This hydrological drought consequently influences and will influence aquatic ecosystem including lakes.

Droughts have been documented to be a key factor that control water quality in the freshwater ecosystems, and can influence the water determinants in multiple ways such as increase in residence time and decrease in flushing rate of waters, changing delivery patterns of water constituents from the catchment, as well as shifted internal process (i.e., photosynthesis, respiration and reaeration) (Caruso, 2002; Worrall and Burt, 2008; Hrdinka et al., 2012). Previous studies indicated water quality deterioration, particularly in regarding to the increases in water acidification, salinity and eutrophication (Qiu, 2010; Mosley, 2015 and references therein). Further, water quality impacts of droughts can be quite variable and specific depending on the heterogeneous biophysical characteristics of water bodies and their associated catchments.

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Given the prediction of increasing frequency and intensity of droughts in inland waters (Dai, 2013), additional studies should be warranted to better understand water quality effects under droughts. The study of drought effects on water quality occurred on 1930s with sparse distribution until 1970s, and a substantial increase in the number of the studies was noticed between 1990 and 2010 (Mosley, 2015). Previous studies endeavored to unravel the dominated effects of droughts on water quality constituents in inland waters, while most determinants (including water temperature, dissolved oxygen, pH, salinity, major ions, nutrients, organic carbon, and metals) showed mixed responses to droughts (cf. Worrall and Burt, 2008; Mosley, 2015 and references therein). Moreover, these studies mostly focused on North America and Europe, studies in Asia-Pacific region would be beneficial to supply some innovative understanding of the drought effects on water quality.

The Murray-Darling Basin (MDB), Australia's largest arid to semi-arid river system, has recently experienced the most severe drought with the lowest catchment flows in over a century of records (Mosley et al., 2014b). This outcome is attributable to rainfall variability, increased evaporation, and management strategy in the highly regulated River (Potter et al., 2008). Declining water flows from the Murray-Darling River have resulted in a marked decline in water levels of the Lower Lakes (Lakes Alexandrina and Albert) at the downstream end of the river system in South Australia, leading to the extensive exposure of pyrite-containing sediments (acid sulfate soils; ASS) in the large freshwater lakes (Mosley et al., 2014b,c). Oxidation and water acidification occur when these exposed sediments are rewet either from local rainfall or lake refill (see pyrite oxidation reaction: $FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-}$, Stumm and Morgan, 1996). This often shifts the *in situ* aquatic metabolic processes and causes distinct physiochemical characteristics in waters. Given projections of increased frequency and severity of droughts in the Murray-Darling River basin (Potter et al., 2008), water quality effects of droughts are therefore of particular importance for water management decisions.

This study focuses on the Lower Lakes (including Lake Alexandrina and Lake Albert) in the Lower Murray River, South Australia. The Lower Lakes are of the major freshwater lakes in Australia, and characterized by typical geomorphological and hydro-climatological characteristics. They are locating near the mouth of the Murray River, at the end of vast MDB (with a catchment drainage area of 1 M km^2) (Fig. 1), and therefore, a good barometer of hydrological dynamics in lakes throughout the catchment. Prior studies have examined water quality particularly metal speciation changes in response to acidification during the drought (Mosley et al., 2012, 2014a,b,c) in the Lower Lakes. Whilst, these studies presented an incomplete coverage of hydrological droughts (e.g., very few reports include pre-drought, drought and post-drought periods) (Aldridge et al., 2011; Mosley et al., 2014b), which may yield biased information on the effect of drought on water quality.

The aim of this study is to evaluate the impacts of hydrological drought on acidification, salinity and eutrophication status from large-scale freshwater water lakes in one of the worlds most drought prone continents. A comprehensive data covering pre-drought (hydrological reference period; Jan. 2004-Dec. 2006), drought (Jan. 2007-Sep. 2010) and post-drought periods (immediate post-drought recovery phase; Oct. 2010-Dec. 2013) were mined for the comparative assessment on water quality using a trophic state index (TSI). We test hypotheses that (1) water quality altered significantly during the drought period with increased levels of salinity and eutrophication status, which were primarily induced by water volume reductions, and (2) water acidification that results in large salinity increases occurred in the shoreline rather than the main body of the lakes. The original contributions of this study, with respect to earlier works, include assessment on the water quality effects of hydrological drought and their magnitudes using a temporally (pre-, drought and post-drought) and spatially (shoreline and main body) complete coverage of hydrological condition. Our study has broad relevance to other locations which are experiencing, or may in the future experience droughts or other regions with acid sulfate soils.

2. Materials and methods

2.1. Study area

The Lower Lakes (Lakes Alexandrina and Albert) (35°25′S, 139°07′E) have a total surface area of 820 km^2 with a water level of approximately +0.75 m AHD (Australian Height Datum) at near full capacity. This area makes up the most downstream freshwater portion of the MDB which extends across around 14% of Australia's total area, spanning an area of 1,061,469 km^2 and encountering alpine, arid and sub-tropical climatic zones, and is a highly regulated river system. These lakes are located adjacent to the coast of the Southern Ocean, about 100 km south-east of Adelaide in South Australia (Fig. 1). Lake Alexandrina (L. Alex.) is on the main river course and has a surface area of 650 km^2, with a volume of approximately 1585 M m^3 and a mean depth of 2.4 m (max. depth is about 4.1 m), discharging to the ocean *via* a barrage that was installed in the early 1940s to prevent seawater ingression and regulate water level for multiple purposes of navigation, irrigation and domestic supply. The smaller Lake Albert (L. Alb.) is located adjacent to the south-east, connecting by a narrow channel to Lake Alexandrina, and has a surface area of 170 km^2 with a volume of approximately 264 M m^3 and a mean depth of 1.5 m (maximum depth is about 2.3 m) (Mosley et al., 2012). The both freshwater lakes are eutrophic and highly turbid (Cook et al., 2010; Mosley et al., 2012). Their main source of inflow is from the Murray River, with limited local catchment input (Li et al., 2016). For this reason, reduced flow allocation from the highly regulated Murray River and evaporation are the key factors that affect water-level in the lake system. During the recent extreme hydrological drought (2007-Sep. 2010), L. Alex. had a surface area of 560 km^2 and a volume of 899 M m^3; its mean depth was 1.6 m. The much smaller and shallower L. Alb. with a mean depth of 0.8 m had a surface area of 144 km^2 and a volume of 113 M m^3 during the drought period (Mosley et al., 2012) (Table 1). The Lake Boggy and three Creeks (Currency, Boggy and Hunters Creeks) are locating the shoreline in the Lower Lakes system.

Sediments in the Lower Lakes are rich in pyritic minerals, and this pyrites can be oxidised and produce acidic protons during the exposure of sediments. When the oxidation causes acidification, the sediments develop acid sulfate soil character. Peripheral sediments below shallow water are characteristic of sandy soils and have a large grain size with low water and organic content (0.4%). In contrast, profundal sediments are black and composed of fine grains with high water and organic content (7.87%) (Skinner et al., 2014). The local climate is subtropical - semi-arid. Annual mean air temperature is 15.0 °C and the mean monthly temperature varies between 10.1 °C (Jul.) and 20.2 °C (Jan.). The average annual rainfall is 423 ± 7.6 mm with large inter and intra-annual variability, and 74.4% of the rainfall falls during the period of April through September (Li et al., 2016). The Lower Lakes are collectively recognised as one of Australia's most significant ecological assets and have been designated a wetland of international importance under Ramsar convention. The lakes also serves the city of Adelaide (a population of 1.2 million) and several regional townships, several large irrigated agricultural areas and recreational activities, and have high cultural values.