Remote sensing and hydrochemistry of lakes-groundwater interaction

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Abstract

Southeast Australia is currently experiencing a severe multi-year drought caused by a significant rainfall deficit and record high temperatures. The vast system of lakes that occupy the Corangamite Catchment is affected by this drought with a significant drop in the water levels and a decline in water quality. Physical and chemical hydrological data are used in combination with remote sensing techniques to study (i) how drought conditions affect groundwater and lakes interaction, and (ii) how this, in turn, impacts on lakes quality. The data record spans over 14 years, and includes a pre-drought (1992-1996) and drought (1997-2006) period. The drought has altered interaction of lakes with the groundwater system. By 2006, 10 of the 28 monitored lakes have changed from groundwater throughflow or discharge lakes to recharge lakes that are now dry. Cl/Br ratios indicate that the remaining lakes are throughflow lakes. The drought has also resulted in increased lake salinity levels. By 2006, 7 lakes have evaporites, where previously none were observed. The increase in lake salinity is due to increased evaporation, or a combination of increases in the evaporation and groundwater to lakes volume ratios. Therefore, although these are throughflow lakes, evaporation is a controlling factor on lakes quality, and although lakes may be sustained by hydraulic gradients with groundwater, there is no guarantee that the water quality will be maintained for ecosystem health.

1. INTRODUCTION

The impact of droughts on lake systems can be extensive and severe. The altered atmospheric and groundwater components in the water budget of the lakes can cause changes in quality and quantity that are detrimental to ecosystem health, particularly in catchments where lakes are already threatened by increasing salinisation and frequent algae blooms. Accompanying these challenges is the fact that many lakes and surrounding shallow groundwater systems are poorly monitored. For sustainable management of lakes in the future, information on the impacts of previous stresses, such as droughts, on hydrological systems is essential. Therefore, new applications and techniques are required for improved understanding of the historical interaction between the surface water and groundwater systems and processes controlling declines in lakes water quality.

To counter issues associated with limited spatial and temporal resolutions for field-based data, recent studies have incorporated remote sensing techniques to monitor groundwater and surface water interactions (e.g. Leblanc et al., 2007; Tcherepanov et al. 2005; Tweed et al., 2007). In addition to remote sensing data, hydrochemistry data can present an accumulative record of dominant hydrological processes affecting lakes water over time. Where time series of physical hydro(geo)logical monitoring data is sparse, both remote sensing and hydrochemistry can be used to constrain dominant relationships between the surface water and groundwater systems.

The objectives of this study are to incorporate remote sensing techniques with field-based physical and chemical hydrogeological data to discuss how the recent drought conditions in southeast Australia since 1997 have affected groundwater and lakes interaction, and subsequent impacts on lakes quantity and quality. This paper is the synthesis of studies to date by Cartwright et al. (2008) and Tweed et al. (2008).

2. STUDY AREA

The study area is the Corangamite Catchment, located in a sub-humid and low relief region of southeast Australia (Fig. 1). In southeast Australia, there has been a meteorological drought over the last decade. Rainfall data for the study area indicate a series of years with significant rainfall deficits from 1997 to 2006, with the exception of 2001 and 2004 (Figure 2).

The Corangamite Catchment covers an area of 13,340 km^2, contains a poorly developed drainage network, and has over 1,500 wetlands and lakes many of which are small, widely dispersed, ungauged, and on private property. Much of the study region is a significant agricultural area, but also contains wetlands with high cultural and ecological value. The lakes are shallow, except for the 3 crater lakes. Many of the lakes are sustained during periods of low rainfall and are therefore thought to be groundwater dependent. However there is limited physical hydro(geo)logical monitoring data to verify this, especially for the smaller lakes.

