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Groundwater–surface water interaction and the impact of a multi-year drought on lakes conditions in South-East Australia

Sarah Tweed [a,*], Marc Leblanc [a], Ian Cartwright [b]

[a] School of Earth and Environmental Sciences, James Cook University, Cairns, QLD 4870, Australia
[b] School of Geosciences, Monash University, Melbourne, VIC 3800, Australia

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SUMMARY

South-East Australia is currently experiencing a severe multi-year drought (~11 years of below long-term average rainfall between 1997 and 2008). To refine our understanding of the impacts of such climate stresses on lake systems, and to overcome the limitations of insufficient field based measurements, lake water levels and lake salinity values are combined with remote sensing data (Landsat-5TM) to analyse water and solute budgets for two large lakes in the Corangamite catchment. For these two lakes, data during pre-drought (1992–1996) and drought (1997–2006) periods are used to investigate the impact of the drought on lake and groundwater interaction and possible changes in mechanisms controlling the salinity of the lakes. For 26 other lakes in the Corangamite catchment with limited or no on-ground data, water and evaporite mapping using remote sensing data (Landsat-5TM) were used as proxies for drought impacts on lake quantity and salinity. Within the study area, this drought has resulted in a 60% loss of lakes area inundated (220×10^6 m^2), and for the two largest lakes the water loss equates to an 80% decrease in volume (714×10^6 m^3). Although the lakes are groundwater-fed, the rapid declines in lake water levels have not resulted in systematic increases in groundwater discharge to lakes across the study region. The lakes that are most sensitive to changes in the hydrologic budget within the catchment (10 of the 28 monitored lakes) have changed from groundwater throughflow or discharge lakes to intermittent recharge lakes. The decrease in lake levels is accompanied by an increase in lake salinity, however the dominant controls on increases in salinity varies for different lakes between just evaporation, and evaporation plus episodes of increased net groundwater discharge. The drought has exacerbated pre-existing high lake salinity levels; by 2006 one quarter of the lakes have evaporites where previously (before 1997) these lakes were evaporite free. These observations on changes in lakes quantity, interaction with groundwater, and salinity highlights the spatial variability in the lakes response to regional drought impacts.

Introduction

Droughts can have severe detrimental effects on society and the environment (White et al., 2008). Compounding the problem of increases in water resource demands, which places stress on all components of the hydrologic budget during a drought (e.g. Hopkin, 2007; Thuiller, 2007), is the reduction in supplies and the degradation of quality (e.g. increased salinity levels; Covich et al., 1997). For a lake, a drought influences the atmospheric, surface and subsurface fluxes. The lakes of the Corangamite system belong to the category of closed lakes; which have been shown to be particularly sensitive to hydroclimatic variations (e.g. Leblanc et al., 2006a). The propagation of a drought through a catchment varies depending on the drought severity, and the hydraulic connectivity of the system. Local variations in hydraulic connectivity often cause spatial variations in lakes and groundwater response to a drought (e.g. Cohen et al., 2006; Peters et al., 2006; Pham et al., 2008). To date, there have been limited studies looking at the impact of prolonged droughts on lakes hydrology from an integrated point of view.

Most of South-East Australia has been experiencing a protracted drought from 1997 to present (2008), which is comparable in severity to only one other period (1936–1945) on record (Murphy and Timbal, 2008). This paper aims to present in situ and remote sensing observations of the impact of this multi-year drought on a system of lakes in South-East Australia. In particular the paper focuses on (a) quantification of the exchanges of water between the lakes system and groundwater, and (b) mechanisms controlling lakes salinity levels during this on-going drought in South-East Australia. During a drought, or during any stress placed on the

* Corresponding author. Address: School of Earth and Environmental Sciences, James Cook University, PO Box 6811, Cairns, Queensland 4870, Australia. Tel.: +61 7 4042 1468; fax: +61 7 4042 1364.
E-mail addresses: sarah.tweed@jcu.edu.au (S. Tweed), marc.leblanc@jcu.edu.au (M. Leblanc), ian.cartwright@sci.monash.edu.au (I. Cartwright).

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hydrologic system, information on the time frames and magnitude of response for groundwater and surface water are essential for sustainable catchment management (e.g. Inbar and Bruins, 2004). In addition to lower rainfall inputs to the lakes, any changes in the groundwater and lakes interactions during the drought may impact on water storage and lakes water quality.

Water elevation and flow data provide the best indication of surface water and groundwater interactions. However in most cases, including many of the groundwater dependent lakes in the Corangamite catchment, the distribution and on-going monitoring of groundwater and lake water level data are insufficient. Therefore in this study, remote sensing data is coupled with field based measurements to overcome the limitations of insufficient spatial and temporal in situ monitoring. Recent studies have incorporated remote sensing techniques to highlight groundwater and surface water processes (e.g. Meijerink et al., 2007). Satellite remote sensing offers the ability to cover large surface areas with relatively fine spatial resolution (e.g. Leblanc et al., 2006b; Pan et al., 2009) and over selected time periods (e.g. French et al., 2006). By incorporating remote sensing data, not only is the extent of spatial and temporal information enhanced, but also is the ability to identify hydrogeological processes at both local and regional scales (e.g. Tweed et al., 2007). The fine resolution across large areas means that there is more opportunity to highlight local scale processes (e.g. Becker, 2006). For example, previous studies have used remote sensing data to determine temperature differences in surface water (e.g. Tcherepanov et al., 2005) and changes in vegetation activity (e.g. Tweed et al., 2007) for mapping groundwater discharge areas. Additionally, remote sensing data has been used to delineate fluctuations in lake areal extent (e.g. Leblanc et al., 2007) and lake levels (e.g. Fredrick et al., 2007) for input into groundwater flow models. In this study, integration of remote sensing data with on-ground measurements is used to perform a systematic analysis at the catchment-scale of the spatial variability of lakes responses to the drought.

