MODELLING OF SEASONAL AND LONGTERM TRENDS IN LAKE SALINITY IN SOUTHWESTERN VICTORIA, AUSTRALIA

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Abstract

In southwestern Victoria a large number of lakes are scattered across the volcanic plains; many have problems with increasing salinity. To identify the hydrologic components behind this problem, three lakes, Burrumbeet, Linlithgow and Buninjon, were selected for detailed water and salt budget modelling using monthly values of rainfall, evaporation, surface inflow and outflow, and groundwater inflow and outflow.

On average, rainfall begins to exceed evaporation with the onset of winter rainfall in May, so lake levels rise and lake salinities decline. In summer lake waters become more saline as the lake levels drop due to evaporation. The modelled lakes have become more saline over the last decade, a time of drought with below average rainfall, and all eventually dried out, their salinities rising to very high levels as they shallowed.

Lake Burrumbeet is generally much less saline than Lakes Linlithgow and Buninjon, because it has substantial groundwater outflow, probably due to leakage through one or more volcanic necks. This limits the amount of time the lake water is subject to evaporation, and also allows significant salt export. The other lakes do not leak.

The modelling indicates that when the lakes dry out, salt is lost from the lake-beds, probably due to wind deflation of salt crusts and leakage into the underlying groundwater. The removal of salt during drying-out phases resets the salinity of the lakes, limiting their ability to become more saline with time. Drying-out phases may therefore be essential in preventing the increased salinisation of lakes and wetland environments across the volcanic plains.

1. INTRODUCTION

The agricultural productivity and surface water quality of the Glenelg-Hopkins catchment in western Victoria is threatened by increasing salinity problems. The basalt plain which forms a large part of the central and eastern region of the catchment is a priority area for treatment under the Glenelg Hopkins Salinity Plan 2005-2008.

A joint project between La Trobe University and Glenelg Hopkins Catchment Management Authority aims to increase the understanding of salinity on the basalt plains by modelling the seasonal and decadal fluctuations in water table across the basalt plains. The initial phase of this project involves study of lake levels as one manifestation of the water table.

In southwestern Victoria a large number of lakes are scattered across the volcanic plains; many have problems with increasing salinity. To identify the hydrologic components behind this problem, three lakes, Burrumbeet, Linlithgow and Buninjon (Figure 1), were selected for detailed water and salt budget modelling using monthly values of rainfall, evaporation, surface inflow and outflow, and groundwater inflow and outflow.