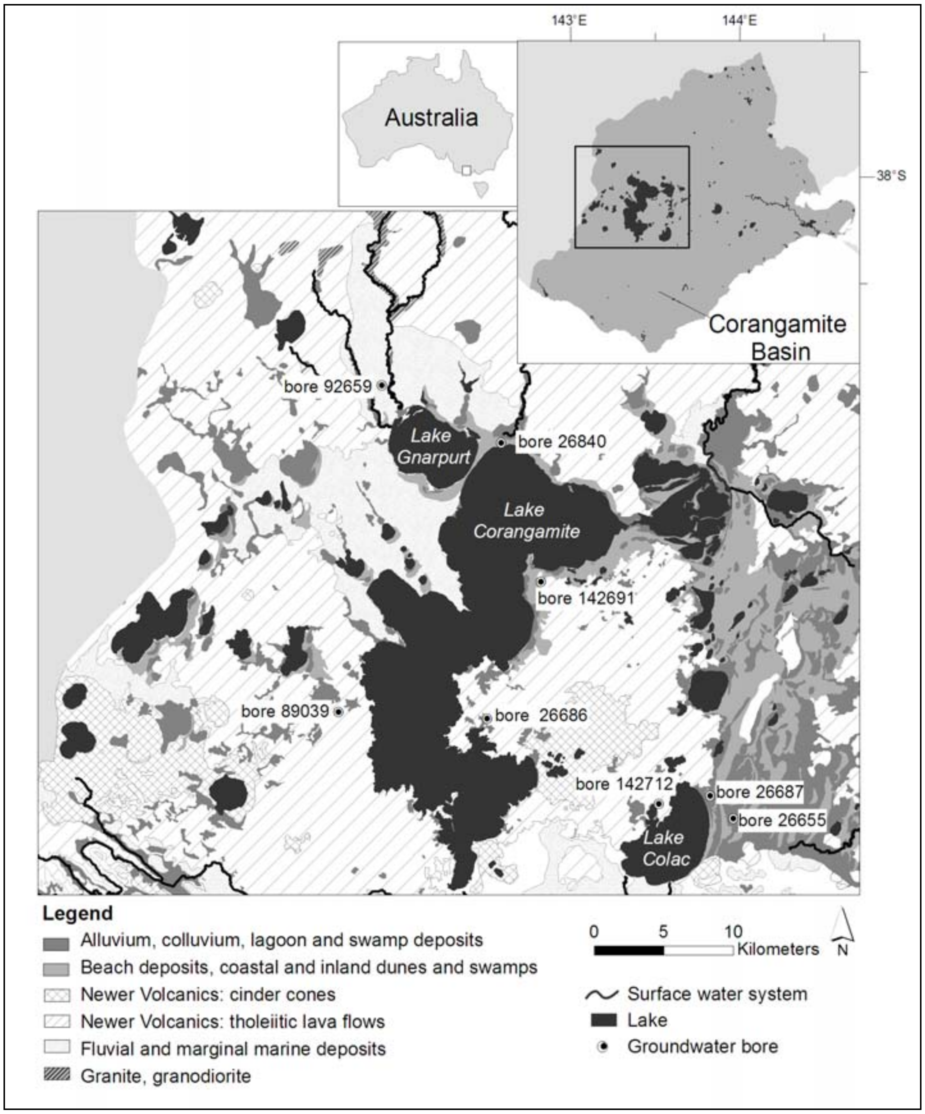

Figure 1. Location of lakes and the major lithologies in the study area. The groundwater bores shown are those used for the hydrograph analysis.

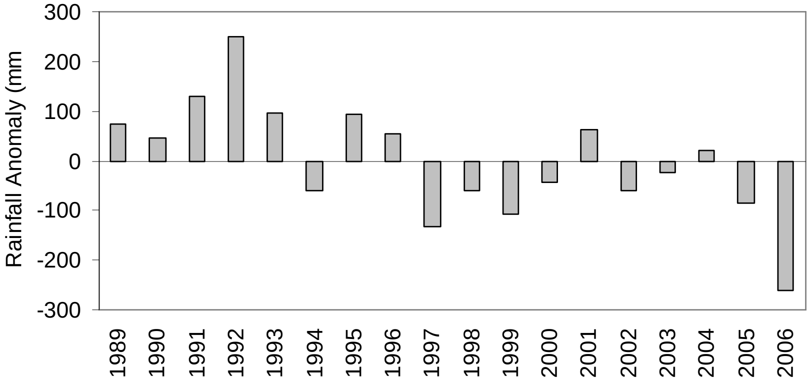

Figure 2. Deviation from average annual rainfall for 1989 to 2006 (Bureau of Meteorology, 2007).

3. DATA AND METHODS

3.1. Hydrochemistry

The lakes major and minor ion and stable isotope chemistry were sampled in November 2006 and June 2007, and Cl and Br concentrations were measured for shallow bores in February 2006 and from springs in May 2007. Cations were analysed using a Varian Vista ICP-AES at the Australian National University on samples that had been filtered through 0.45µm cellulose nitrate filters and acidified to pH 2. Anions were analysed on filtered unacidified samples using a Metrohm ion chromatograph at Monash University. Precision of anion and cation concentrations is ±2%. Charge balances were all within ±10%.

3.2. Groundwater and surface water levels and EC values

There are 3 lakes in the study area that have groundwater and lakes hydrograph data, these data were used to investigate temporal changes in groundwater and lakes interaction. Data includes water levels and EC values for lakes and shallow groundwater (30 m or less in depth). The groundwater data were sourced from the Victorian groundwater database, and the surface water level data are from the Corangamite Catchment Management Authority (CCMA). The Lake EC values are from the CCMA, De Deckker and Williams (1988), Williams (1995), Victorian data warehouse, and archived Rural Water Corporation data.

3.3. Lakes water budgets

Water budgets were calculated for two lakes (Corangamite and Colac), as these lakes had sufficient lake level data to undertake the analysis. Both monthly and annual (calculated from December to November only for years where all months have data) values were calculated for the groundwater component. To calculate lakes water budgets, a hypsographic curve was created using the surface area of lakes water mapped using Landsat described in section 3.4, and on-ground lake level monitoring data. Using the hypsographic curve for each lake, the water budget data is extended to pre-drought conditions. Input data and data sources for the water budgets are summarized in Table 1. The results are presented as the net groundwater inflow and outflow for the lake, which may also include any interflow via the unsaturated zone into the lake.