Study area

The study area is the Corangamite catchment, located ~40 km from the ocean in a sub-humid region of South-East Australia (Fig. 1). Meteorological data for the catchment are available from the Australian Bureau of Meteorology (2008). The region has a long-term average annual rainfall of 730 mm, with 60% of rainfall occurring during the winter/spring months from June to November (1899–2008). The spatial average for the study area of the gridded average annual potential evapotranspiration (1961–1990) is 1000 mm. Within the study area, a deficit in rainfall from the long-term average is observed during 1994, and then for 11 of the 12 years between 1997 and 2008. Rainfall values from 1997 to 2008 are on average 121 mm/year (or 1454 mm cumulated) below the long-term mean, and this is the longest period of consecutive years below average since 1899 (Fig. 2). Therefore the region is currently experiencing a severe multi-year meteorological drought.

The Corangamite catchment covers an area of 13,300 km^2, and is characterized by low relief plains and local topographic highs formed by volcanoes. Most of the study region is dedicated to agriculture, with land use comprised of 73% and 10% grazing and cropping respectively, and regionally there has been a significant shift from grazing to cropping in recent years (Ierodiaconou et al., 2005). These agricultural practices have replaced native grasslands since the 1930s (e.g. Dahlhaus et al., 2008). The unconfined shallow aquifers of the study region are hydraulically connected and predominantly consist of the Moorabool Viaduct Formation; a marine deposited clayey-sand which is usually less than 10 m thick, and the overlying and adjacent Newer Volcanics basalt, which generally is 20–25 m thick (Edwards et al., 1996). Underlying these aquifers is the Gellibrand Marl, which is over 180 m thick (Edwards et al., 1996) and forms a confining unit preventing mixing between shallower and deeper groundwater systems (Fig. 1).

The catchment has a poorly developed surface water drainage network, however there are over 1500 widely dispersed wetlands and lakes, many of which are small, shallow, often disconnected from the drainage network, ungauged, and on private property. This study investigates 28 lakes and wetlands, six of these are recognized for having a high cultural and ecological value and form the Western District Lakes Ramsar site. These six lakes have been recognized to provide support for diverse native plant and animal species (~140 species), and a drought refuge for water birds (Department of Natural Resources and Environment, 2002). Lake areas range from 0.13 to 241 km^2, and most lakes in the study area are shallow (average ranges: 0.5–6 m), except for the three crater lakes located in the southwest (15–66 m) (De Deckker and Williams, 1988). The lake water salinity levels range from fresh (<0.5 mS/cm) to brines (>400 mS/cm). Some lakes are poorly degraded due to high phosphorus and nitrogen levels (e.g. Khalifé et al., 2005), or due to high turbidity levels (e.g. Khan, 2003). Some of the ephemeral lakes have evaporites on the lakebed surface; these evaporites include halite, gypsum, calcite, dolomite and magnesite (De Deckker and Last, 1989).

Many of the lakes are connected to the water table and are potentially sustained by groundwater during periods of low rainfall. A recent study undertaken in the region by Turnbull (2006) distinguished recharge from throughflow and discharge lakes using stable isotopes of water (δ^2H and δ^{18}O) and Cl/Br ratios. A throughflow lake both receives and loses groundwater usually at opposite sides of the lake, a discharge lake is below the water table and therefore receives groundwater from all sides of the lake, and a recharge lake is above the water table and therefore loses water to the aquifer. Turnbull (2006) studied eight of the 28 lakes investigated in this paper, and assigned these as throughflow lakes. These results however reflect the long-term (decades) and dominant groundwater–lakes interaction. The impact of the drought on groundwater–lakes interaction and the role of shallow aquifer systems to maintain storage and water quality in the lake system during a prolonged drought remain unknown.

Data and methods

In this study, information from remote sensing data (Landsat-5TM), GIS interpolated data (water table contours), and time series point data (groundwater hydrographs and lake level time series) are integrated to assess the impacts of the drought on 28 lakes throughout the region. For two of the larger lakes, Lake Corangamite and Lake Colac, field measurements of water levels and EC values are combined with inundation mapping using Landsat-5TM data (30 m resolution) to analyse water budgets and solute loads for the lakes from 1992 to 2006. For the remaining 26 lakes with no or limited on-ground monitoring data, mapping the extent of water inundated and evaporites using Landsat-5TM data were used as proxies for temporal changes in lakes quantity and salinity, respectively. The inter-annual variability of lakes–groundwater interaction and changes in lakes quantity and salinity are examined during a higher rainfall period (1992–1996) and a lower rainfall period (1997–2006).

Groundwater and surface water levels and EC values

The groundwater data are from the Victorian Water Resources Data Warehouse (VWRDW, 2008), and the Center for Land Protection Research database. A number of studies (e.g. De Deckker and