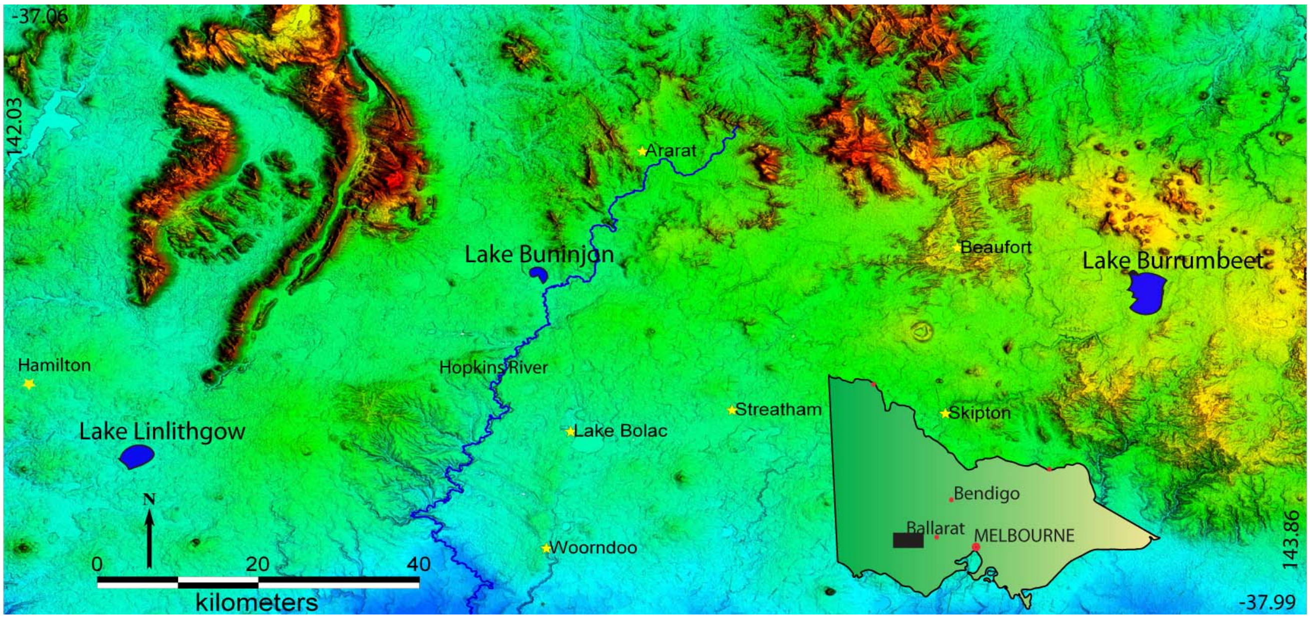

Figure 1 Location map of lakes studied

2. REGIONAL SETTING

The volcanic plains of western Victoria are topographically subdued with an average elevation of ~200 mAHD, gently increasing to the northeast (Figure 1). Drainage is typically poor with many ephemeral swamps and lakes. Several volcanoes rise above the plain.

The basement geology of the area consists of Early Palaeozoic volcanics and turbidites and Silurian sandstone, intruded by Devonian granites. These basement rocks outcrop over limited areas, and are overlain by an extensive cover of Cenozoic basalt, colluvium and alluvium. Most of the lakes' catchments are covered by Pleistocene basalt of the Newer Volcanics. Underlying the basalts in the centre of the catchment are Miocene and Pliocene ligneous clays, sands and gravels (Calivil Formation), called deep leads, and representing the pre-existing stream system incised deeply into the highly weathered early Cainozoic palaeo-surface. The disruption of the drainage system by the basalt flows formed the lakes across the surface of the basalt plain.

3. METHODOLOGY

For Lakes Burrumbeet and Buninjon, water level and salinity data were measured (usually monthly) for 1998 and 1995 to the present respectively; a longer time period of data (1964-present) is available for Lake Linlithgow. Monthly rainfall and evaporation values from the nearest weather stations were obtained for each lake. For Lake Burrumbeet there is a gauging station on the main stream feeding the lake, and inflow from minor streams was calculated using catchment area ratioing. For the other two lakes there is no stream inflow gauging data, so inflows were estimated from gauging stations on nearby streams. Lake Linlithgow is a closed drainage basin, so there is never any stream outflow, and the levels of Lakes Burrumbeet and Buninjon were below the height of the outflow barriers for the modelling period (1998-2006), so they too did not record any stream outflow. Groundwater inflow and outflow were estimated using Darcy's Law; hydraulic conductivity values were obtained from pumping tests in the area or in equivalent aquifers nearby, the hydraulic gradients were calculated from potentiometric surface maps, and the cross-sectional area was estimated from the lake perimeter and aquifer thickness. Geological and geophysical maps, including radiometric, magnetic and gravity data, were employed to construct geological cross sections and constrain the extent and thickness of aquifers around the lakes, and nested bore hydrographs were analysed to determine the extent of hydraulic connectivity between aquifers and between aquifers and lakes. None of the lakes shows a perched water table that buffers/maintains the lake level.

For the modelling it was necessary to convert the measured lake depths to lake volumes. Bathymetry data are not available for any of the lakes; however the relationship between lake area and depth was established by measuring the area on 12 Landsat images taken between 1972 and 2004, plotting this against the measured lake depth in the month when the images were taken, and determining a line of best fit. There is a polynomial relationship between lake area and lake depth, due to the lakes' relatively flat beds and steep banks.