3.4. Mapping lakes water and evaporites

Lakes water and evaporite deposits from 1989 to 2006 were mapped using satellite imagery. The highest quality scenes from the Landsat-5TM archive were used and include images from summer months; December 1989, January 1991, February 1993, February 1995, January 1998, and December 2006. The scenes were orthorectified and radiometrically corrected prior to purchase and registered to the Geographic Datum of Australia (GDA), zone 54. Images from 1989 to 1998 were previously normalized by AGO. To use the December 2006 image as part of the time series, this image was rectified for the study area, and then normalized using pseudo-invariant targets to the

1998 image. The linear regression R^2 value for targets (buildings and deep lakes) in bands 1 and 5 were 0.97 and 0.95 respectively.

The extent of inundated water bodies in these images were delineated using a simple density slicing technique (threshold) in the mid infra-red (band 5). All pixels with a digital value including and below the threshold of 20 in band 5 (1.55 – 1.75 μm) were identified as 'wet'. Evaporite deposits were also mapped using a threshold technique, but in the visible band 1 (0.45 – 0.52 μm), where pixels with values greater than 95 were classified as having evaporite deposits. Threshold values were chosen by ground-truthing the locations of indundated areas and evaporite deposits in December 2006.

Using an error matrix, the overall accuracy for mapping evaporites, water, dry land and evaporites under water for the December 2006 Landsat data is 98.9% (Kappa Coefficient is 93.7%), and the producer's and user's accuracies range from 65.8 to 100 %. The high accuracy for these results is due to mapping spectral classes such as water and evaporites that have relatively distinctive spectral signatures. Results of mapping lakes surface area includes some that are > 100%, this is because areas are recorded as a percentage of inundation relative to the shoreline for lakes in 1994, and in some years the lakes flood.

Table 1. Data for lakes water budgets

Data	Source	Comments
Water area	Landsat-5TM: December 1989, January 1991, February 1993, February 1995, January 1998, and December 2006	Lake Colac: satellite images cut off small areas in 2 scenes (2006 and 1993); surface areas were estimated for these areas (using extent of water from closest date)
Water level	CCMA	
Lake depth	Coram (1996), De Deckker and Williams (1988), Khan (2003)	Maximum values used.
Shoreline location	Victorian Geospatial Data Library (1994)	
Shoreline elevation	Lidar	Acquired during the period 19/07/03 to 10/08/03
Evaporation	Pan evaporation data from Wurdiboluc Reservoir (Bureau of Meteorology, 2007)	Data is available for most months between 1969-2007. For months where there was no data (prior mar69, aug79, may84, dec84, aug85, jan86-dec86, dec06, jan07, feb07), the monthly values from 2004 were used. A coefficient of 0.7 was applied.
Rainfall	Bureau of Meteorology	Calculated mean monthly values from gridded data for the study area
Surface water inflow	The surface water inflows via all creeks were very small compared with other water budget components and therefore were not included.	For Lake Colac, Deans Creek and Barongarook Creek seasonally flowing into the lake. Deans creek has an average input of 13.8 ML/day and overall tributary inflow is ~ 1000 ML/d (Khalifé et al., 2005). Lake Colac also receives treated sewage for the region, however this is only on average 4.7 ML/day. For Lake Corangamite there is a small ephemeral creek (Pirron Yallock Creek) and overflow from the normally dry Lake Gnarpurt in abnormally wet years.

4. RESULTS AND DISCUSSION

4.1. Groundwater and lakes interaction from the hydrochemistry

Physical hydro(geo)logical monitoring data is limited for many lakes in the study area, therefore hydrochemistry data were used to identify the dominant groundwater and surface water processes. The schematic diagram in figure 3 illustrates groundwater and lake water interactions for recharge, throughflow and discharge lakes. Figure 3 also highlights that within a catchment prone to salinity, recharge lakes will have no evaporites present and are ephemeral, whereas groundwater throughflow and discharge lakes can have evaporites (particularly in the summer months) and can be sustained during drier months by the groundwater component.

The Cl/Br ratios and Cl concentrations also provide a mechanism to distinguish these different types of groundwater and lakes interaction. Cl/Br ratios remain constant with increasing lake salinity in recharge lakes because no evaporites (e.g. halite) are precipitated. In comparison, in discharge lakes there is a high rate of evaporation relative to groundwater outflow, therefore evaporites precipitate over time. The precipitation of evaporites results in a decrease in Cl/Br ratios with increasing lake salinity levels (Figure 3). Throughflow lakes present a different scenario; even where evaporites are present the Cl/Br ratio remains relatively moderate compared with the low Cl/Br ratios of discharge lakes. This is due to the throughflow lakes inflow of moderate Cl/Br groundwater and outflow of lower Cl/Br lake water. Obvious exceptions to this model, are where the salinity of entering groundwater is high and/or and the relative rate of evaporation far exceeds groundwater throughflow.