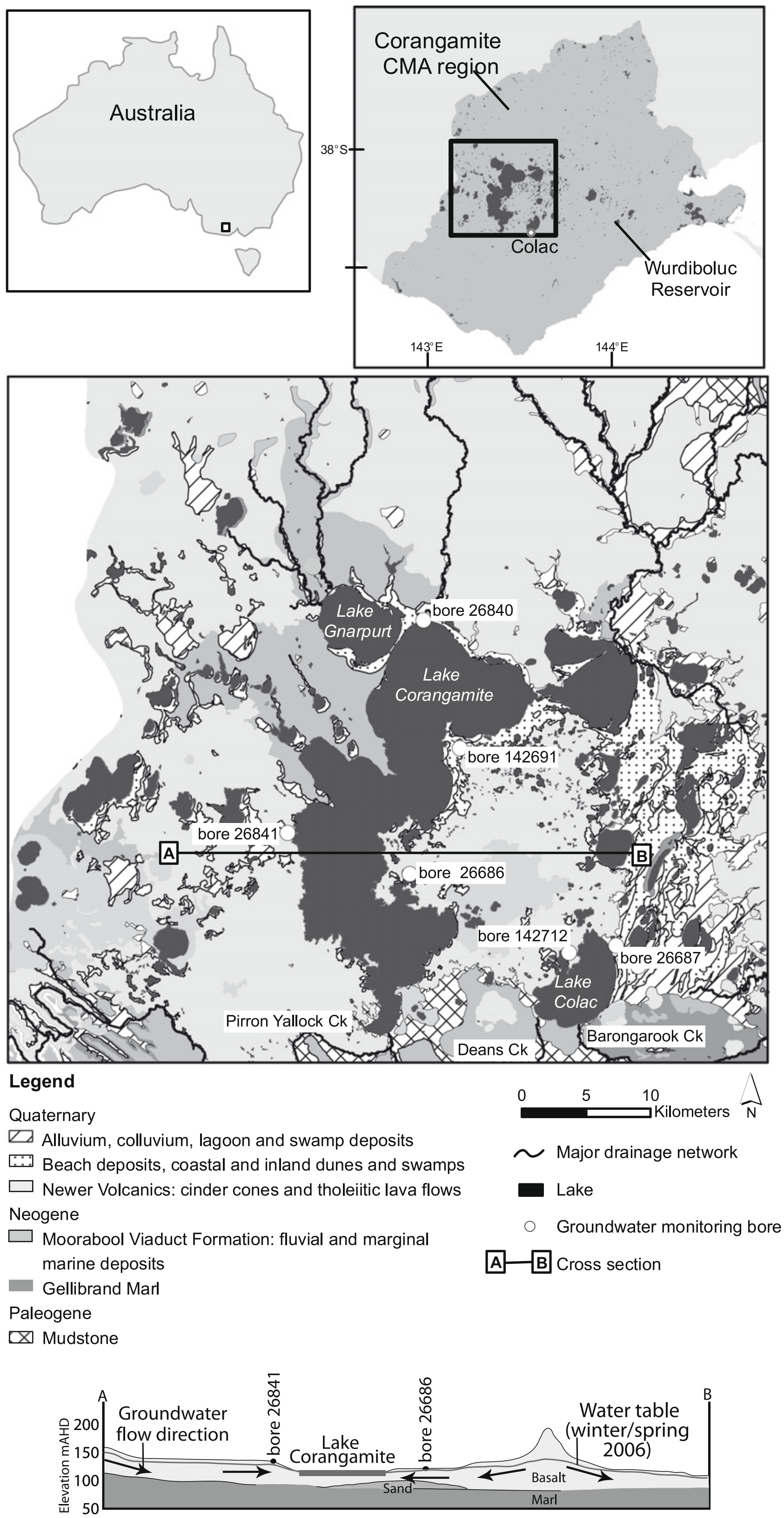

Fig. 1. Location of lakes, groundwater monitoring bores selected for hydrograph analysis, and the distribution of the major lithologies in the study area. The lithologies and general groundwater flow direction are presented in the schematic east–west cross-section (after Turnbull, 2006).

Williams, 1988; Williams, 1995), and monitoring programs (data archived at Rural Water Corporation, Corangamite Catchment Management Authority (CCMA), and VWRDW) have recorded EC values for Lakes Colac and Corangamite over the past 20 years. In this study, to limit the heterogeneity of values associated with data from different sources, either due to changes in sampling location or field equipment, the lake water level and EC values were sourced firstly from the VWRDW and secondly from the CCMA.

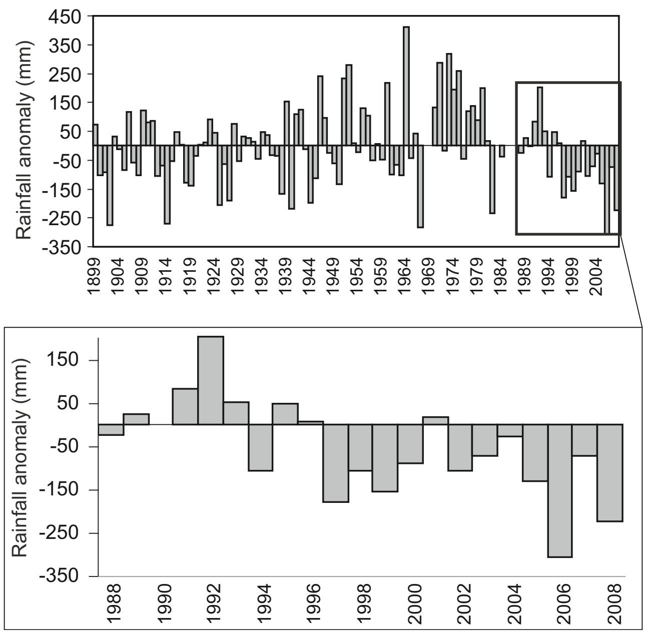

Fig. 2. Deviation from the long-term average annual rainfall for data from the Colac station during 1899–2008, and a section enlarged highlighting the recent deficits resulting in the multi-year drought (Australian Bureau of Meteorology, 2008).

Lake EC data were converted to total dissolved solids (TDS) using the relationship:

$$TDS = 9.8 \times 10^{-7}EC^2 + 0.759EC \quad (1)$$

where TDS is in mg/L, and EC is electrical conductivity (μS/cm). The equation is the least square best-fit trend line for EC and TDS values measured during a previous study (19 lakes and 13 groundwater samples; Turnbull, 2006).

Lake Corangamite EC values are up to 206 mS/cm, therefore lake water levels were corrected for density ($h_{density}$) using TDS (mg/L) following the relationship (Collins, 1975):

$$h_{density} = 6 \times 10^{-13} \times TDS^2 + 7 \times 10^{-7}TDS + 1 \quad (2)$$

Density corrections were limited to periods where lake EC data has been monitored.