Monthly time-step modelling of the water level in each lake was carried out using Excel spreadsheets, and the water budget result was the used as input for the salt budget. The lake water balance is computed by estimating all the lake's water gains and losses, and the corresponding change in volume expressed as:

$$\textbf{Volume change=Surface water+Rainfall +}Q_{in}\textbf{ – Evaporation – }Q_{out} \quad (1)$$

where Q_{in} is the groundwater inflow and Q_{out} the groundwater outflow from the dynamic groundwater aquifer linked to the lake. The difference between the two (Q_{in} - $Q_{out)}$ is the net groundwater flux. It is derived from the following relation.

$$Q=C\ (H_{lake}-H_{aquifer}) \text{ in } m^3\ month^{-1} \quad (2)$$

Where, C is the hydraulic conductivity of the lake bed sediments (m^2 $month^{-1}$) and H is the water level in the lake and surrounding aquifer (m).

The water level in the surrounding aquifer is updated using the inflow and outflow calculated for the previous month (H_{pre})

$$H_{pre} = Q/A*S_y\ (m^3\ month^{-1}) \quad (3)$$

$$H_{aquifer\text{-}new}= H_{in\text{-}old} + H_{in}\ (m) \quad (4)$$

where A is the surface area and S_y is the specific yield of the aquifer.

The model is optimized by minimizing the sum of squared difference between observed and simulated lake levels. The optimizing model parameters were constant groundwater outflow/ inflow, the hydraulic conductivity and specific yield of the aquifer in direct link with the lakes.

The model requires known recorded hydrometeorological data and tries to estimate the unknown components of the water balance (often groundwater) as a residual by comparing recorded and simulated lake levels. The same model provided reliable information on groundwater inputs and outputs for the Ethio-Kenyan rift lakes (Ayenew *et al*., 2007).

A salt budget has also been calculated on a monthly basis using the fluxes derived from the water budget and salinity data obtained during this study, to identify the major controls on lake salinity. The salt budget is calculated on a mass basis as follows:

$$\Delta ML(t)=MP(t)–ME(t)+MSi(t)+MGi(t)–MGo(t) \quad (5)$$

where ΔML(t) is the change in salt storage in the lake, MP(t) is the mass in precipitation, ME(t) is the mass in evaporation, MSi(t) is the mass in surface inflow, MGi(t) is the mass in groundwater inflow and MGo(t) is the mass in groundwater outflow. Salt removal from the lake by evaporation is considered negligible, and hence ME(t) can be removed from equation 5. Replacing M for all components with V (volume) and C (concentration) for each parameter gives:

$$\Delta VL(t)CL(t)=VP(t)CP(t)+VSi(t)CSi(t)+VGi(t)CGi(t -VGo(t)CGo(t) \quad (6)$$

The total mass of salt stored in lake in any given month is given by:

$$VL(t)CL(t) = VL(t\text{-}1)CL(t\text{-}1) +\Delta VL(t)CL(t) \quad (7)$$

where VL(t-1) and CL(t-1) refer to the volume of water and salt concentration from the previous month.

By substituting equations 5 and 6 into 7, the salt balance becomes:

$$VL(t)CL(t)=VP(t)CP(t)+VSi(t)CSi(t)+VGi(t)CGi(t)-VGo(t)CGo(t)+VL(t-1)CL(t-1) \quad (8)$$

The volume parameters have already been calculated from the water budget and the concentration variables can be estimated. The equation can then be solved for V L(t)CL(t) (i.e. ML(t)) for each month. The reliability of the model is checked by comparing the calculated to the measured TDS of the lake water (Figure 3).

The methodology is centred on optimization and calibration of this spreadsheet hydrological model. The calibration parameters were based on estimates derived from available data sources. The model is calibrated against the historical measurements of lake levels and salinities. The water balance components used are inflow from the rivers, rainfall on the lake surface, evaporation from the lake, and a dynamic groundwater component that takes the interactions of the lake with the surrounding aquifer into account. The model tries to estimate the unknown net groundwater flux by comparing the simulated and recorded lake levels.