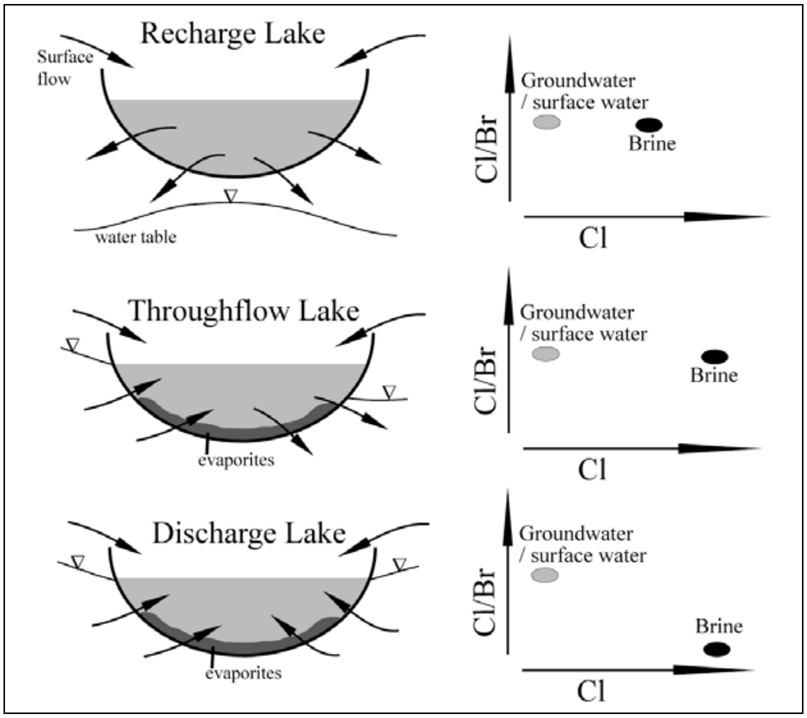

Figure 3. Illustration of groundwater flow paths and Cl/Br ratios that distinguish lakes between recharge, throughflow and discharge systems in a salinity-prone catchment. Evaporites can also be present in throughflow and discharge lakes.

The hydrochemistry of the lakes water in the study area indicates that most lakes are throughflow. Figure 4 shows the results of lakes and groundwater sampling. With the exception of one lake (Lake Cundare), Cl/Br ratios remain relatively constant (503 – 865) and within the range of the groundwater values. Lower Cl/Br ratios for lakes in summer (November 2006) reflect the increased evaporation rate resulting in increased evaporite precipitation. In comparison, during winter (June 2007) increased rainfall results in greater dissolution of halite minerals and therefore higher Cl/Br ratios.

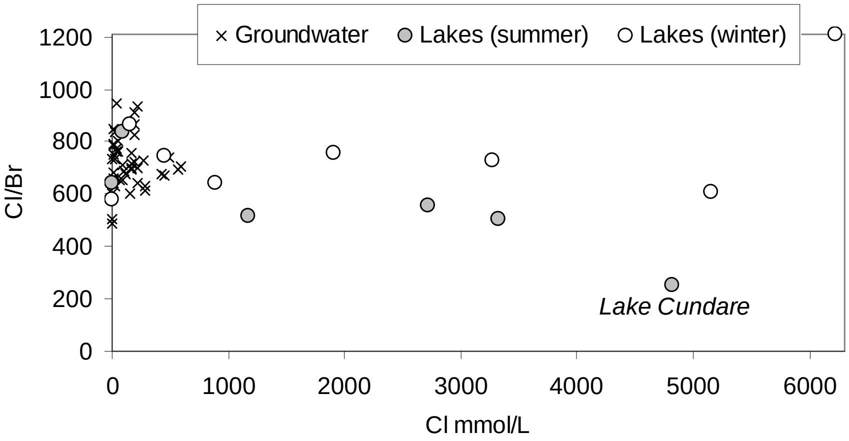

Figure 4. Cl/Br ratios for lakes and groundwater in the study area. Location of Lake Cundare is shown in figure 9 as lake number 27.

4.2. Temporal trends in lake quality, quantity and interaction with groundwater

The results from the hydrochemical analysis present the dominant groundwater and lakes interaction occurring during drought conditions. To determine the seasonal and inter-annual variability of these lakes-groundwater interactions, the temporal variability during high rainfall (1992-1996) and low rainfall (1997-2007) periods is investigated using time-series data, and water and solute budget calculations.

4.2a Water levels and EC time-series

Time series of water levels and EC values for 2 lakes, Lake Colac and Lake Corangamite are shown in figure 5. Results show the decline in lake water levels and the corresponding rise in lake EC values, particularly from 1997 onwards. From 1997 to 2006, the lake water levels have decreased by 1.39 and 2.55 m in Lakes Colac and Corangamite respectively. The most recent EC values (February 2008) are over 10 times and 4 times the values reported in February 1997 for Lakes Colac and Corangamite respectively.

Groundwater data indicate that across the region the water table during drought conditions (2006) is lower on average by 0.73 m in summer/autumn and 1.24 m in winter/spring compared with the water table during pre-drought conditions (1992). For 2 lakes with water level records, the hydrographs for the groundwater from surrounding