To investigate changes in groundwater elevations from pre-drought to drought, hydraulic head data from summer/autumn (December–May) and winter/spring (June–November) in both 1992 and 2006 were used to generate four maps of equipotentials and groundwater flow lines for groundwater in the shallow aquifers. The unconfined shallow aquifers generally have a combined thickness of 30–35 m, therefore only bores that are 30 m or less in depth were used. For each time period, water table contours were generated from groundwater elevation data using a kriging method. The input data included averages of groundwater hydrograph measurements from 66 monitoring bores. Only the map of the winter/spring 2006 water table is presented in the results section, but averaged data from the other three maps are included for comparison of temporal changes in water table elevations.

Lakes water budgets

A water budget analysis was undertaken for two lakes (Corangamite and Colac), as these lakes had sufficient lake level data. The general water balance for a lake can be written as:

$$\Delta V_L = P_L + Q_{in} + GW_{in} - E_L - Q_{out} - GW_{out} \quad (3)$$

where ΔV_L is the change in lake volume, P_L is the precipitation over the lake, E_L is the evaporation over the inundated area, Q_{in} and Q_{out} are the surface runoff flows into and off the lake, respectively, and GW_{in} and GW_{out} are the groundwater inflow to the lake and outflow from the lake, respectively, which includes interflow (all terms of Eq. (3) are measured in volumes, e.g. m^3, for a specific time period).

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 two 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	
Shoreline elevation	LiDAR	Acquired during the period 19/07/03–10/08/03
Evaporation	Pan evaporation data from Wurdiboluc Reservoir (Australian Bureau of Meteorology, 2008)	Data is available for most months between 1969 and 2007. For data gaps in August 1979, May 1984, December 1984, August 1985, January 1986-December 1986, December 2006, January 2007, February 2007, the monthly values from 2004 were used. The values presented in Fig. 6 show the ranges where pan coefficients of 0.5 to 0.9 are applied to estimate the evaporation volumes from the lake
Rainfall	Australian Bureau of Meteorology	Computed mean monthly values from gridded data for the study area (cell size 1 km, rain gauge data from Australian Bureau of Meteorology, 2008). Fig. 7 shows the ranges in volumes where values are calculated using (a) the maximum lake shoreline as the area (to include surface runoff) and (b) lake inundation as the area of direct rainfall recharge
Surface water inflow	The surface water inflows via all creeks (and including interflow via the unsaturated zone to the lakes) are very small compared with other water budget components and therefore were not included	For Lake Colac, Deans Creek and Barongarook Creek seasonally flow 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

The groundwater flows into and out of the lake can be combined into a net groundwater component of the lake water budget:

$$GW_{net} = GW_{in} - GW_{out} \tag{4}$$

where $GW_{net} > 0$ there is net discharge of groundwater to the lake, and where $GW_{net} < 0$ there is a net recharge of the groundwater system by the lake water. Lakes Corangamite and Colac are closed lakes, and within the study area the surface water drainage network is limited (e.g. a maximum of 2% annual contribution at Lake Colac), therefore Q_{in} and Q_{out} were not included in the water budget calculations in this study, and Eq. (3) was simplified for the two lakes as:

$$\Delta V_L = P_L + GW_{net} - E_L \tag{5}$$

Input data and data sources for the water budget calculations using Eq. (5) are summarized in Table 1. The water budgets had monthly time steps. To estimate the inter-annual variability of lake and groundwater interaction, the results are presented as the total annual (based on a seasonal annual from December–November) for years with full datasets. To estimate the area of the lake and ΔV_L for each time period a hypsographic curve (lake level-area) and a lake depth–volume curve (Fig. 3) were created using the surface area of lakes water, mapped from the Landsat data described in the following section, and concurrent lake level data.

To account for uncertainty in the rainfall and evaporation estimates for lakes, a range in values were used in the water budget calculations (Table 1). Ranges in rainfall volumes (P_L) were calculated using the total monthly rainfall over the inundated area (minima), and over the total lake area defined by the shoreline (maxima). Various factors such as the pan structure and site conditions can influence the pan coefficient (e.g. Chiew and McMahon, 1992; Fu et al., 2004). Adams (1990) measured monthly class A pan coefficients for Lake Corangamite ranging from 0.66 to 0.97. The measured pan evaporation rates are normally 30% higher than lake evaporation; therefore 0.7 is a commonly used pan coefficient value in lakes studies (e.g. Linacre, 2004). In this study for both Lakes Corangamite and Colac a range of pan coefficient values for the lakes is defined as 0.7 ± 0.2. In addition, there is an inverse relationship between the TDS of lake water and evaporation rates (e.g. Ahmadzadeh Kokya and Ahmadzadeh Kokya, 2008). After a study in South-East Australia by Jones et al. (2001), the following equation was used to estimate evaporation rates from Lakes Corangamite and Colac:

$$E_{salt} = \frac{E_{fresh}}{(1 + \mathrm{TDS} \times 10^{-6})} \tag{6}$$

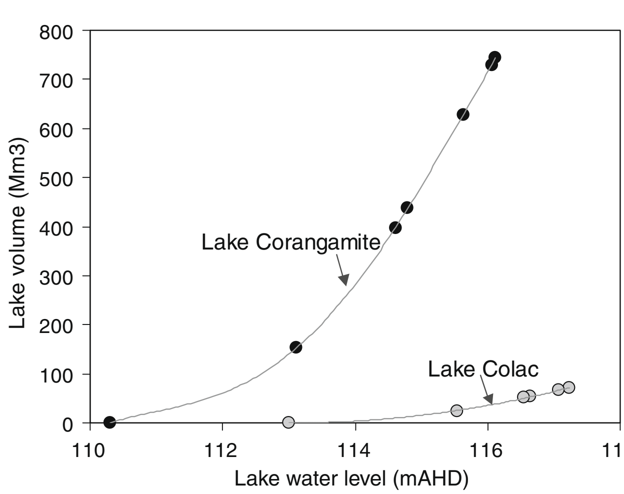

Fig. 3. The depth–volume curves used in this study, and the least square best-fit trend line (polynomial order 4 and 2 used for data from Lakes Corangamite and Colac, respectively).

where the evaporation rates after applying the pan coefficient ($E_{fresh,}$ mm/month) were converted to evaporation rates more representative of the lake's water ($E_{salt,}$ mm/month) due to changes in lake TDS concentrations (mg/L). Lake TDS data were calculated from lake EC values using Eq. (1), and where monthly EC data was missing (21% of the dataset for Lake Corangamite and 2% for Lake Colac) these values were linearly interpolated. Accounting for lake salinity using Eq. (6) implied a 4% reduction in evaporation rates in 1992, to a 9% reduction during 2005 at Lake Corangamite. The estimate of the net groundwater component for each lake will therefore range from the minima calculations (rainfall contribution to lake budget only over inundated areas and a pan coefficient of 0.9), to the maxima calculations (rainfall contribution to lake budget over the total lake area defined by the shoreline and a pan coefficient of 0.5).