A good fit was obtained for all lakes between measured and modelled lake levels and salinity, for both seasonal and long term trends (Figures 2 and 3).

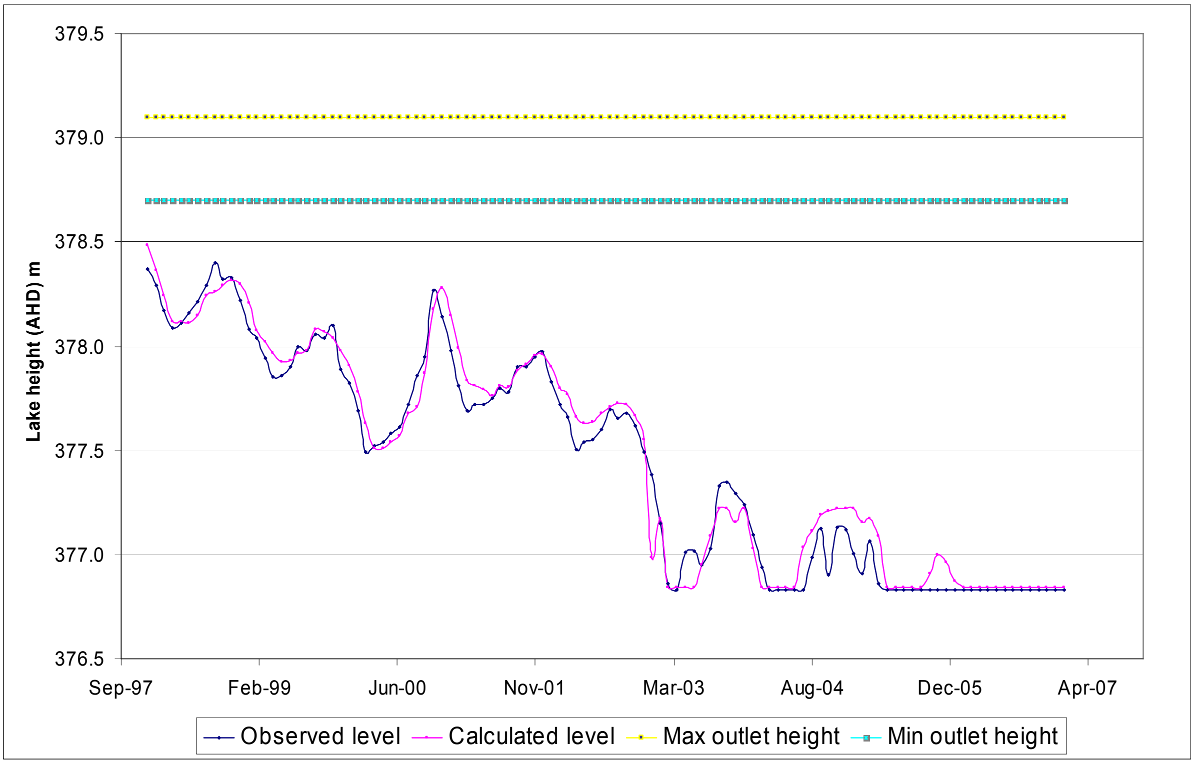

Figure 2 Measured and modelled lake depth for Lake Burrumbeet

4. SEASONAL AND LONGER TERM FLUCTUATIONS IN LAKE LEVEL AND SALINITY

On average for each lake, rainfall input begins to exceed evaporation losses with the onset of winter rainfall in May, so both stream hydrographs and lake levels rise and lake salinities decline. In summer lake waters become more saline as the lake levels drop due to evaporation, and solutes in the lakes (mostly derived directly from rainfall onto the lake surface and indirectly via runoff) are concentrated.