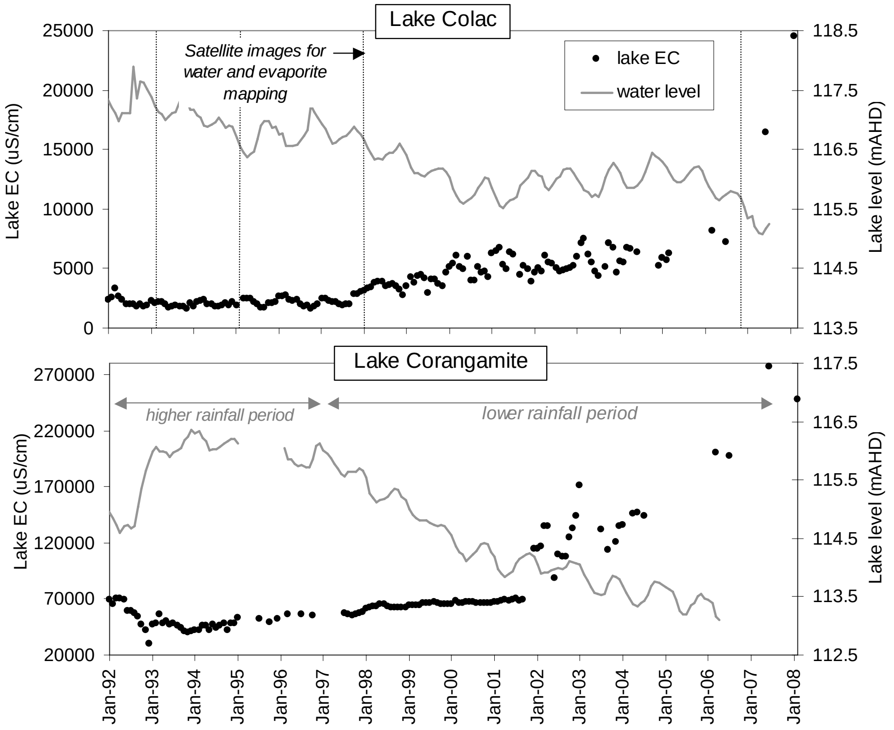

Figure 5. Lake water levels and EC values. Vertical lines show dates for satellite images used to map water and evaporites for Lakes Corangamite and Colac (lake numbers 15 and 29 respectively in Fig. 9).

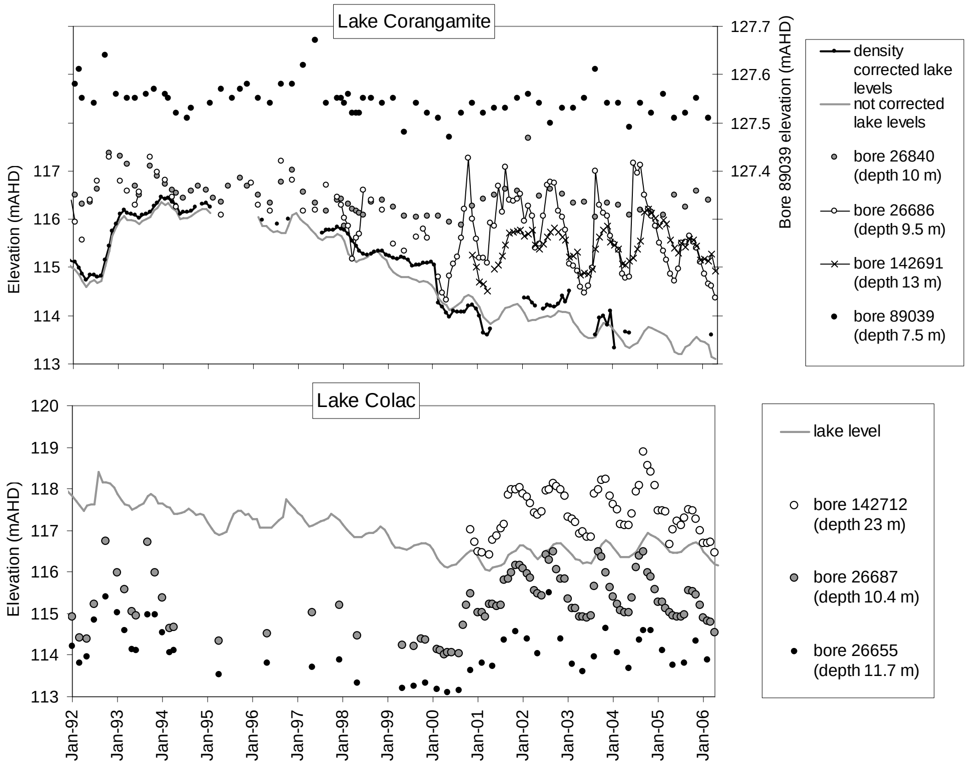

Figure 6. Lake and groundwater hydrograph data. Locations of groundwater bores are presented in figure 1.

bores indicate a decrease in groundwater elevations (Figure 6). The lake levels decrease at a more rapid rate than the groundwater levels; therefore the hydraulic gradients between groundwater and lakes have changed during the drought. The data indicates that Lake Corangamite remains a discharge lake and Lake Colac remains a throughflow lake throughout the drought (Figure 6). However, the distribution of monitored groundwater bores surrounding the lakes are limited compared with the size of these lakes (Figure 1), therefore to explore the changes in lake-groundwater interaction a water budget is calculated for these 2 lakes.

4.2b Lakes water budgets

Reduced rainfall during the drought is the primary control on decreasing lake levels. Secondary to rainfall, are decreases in groundwater discharge and increases in evaporation. The results from the geochemical analysis of the lakes using Cl/Br ratios indicate that the lakes are groundwater dependent. During drought conditions, the groundwater/lake volume ratio may increase, as lakes are often sustained by groundwater inflows during periods of low rainfall. Additionally, groundwater and lake hydrographs indicate an increase in hydraulic gradients between groundwater and lakes during the drought. To determine whether changes in groundwater discharge or evaporation during the drought has a greater impact on lake levels, a water budget analysis is undertaken for Lakes Corangamite and Colac.