Lakes solute load

To analyse dominant mechanisms controlling the increase in lake salinity from the pre-drought to drought period, the patterns in solute loads (Sol_L) with time were observed:

$$\mathrm{Sol}_L = \mathrm{TDS}_L \times V_L \tag{7}$$

where Sol_L is the total mass of dissolved ions in the lake at any time (tonnes), TDS_L is TDS of the lake (tonnes/m^3), and V_L is the lake volume (m^3). The possible origins for an observed change in total lake solute load includes changes in the net groundwater flow to the lake or average groundwater TDS over time, changes in the solute load input from rainfall, and precipitation or dissolution of evaporites.

Mapping lakes water and evaporite areas

Lakes water and evaporite deposits from 1989 to 2006 were mapped using satellite imagery for 28 lakes in the study area. 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 (Tables 2 and 3). The scenes were orthorectified and radiometrically corrected images from 1989 to 1998, and were normalized by the Australian Greenhouse Office (Furby, 2002). To use the December 2006 image as part of the time series, this image was rectified for the study area (using 51 ground control points), and then normalized to the 1998 image using pseudo-invariant targets. The linear regression R^2 value for targets (buildings, geological outcrops and deep lakes) in bands 1 and 5 were 0.97 and 0.95, respectively.

The extent of inundated areas in these images was delineated using a simple density slicing technique (threshold) in the shortwave infrared (band 5; 1.55 – 1.75 μm). All pixels with a digital value including and below the threshold of 20 in band 5 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 in accordance with GPS ground surveys of five lakes for indundated areas and evaporite deposits in December 2006.

An areal survey concurrent with the December 2006 Landsat-5TM image was conducted over 19 lakes for ground-truthing. 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 average 89.9% and 93.7%, respectively. The high accuracy for these results is due to mapping spectral classes such as water and evaporites that have distinctive spectral signatures from other features of the landscape.

Table 2
Percentage of lakes area inundated relative to shoreline.

Lake number	Lake name	December-1989	January-1991	February-1993	February-1995	January-1998	December-2006
1	Gnotuk	96	95	97	96	97	94
2	Bullen Merri	95	93	95	94	94	93
3	Purrumbete	97	96	97	97	97	95
4	Logan	81	70	80	0	0	0
5	Tooliorook	98	96	99	94	93	53
6	Koorawerra	75	80	102	89	83	0
7	Koorawerra	77	72	96	76	73	0
8	Koorawerra	161	128	165	146	153	25
9	Milangil	113	114	121	115	114	0
10	Round	86	83	99	91	84	0
11	Colongulac	98	96	103	102	100	68
12	Kariah	73	68	105	94	76	0
13	Koreetnung	82	72	96	92	87	0
14	Weeranganuk	95	89	123	105	96	0
15	Corangamite	92	91	99	98	96	45
16	Terangpom	94	90	94	74	74	0
17	Tatutong	89	87	95	90	91	33
18	Punpundal	78	74	93	76	72	0
19	Terang Goodwitch	89	84	110	87	84	0
20	Coradgill	95	92	102	82	58	0
21	Gnarpurt	104	102	108	100	98	0
22	Struan	90	76	91	72	70	66
23	Rosine	97	96	97	95	94	66
24	Weering	97	No data	No data	98	95	No data
25	Martin	93	91	129	44	82	0
26	Cundare	93	No data	96	60	78	0
27	Beeac	96	No data	97	96	89	0
28	Colac	101	No data	No data	103	103	No data

Table 3
Percentage surface area of evaporites in lakes relative to shoreline.

Lake number	Lake name	December-1989	January-1991	February-1993	February-1995	January-1998	December-2006
1	Gnotuk	0	0	0	0	0	0
2	Bullen Merri	0	0	0	0	0	0
3	Purrumbete	0	0	0	0	0	0
4	Logan	0	0	0	0	0	0
5	Tooliorook	0	0	0	0	0	6
6	Koorawerra	0	0	0	0	0	0
7	Koorawerra	92	86	0	2	70	81
8	Koorawerra	0	0	0	0	0	0
9	Milangil	0	0	0	0	0	0
10	Round	0	0	0	0	0	0
11	Colongulac	0	0	0	0	0	8
12	Kariah	0	0	0	0	0	0
13	Koreetnung	0	1	0	0	0	0
14	Weeranganuk	0	0	0	0	0	0
15	Corangamite	0	0	0	0	0	13
16	Terangpom	0	0	0	0	0	12
17	Tatutong	0	0	0	0	0	99
18	Punpundal	0	1	0	2	0	81
19	Terang Goodwitch	0	7	0	0	0	79
20	Coradgill	0	0	0	0	0	0
21	Gnarpurt	0	0	0	0	0	0
22	Struan	0	0	0	0	0	0
23	Rosine	0	0	0	0	0	0
24	Weering	0	No data	No data	0	0	No data
25	Martin	0	0	0	2	0	0
26	Cundare	98	No data	94	102	44	94
27	Beeac	99	No data	98	99	95	71
28	Colac	0	No data	No data	0	0	No data

Results

Water levels and hydraulic gradients

Time series of water level data for Lakes Corangamite and Colac, are shown in Figs. 4a and 5a, respectively. Results for both lakes show the decline in lake water levels from 1997 onwards. For Lake Colac, from October-1996 to October-2005 the lake water levels have decreased by 1.04 m, and over the same time period the corrected water levels at Lake Corangamite have decreased by 2.23 m.