The modelled lakes have all become more saline over the last decade, a time of drought with below average rainfall, and all eventually dried out, their salinities rising to very high levels as they shallowed (up to 22, 63 and 67 mS/cm for Lakes Burrumbeet, Linlithgow and Buninjon respectively). Monitoring across the region (Dixon 2005) of lake salinity trends showed that from 1998 there were sharp increases in salinity levels in many lakes and wetlands, due to limited or no runoff and very little rainfall. Lake Linlithgow, with its longer monitoring period (1964 to present) shows this trend best. Normally its salinity fluctuates seasonally from 10 mS/cm in winter and spring to 16 mS/cm in late autumn, but in 1999, the lowest salinity levels recorded were 25 mS/cm and peaked at 50 mS/cm (seawater) in autumn.

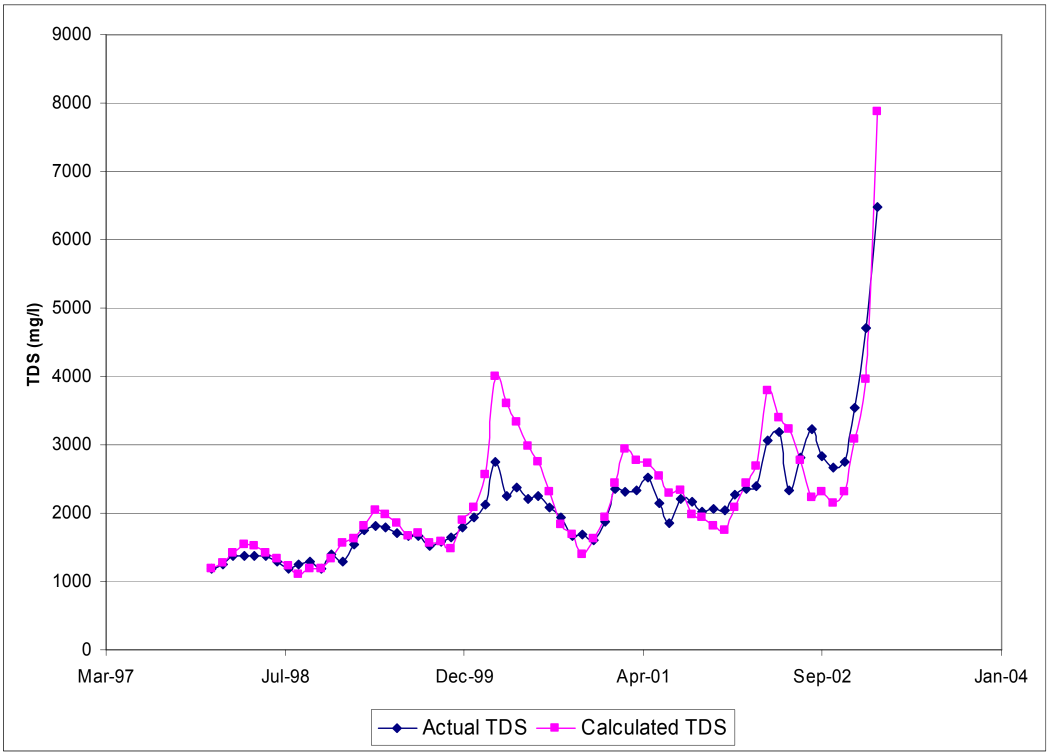

Figure 3 Measured and modelled lake salinity for Lake Burrumbeet

5. LAKE COMPARISONS

Table 1. Comparison of water budgets and salinity for the lakes studied

Average values for 1998-2006	Lake Burrumbeet	Lake Linlithgow	Lake Buninjon
Rainfall (% of inputs)	48	74	49.9
Rainfall (ML/month)	644	238	70
Stream inflow (% of inputs)	49	8	50
Stream inflow (ML/month)	661	25	71
Evaporation (% of losses)	69	99.9	99.9
Evaporation (ML/month)	1165	452	157
Groundwater inflow (% of inputs)	3	18	0.1
Groundwater inflow (ML/month)	36	59	0.5
Groundwater outflow (% of losses)	31	0.1	0.1
Groundwater outflow (ML/month)	521	0.3	0.3
Median salinity (mS/cm)	3.7	17.2	12.6
Maximum lake area (km^2)	23	10.1	2.9
Catchment area (km^2)	298	85	210
Maximum depth (m)	2.27	2.9	3.5

For Lakes Linlithgow and Buninjon, evaporation and direct rainfall input are the major influences on the water budget (Table 1), and these results are comparable to calculations for Lakes Keilambete, Murdeduke, Beeac, Bookar, Colongulac and Gnarpurt, which lie on the southern part of the western Victorian volcanic plains (Coram 1996; Jones *et al.* 2001).

