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Research papers

Cyclic heliothermal behaviour of the shallow, hypersaline Lake Hayward, Western Australia

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ABSTRACT

Lake Hayward is one of only about 30 hypersaline lakes worldwide that is meromictic and heliothermal and as such behaves as a natural salt gradient solar pond. Lake Hayward acts as a local groundwater sink, resulting in seasonally variable hypersaline lake water with total dissolved solids (TDS) in the upper layer (mixolimnion) ranging between 56 kg m^{-3} and 207 kg m^{-3} and the deeper layer (monimolimnion) from 153 kg m^{-3} to 211 kg m^{-3}. This is up to six times the salinity of seawater and thus has the highest salinity of all eleven lakes in the Yalgorup National Park lake system. A program of continuously recorded water temperature profiles has shown that salinity stratification initiated by direct rainfall onto the lake's surface and local runoff into the lake results in the onset of heliothermal conditions within hours of rainfall onset.

The lake alternates between being fully mixed and becoming thermally and chemically stratified several times during the annual cycle, with the longest extended periods of heliothermal behaviour lasting 23 and 22 weeks in the winters of 1992 and 1993 respectively. The objective was to quantify the heat budgets of the cyclical heliothermal behaviour of Lake Hayward.

During the period of temperature profile logging, the maximum recorded temperature of the monimolimnion was 42.6 °C at which time the temperature of the mixolimnion was 29.4 °C.

The heat budget of two closed heliothermal cycles initiated by two rainfall events of 50 mm and 52 mm in 1993 were analysed. The cycles prevailed for 11 and 20 days respectively and the heat budget showed net heat accumulations of 34.2 MJ m^{-3} and 15.4 MJ m^{-3}, respectively. The corresponding efficiencies of lake heat gain to incident solar energy were 0.17 and 0.18 respectively. Typically, artificial salinity gradient solar ponds (SGSP) have a solar radiation capture efficiencies ranging from 0.10 up to 0.30. Results from Lake Hayward have implications for comparative biogeochemistry and its characteristics should aid in identification of other hitherto unknown heliothermal lakes.

1. Introduction

Saline lakes are not uncommon features on all continents, however, natural meromictic lakes are less common (Hull et al., 1989) and less than 200 have been documented (Walker and Likens, 1975, Stewart et al., 2010). Lake Hayward can be classified as a Type Ib meromictic lake according to the typology proposed by Walker and Likens (1975). However, their classification does not include consideration of thermal heating characteristics. Meromictic lakes that are also heliothermal are even rarer and number less than 30 worldwide (Sonnenfeld and Hudec, 1980; Hull et al., 1989, Chapter 2). The earliest reports of natural heliothermal lakes date back over a century to Hungary (Kalecsinsky, 1901), and lakes in Romania (Schafarzik, 1908, Maxim, 1929) where the salt is derived from near-surface salt domes. Alexe et al. (2017) have reviewed the limnology and plankton diversity in the Romanian heliothermal lakes and Zachara et al. (2016) emphasise the unique biogeochemical attributes of a heliothermal lake in Washington State. Sonnenfeld and Hudec (1980) note that not all meromictic lakes are heliothermal and proposed a nomenclature of thermal stratification in heliothermal lakes, which has been adopted in this paper. Thus the upper, less dense layer is termed the mixolimnion and the deeper dense and hot layer the monimolimnion

Lake Hayward is located in a group of eleven coastal interdunal lakes, approximately 100 km south of Perth, Western Australia (Fig. 1). All eleven lakes are located within the Yalgorup National Park in southwest Western Australia where the regional climate is Mediterranean,

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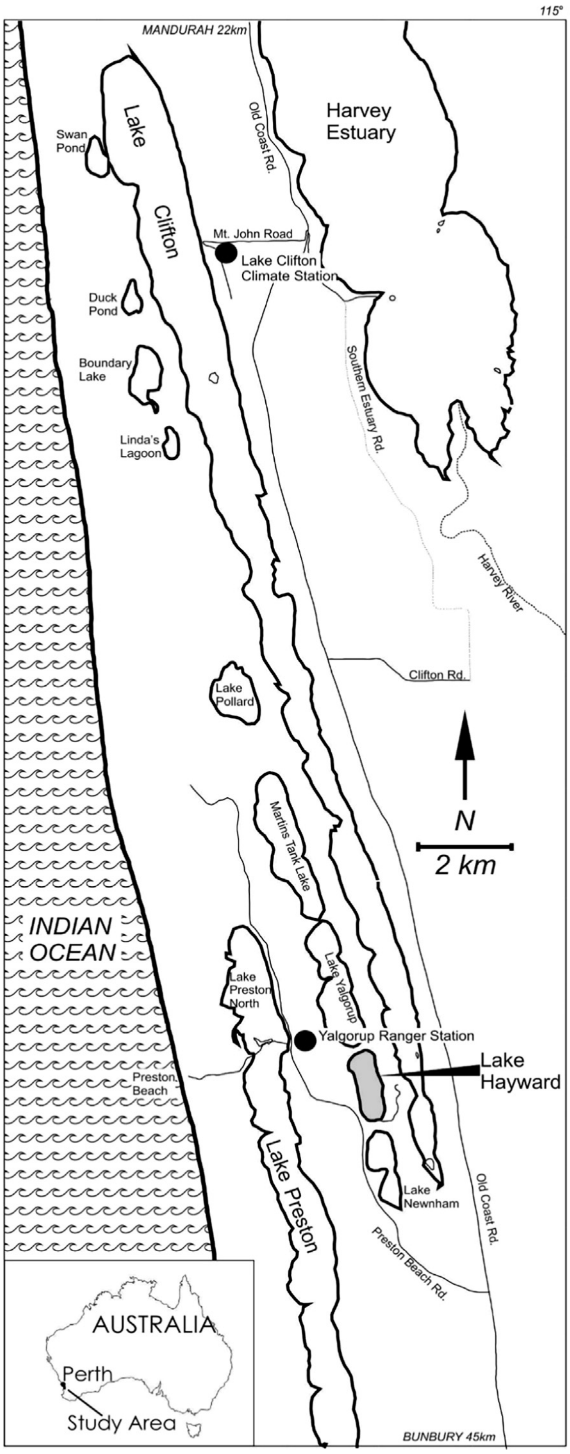