Groundwater flow lines during both 1992 and 2006 indicate that regionally groundwater flow is to the east; the results for winter/spring 2006 mapping are presented in Fig. 6. Horizontal hydraulic gradients vary from 3.5‰ in the northwest to 0.2‰ in the east. A comparison of hydraulic head values from pre-drought (1992) to drought (2006) indicates a decline in the water table during drought conditions. In the drier summer/autumn months the water table is on average lower by 0.73 m, and in the wetter winter/spring months the water table is on average lower by 1.24 m during the drought compared with the pre-drought conditions. Additionally there has been a decline in the seasonal variation of the water table. Prior to the drought, the water table seasonal amplitude was on average 0.55 m, whereas during the drought it is only 0.06 m.

Groundwater flow lines indicate Lake Colac is a throughflow lake (Fig. 6), and groundwater hydrograph and lake level data indicate there is no reversal in groundwater–lake hydraulic gradients during the drought (Fig. 5a). At Lake Colac, groundwater levels during the drought show an increase from 1999 to 2004 (by 0.10–0.35 m/year) and then a decrease to 2007 (by 0.56–1.15 m/year). Over the same periods lake levels show smaller magnitudes in a water level rise (0.09 m/year) and then decline (0.35 m/year),

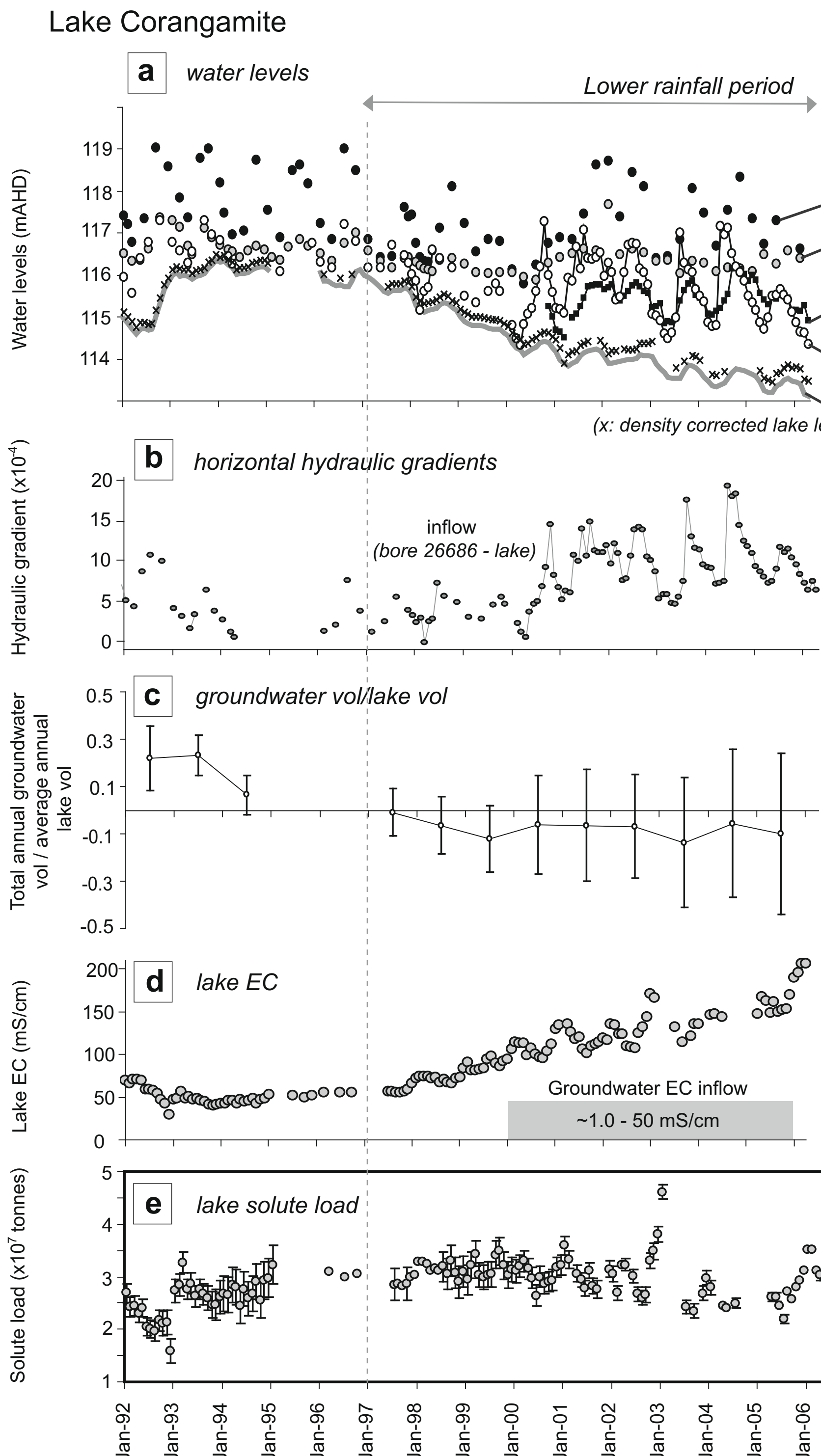

Fig. 4. Time series data for Lake Corangamite: (a) water levels for the lake and surrounding shallow groundwater; (b) horizontal hydraulic gradient from the bore 26,686 to the lake; (c) ratio of the total annual groundwater to average annual lake volume, where positive values indicate net groundwater discharge to the lake, and negative values indicate net lake recharge to groundwater; (d) lake and groundwater EC values; and (e) lake solute load.