However, the water balance of Lake Burrumbeet shows that groundwater outflow has a major influence on lake levels (average 31% of water losses; Table 1), whereas this has only a minor effect for Lakes Buninjon and Linlithgow. The substantial groundwater outflow for this lake is probably due to leakage through a maar at one end of the lake into the underlying deep lead aquifer. Also there is a likelihood of anomalously high flow through the lake floor disturbed by the volcanic rocks, located at the centre of the lake bed. Geological reconstruction of the course of the deep lead show that it runs directly beneath Lake Burrumbeet. This loss of groundwater limits the amount of time the lake water is subject to evaporation, and also allows significant salt export. Lakes Buninjon and Linlithgow are underlain by thick clay-rich soils, so they do not leak. As a result Lake Burrumbeet is generally much less saline than Lakes Linlithgow and Buninjon (median salinities of 3.7, 17.2 and 12.6 mS/cm respectively). Lake Buninjon is less saline than Lake Linlithgow, probably because it has a lower area/depth ratio than Lake Linlithgow (0.8 compared to 3.5) and dries out less often.

6. SALINITY LOSSES DURING DRYING OUT PHASES

The salinity modelling initially assumed that no salt was lost from the lake-bed during drying-out phases. However, this resulted in a large deviation between the modelled and measured data for years when the lakes dried out, suggesting that salt was lost from the lake-bed at these times. Observations during the 2001/2002 dry phase showed that salt efflorescences on the lake floor of Lake Linlithgow were removed by wind (Bennetts 2005). It is also possible that salts are flushed into the underlying aquifer by rainfall infiltrating through the dry lake-bed, as commonly occurs in salt lakes in the Murray-Darling Basin (Cartwright *et al.* 2004).

The models were subsequently recalculated assuming that a proportion of salt was lost; for the best fit to the measured data following dry phases, 20-30% of the total salt stored in the lake-bed immediately prior to drying had to be removed. The relative influence on the salt loss of wind deflation of salt crusts on the dry lake bed versus leakage into the underlying groundwater is uncertain, but the groundwater outflow is small for Lakes Linlithgow and Buninjon, unlike Lake Burrumbeet, so deflation may be the main process. The dry bed of Lake Burrumbeet is quickly covered by grass as it dries out, so wind deflation of salt crusts is not likely to be significant for this lake.

7. CONCLUSIONS

The modelling results show that the lake levels are primarily driven by the volumes of surface water inflows and direct rainfall during wetter months, and evaporation during drier periods. Furthermore, lakes dominated by input of rainfall and surface water and with substantial outflow, either by outflowing streams or groundwater leakage like Lake Burrumbeet, are likely to be relatively fresh because there is a significant amount of salt export in the outflow, and because the amount of time the lake water is subject to evaporation is limited. Nevertheless, the water and salt budget for Lake Burrumbeet demonstrates that the major cause of salinity here, as at the other lakes, is evaporation; solutes mostly derived from rainfall and runoff are concentrated by evaporation.

It is evident that these lakes are a major local salt source for the surrounding landscape and/or underlying groundwater system, and these offsite impacts must be considered in their management. The removal of salt during drying-out phases resets the salinity of the lakes, limiting their ability to become more saline with time. Drying-out phases may therefore be essential in preventing the increased salinisation of lakes and wetland environments across the volcanic plains, wherever the water and salt budget causes salts to accumulate in the lake over time. This is particularly important for Lake Linlithgow, which is a major refuge for many threatened floral and faunal species.

8. ACKNOWLEDGMENTS

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