The ratios of monthly groundwater, annual groundwater and evaporation to lake volume results from the water budgets analysis are presented in figure 7. Hydrochemistry data indicate most lakes monitored are throughflow lakes. However, fluctuations in the groundwater component of the lakes water budget highlight seasonal variability between lakes discharging (53% of calculations for Corangamite and 57% of calculations for Colac) and recharging groundwater. Annual calculations of the lakes water budgets indicate there is net annual groundwater discharge to the lakes. Lake Colac shows 2 consecutive years where the budget indicates net annual recharge from the lake to the groundwater system and these correspond to the wetter period (Figure 7). The annual groundwater component for Lake Corangamite shows less discharge of groundwater to lakes (relative to the lake volume) during the drought, however seasonal variations show large fluctuations between net groundwater recharge and discharge. In contrast, Lake Colac shows little change in the seasonal fluctuations, and an increase in the net annual groundwater discharge during drought conditions. The results of evaporation/lake volume ratios for the 2 lakes indicate an increase during drought conditions (Figure 7).

Therefore during the drought, in addition to lower rainfall levels, the decrease in lake water levels for Lake Corangamite is due to both the increase in evaporation and the decrease in annual groundwater discharge. In comparison, the decrease in lake water levels for Lake Colac is largely due to the increase in evaporation rather than any change in the groundwater component.

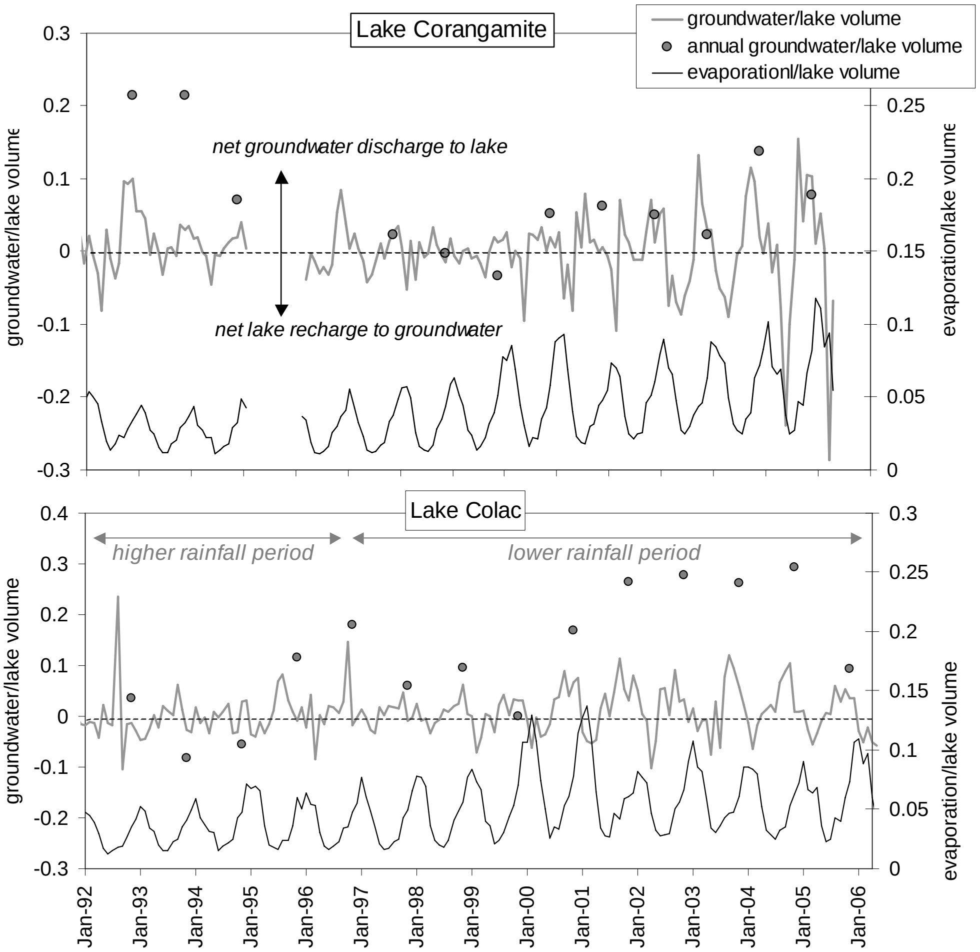

Figure 7. Ratios of monthly groundwater, annual groundwater, and evaporation with lake volumes for Lake Colac and Lake Corangamite during the period 1992-2006. For groundwater/lake volume ratios, positive values indicate net groundwater discharge to the lake, and negative values indicate net lake recharge to groundwater.

4.2c Lakes solute budgets

To determine the dominant controls on the increase in lake EC values during the drought, a solute budget is calculated for Lakes Corangamite and Colac. Although the groundwater EC values remain relatively constant, an increase in the groundwater/lake volume ratio corresponding to a decrease in rainfall input can result in increases in the lake salinity, particularly since groundwater in the region can exceed 60 mS/cm. Another process that may contribute to the increase in lake salinity is an increase in the evaporation/lake volume ratio during drought conditions. The fractionation of stable isotope values indicates that the lakes are subject to evaporation (Cartwright et al., 2008). Therefore, an increase in either groundwater/lake volume or evaporation/lake volume ratios may control the increase in lake EC values.