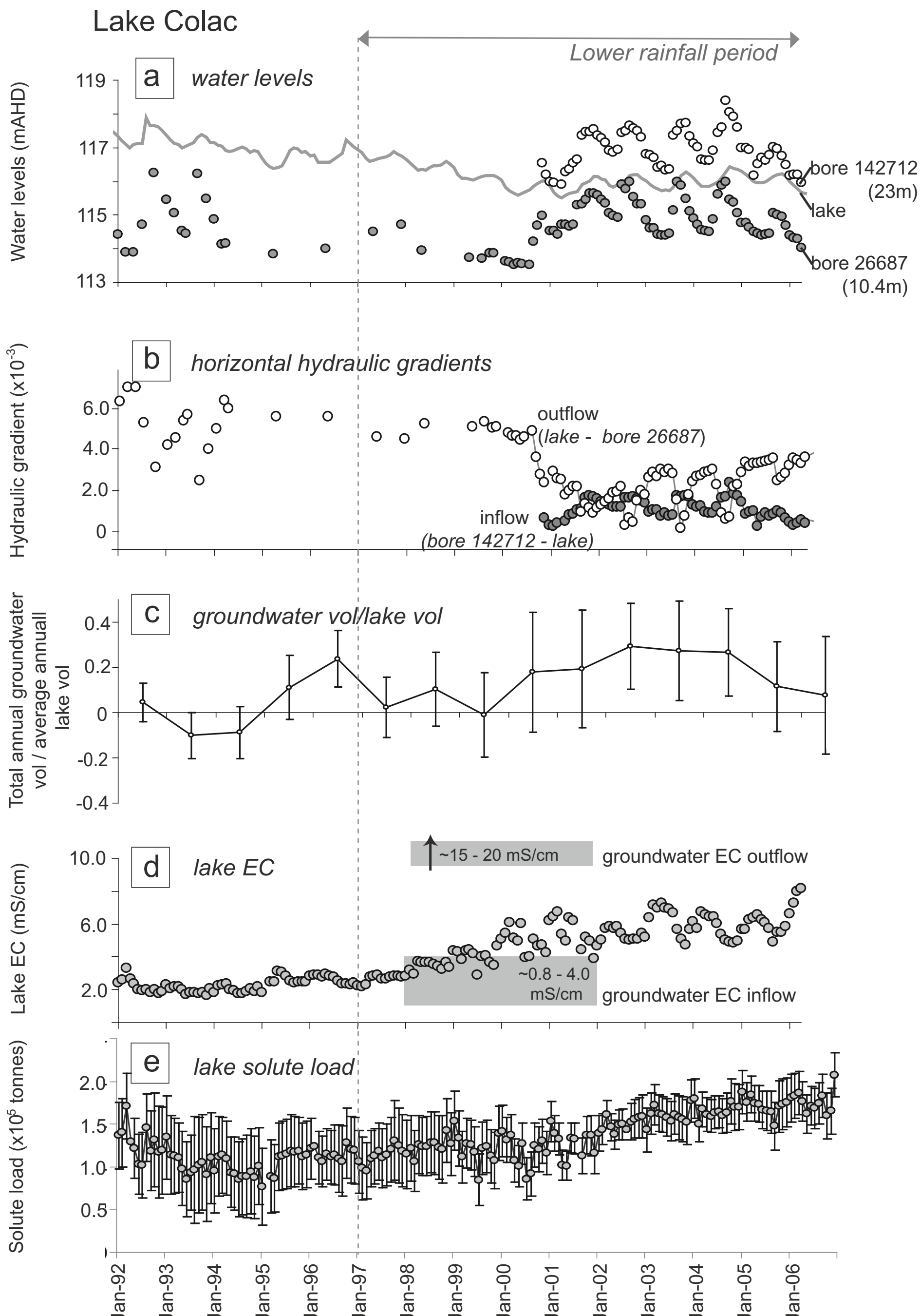

Fig. 5. Time series data for Lake Colac: (a) water levels for the lake and surrounding shallow groundwater; (b) horizontal hydraulic gradient from the bore 142,712 to the lake, and from the lake to the bore 26,687; (c) ratio of the total annual groundwater to average annual lake volume, where positive values indicate net groundwater discharge to the lake, and negative values indicate net lake recharge to groundwater; (d) lake and groundwater EC values; and (e) lake solute load.

respectively, resulting in temporal variations in horizontal hydraulic gradients (Fig. 5b). For example, from 1999 to 2004 there is an increase in the potential for groundwater inflow and a decrease the potential for lake outflow to groundwater.

The groundwater flow lines indicate that the largest lake, Lake Corangamite, is groundwater-fed (Fig. 6), however it is inconclusive whether this lake is a throughflow or discharge system. The southeast and the northeast margins of the lake lack sufficient monitoring bores to determine hydraulic gradients. From the data available, the time series highlights lake levels that decrease at a more rapid rate during the drought compared with the groundwater levels. For example, from November 2000 to November 2005 the lake levels decrease by 0.17 m/year, whereas the groundwater bore 26,686 shows decreasing hydraulic head values at 0.12 m/year (Fig. 5a). As a result the horizontal hydraulic gradients between groundwater and the lake increase during the drought (e.g. 0.11–0.63‰ from February-1997 to February-2006; Fig. 5b), therefore resulting in increased potential for groundwater inflow to the lake during the drought.