Fig. 1. Location map of the eleven lakes in the Yalgorup National Park, Western Australia showing Lake Hayward, the (temporary) Lake Clifton Climate Station, and the Yalgorup National Park Ranger Station.

with hot and dry summers and temperate, wet winters. Rainfall data from 1982 to 1995 (Table 1) show annual totals of between 703 and 1075 mm.

Annual Class A pan evaporation rates have been shown to be greater than twice the annual rainfall ranging from 1557 to 1913 mm (Rosen et al., 1996). Several authors have studied the hydrochemistry, limnology and sedimentology of Lake Hayward and a number of other lakes in the Yalgorup lake system (Burne and Moore, 1987; Burke and Knott, 1989; Moore, 1993; Rosen and Coshell, 1992; Coshell and Rosen, 1994; Rosen et al., 1995, 1996) while Forbes and Vogwill (2016) have investigated the hydrological regime of the adjacent Lake Clifton in relation to its unique thrombolite reef.

Table 1
Summary of yearly climate data at Mandurah, Western Australia (1982–1995) (Jeffrey et al., 2001) and maximum monimolimnion temperatures observed in Lake Hayward between 1991 and 1994. The positive linear correlation between annual rainfall and maximum monimolimnion temperature is Max Temp (°C) = Rainfall (mm) × 0.218 + 20.5.

Year	Ave Max Temp (°C)	Ave Min Temp (°C)	Rainfall Total (mm)	Class A pan Evaporation. Total (mm)	Maximum Monimolimnion Temperature (°C)
1982	23.9	13.5	954.3	1631.4	
1983	24.4	14.4	835.5	1639	
1984	23.3	13.5	972.6	1599.6	
1985	23.9	13.8	857.8	1611	
1986	22.2	12.6	783.7	1557.4	
1987	23.1	13.2	703.6	1706	
1988	23.4	14.2	857.6	1839.2	
1989	22.9	13.5	953.4	1730.2	
1990	22.6	12.8	804.8	1558.2	
1991	32.1	13.3	1075.2	1599.8	46
1992	22.8	13.2	969.4	1591.2	38.5
1993	22.9	12.3	684.8	1648.4	32.5
1994	24.0	12.8	708.6	1913.6	40
1995	23.8	12.9	882.4	1801.8	

The eleven lakes form three linear chains oriented in a north-south direction parallel to the coast and at a minimum distance of 1 km (Lake Preston) and maximum distance of 4 km (Lake Clifton) from the Indian Ocean. Lake Hayward is located about 3 km from the coastline and lies at the southern end of the central chain of eight lakes between the two largest and longest of the system, namely Lakes Clifton and Preston (Fig. 2).

The eleven lakes range in salinity from brackish to hypersaline with the hypersaline Lake Hayward consistently having the highest salinity of all eleven (Noble, 2010). This is due to a combination of factors that include high marine aerosol deposition at its near-coastal location driven by prevailing onshore winds, its low lake-bed elevation of about 2.5 m below sea level, its low surface water elevation and a regionally flat groundwater hydraulic gradient that limits groundwater and thus solute flow and discharge to the ocean.

In combination, these conditions result in the lake acting as a local groundwater sink and, due to evaporative loss, being hypersaline. The brine density itself (ranging between 1.04 and 1.09) also contributes to a reduction in the lake surface water elevation.

It is considered that marine-derived salt has accumulated via aerosol deposition (Farrington et al., 1993) in the Yalgorup lake system as a result of the long-term (hundreds to thousands of years) balance between the rates of marine aerosol deposition and the rate of advective discharge of salt return to the ocean by groundwater flow. Interestingly it is the interplay between these long-term quasi-stable physical, hydrological and hydrogeochemical conditions and the very short term transient annual rainfall cycles that finds a resonance resulting in the heliothermal condition of Lake Hayward.

Lake Hayward is heliothermal for part of its annual hydrological cycle and displays characteristics similar to Lago Pueblo on El Gran Roque Island in the Caribbean; (Hudec and Sonnenfeld, 1974), a solar pond located on the Sinai Peninsula (Por, 1968, Eckstein, 1970) and the Pretoria Salt Pan in South Africa (Ashton and Schoeman, 1988). The heliothermal characteristics of most of these lakes appear during the wettest part of the year or at other times during the year when rainfall or other low total dissolved solids (TDS) surface inputs are sufficient to reduce the density of the surface layer. The disappearance of heliothermal conditions is due to progressive downward mixing of the mixolimnion with the monimolimnion and to some extent evaporation