Results show that for Lake Corangamite, the increase in lake salinity is largely proportional to the decrease in lake volume, and therefore indicates that evaporation is a

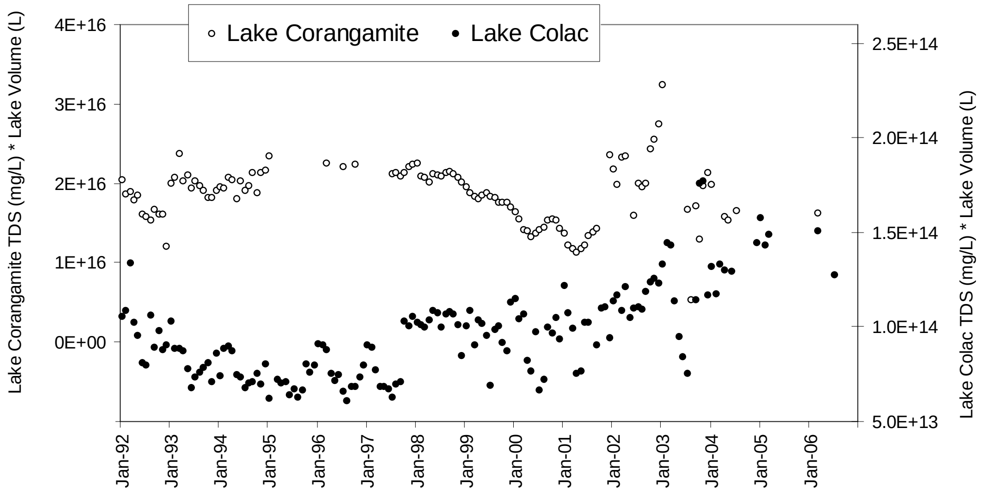

Figure 8. Solute budgets for Lake Colac and Lake Corangamite during the period 1992-2006.

dominant control on lakes salinity (Figure 8). In comparison, for Lake Colac, during the drought the lake salinity values increase at a greater rate than the decreases in lake volume, and therefore indicate that there is an additional salt load input to the lake from groundwater (Figure 8). These results for Lake Colac are consistent with the water budget that highlights an increase in the net annual groundwater discharge during drought conditions (Figure 7).

4.3. Spatial and temporal trends from remote sensing

The hydrograph data indicates that drought impacts on groundwater dependent lakes of the study area include lowering water levels and increasing lake EC values. However, from the water budget calculations for 2 of the lakes, it is evident that the lakes response to atmospheric changes can vary. To investigate the response of 26 other lakes in the study region to the drought, remote sensing data was used.

The extent of water inundation provides a valuable proxy to changes in lake water level with time. Lakes inundated areas were mapped over the period 1989 to 2006 (Table 2), and results for December 2006 are shown in figure 9. All of the lakes, except for the volcanic crator lakes (12-14), show a decrease in the surface area of water by 2006, and most show a rapid decrease in water surface area between January 1998 and December 2006. By December 2006 lakes are on average 15% of their total lake area under ‘normal’ conditions, whereas between 1989 and 1998 the average lake water area covers 92% of the lake area under ‘normal’ conditions. Evaporite deposits in lakes were also mapped over the period 1989 to 2006 (Table 3). For 10 of the 28 lakes, evaporites are present in December 2006 (Figure 9). With the exception of 3 of these lakes, the evaporites appear only in December 2006, which corresponds to the drop in water areas. For 3 lakes (lakes 4, 27 and 28) evaporites are present in most images from 1989-2006.

Table 2. % surface area of water (m2)

lake number	Dec-89	Jan-91	Feb-93	Feb-95	Jan-98	Dec-06
1	81	70	80	0	0	0
2	98	96	99	94	93	53
3	75	80	102	89	83	0
4	77	72	96	76	73	0
5	161	128	165	146	153	25
6	113	114	121	115	114	0
7	86	83	99	91	84	0
8	98	96	103	102	100	68
9	73	68	105	94	76	0
10	82	72	96	92	87	0
11	95	89	123	105	96	0
12	96	95	97	96	97	94
13	95	93	95	94	94	93
14	97	96	97	97	97	95
15	92	91	99	98	96	45
16	94	90	94	74	74	0
17	89	87	95	90	91	33
18	78	74	93	76	72	0
19	89	84	110	87	84	0
20	95	92	102	82	58	0
22	104	102	108	100	98	0
23	90	76	91	72	70	66
24	97	96	97	95	94	66
25	97	no data	no data	98	95	no data
26	93	91	129	44	82	0
27	93	no data	96	60	78	0
28	96	no data	97	96	89	0
29	101	no data	no data	103	103	no data

Table 3. % surface area of SALT (m2)

lake number	Dec-89	Jan-91	Feb-93	Feb-95	Jan-98	Dec-06
1	0	0	0	0	0	0
2	0	0	0	0	0	6
3	0	0	0	0	0	0
4	92	86	0	2	70	81
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	8
9	0	0	0	0	0	0
10	0	1	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	13
16	0	0	0	0	0	12
17	0	0	0	0	0	99
18	0	1	0	2	0	81
19	0	7	0	0	0	79
20	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0
25	0	no data	no data	0	0	no data
26	0	0	0	2	0	0
27	98	no data	94	102	44	94
28	99	no data	98	99	95	71
29	0	no data	no data	0	0	no data

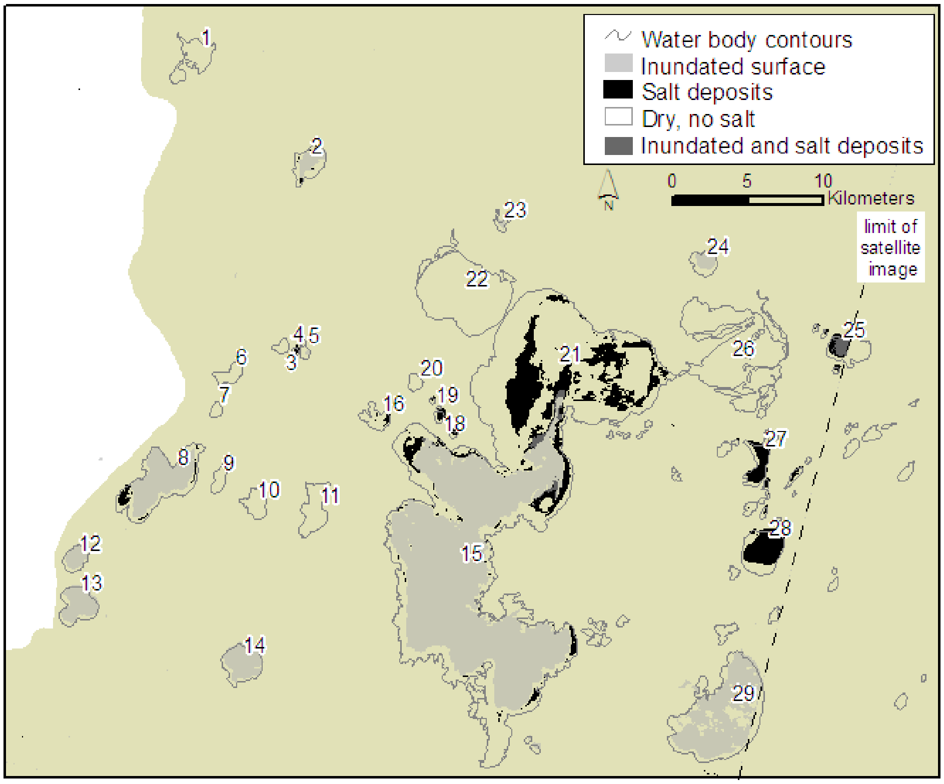

Figure 9. Lakes water and evaporite mapping for the study area in December 2006.

5. CONCLUSIONS

For all lakes, the drought has altered interaction between lakes and the groundwater system. The extent of these changes reflects local hydraulic controls on groundwater-lake flow rates, location in the landscape and lake bathymetry. By 2006, 10 of the 28 lakes have no water or evaporites, whereas prior to the onset of drought conditions all of these lakes were inundated. Therefore, with decreasing groundwater levels, these 10 lakes have changed from groundwater throughflow or discharge lakes to recharge lakes. Cl/Br ratios indicate that the remaining 18 lakes monitored are throughflow lakes. However, the annual groundwater/lake volume ratios for 2 of these lakes highlight varying responses to drought stresses. The largest lake in the region, Lake Corangamite, shows a decrease in the net annual groundwater discharge. Therefore, changes to all components of the lakes water budget; decreased rainfall, decreased groundwater discharge and increased evaporation, contribute to decreasing lake levels during the drought. In comparison, Lake Colac shows an increase in the net annual groundwater discharge, therefore the decrease in lake level during the drought is controlled by the atmospheric inputs; rainfall and evaporation.

The drought has resulted in increased salinisation of lakes across the region as characterized in this study by evaporite deposits, and in some cases lakes that were previously evaporite free now have evaporite deposits. Prior to the drought, inundated areas peaked in 1993 and, with the exception of 2 lakes, no evaporites were present which reflects the relatively high rainfall. By 2006, 7 of the lakes show a decline in water level correlating to the onset of evaporites. The evaporites were mapped during summer months, and the extent or even presence of these minerals is likely to vary seasonally (e.g. De Deckker and Last, 1989). One of these lakes is Lake Corangamite, where it is evident that there are changes to the lakes and groundwater interaction during the drought. However, the solute budget results suggest that the increase in lake EC and increase in evaporites are largely due to the increase in the evaporation/lake volume ratio compared with changes in the groundwater/lake volume ratio. In comparison, changes in the salinity levels of Lake Colac reflects both groundwater and evaporation changes relative to lake volume.

The response of these lakes to drought presents a scenario for impacts of low rainfall conditions in a region already compromised by salinisation and algal bloom processes. The concentration of dissolved ions in lakes waters will also impact lakes health via increased nutrient levels (e.g. Khan, 2003). This study highlights that even for groundwater throughflow and discharge lakes, any change in the evaporation/lake volume ratio can have an over-riding impact on lakes water quantity and quality.

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