Lake water budgets

The results for the water budgets (Fig. 7) show that the major input to the lakes is from rainfall rather than from groundwater

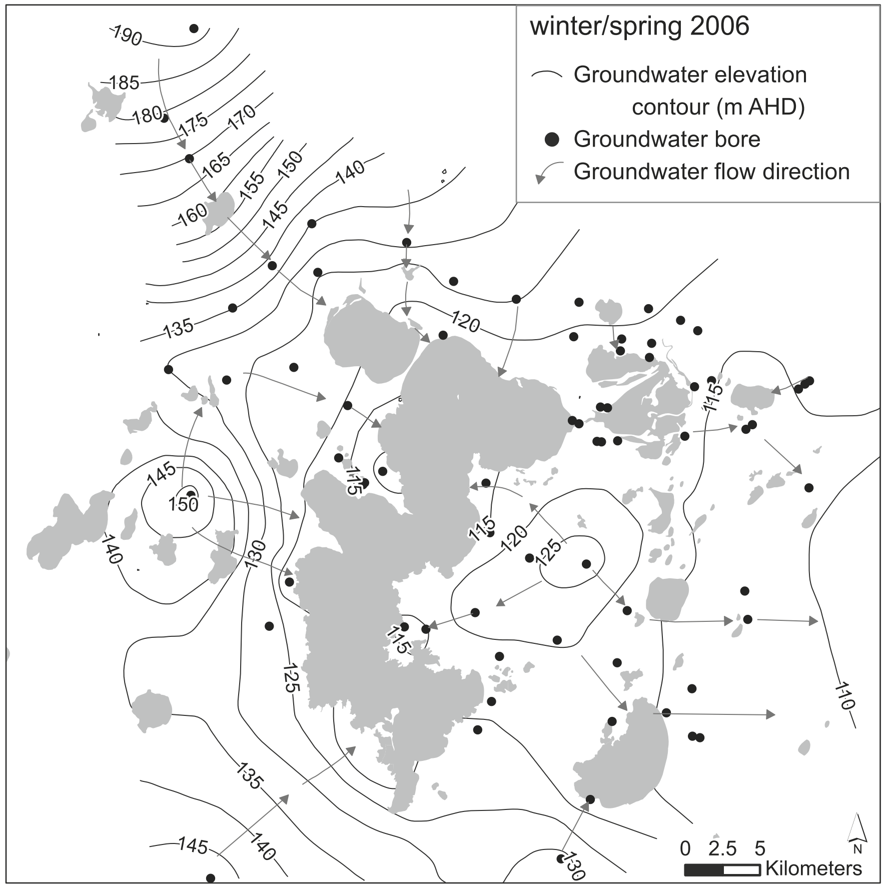

Fig. 6. Contoured water table data for winter/spring 2006 and groundwater flow directions.

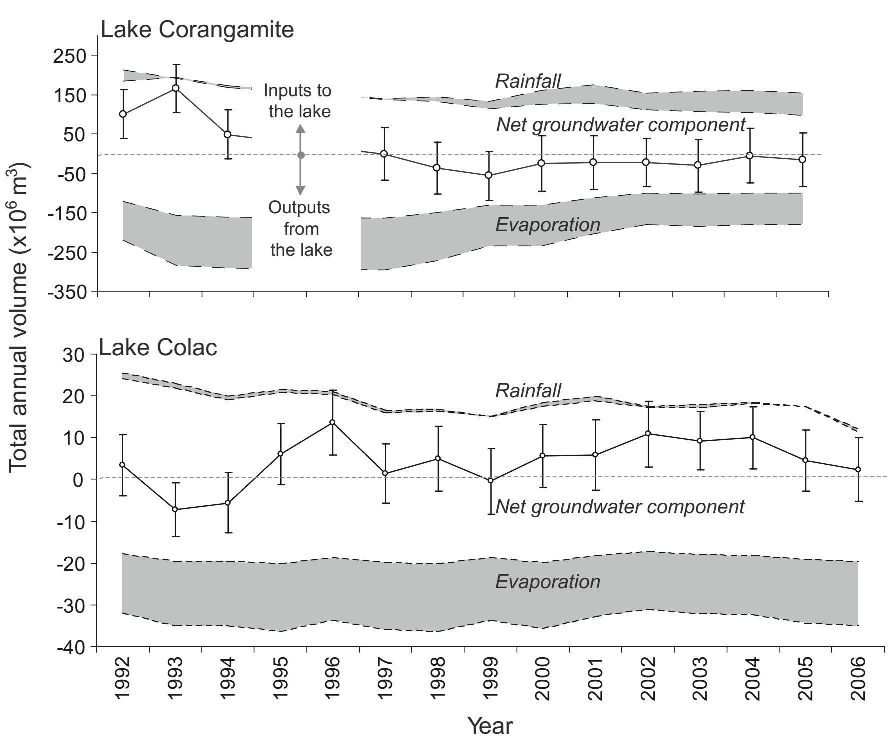

Fig. 7. Total annual volumes of the lake water budget components for Lakes Corangamite and Colac. Calculated inputs include rainfall and groundwater (where values are >0), and outputs include evaporation (where more negative evaporation values indicate increasing output from the lake) and groundwater (where values are <0). The ranges in values reflect maxima and minima input values for evaporation and rainfall.

(Fig. 7). From 1992 to 2006 the percentage of input to lakes from rainfall (calculated using the average of minimum and maximum values) ranges from 53% to 100% (mean 93%) for Lake Corangamite, and from 51% to 100% (mean 80%) for Lake Colac. In comparison, the percentage of input to lakes from groundwater ranges from 0% to 49% (mean 7%) for Lake Corangamite, and 0% to 47% (mean 20%) for Lake Colac.

The water budget results also highlight the decrease in lakes extent and volumes during the drought. Over the period 1992 to 2006, for Lakes Corangamite and Colac the surface area decreases from 250 to 140×10^6 m^2 and 29 to 25×10^6 m^2, respectively, and the volumes decrease from 800 to 150×10^6 m^3 and 100 to 25×10^6 m^3, respectively. The potential controls on the observed declines in lake water volumes (during 1992–2006) include reduced rainfall (ranges from 4 to 118 mm/month), decreased groundwater discharge to lakes, and increased lake evaporation (ranges from 39 to 239 mm/month). Even when evaporation or rainfall rates remain constant, the respective inputs and outputs to the lakes budget may vary greatly as the lake extent varies. This phenomenon is exemplified for shallow lakes.

The decline in lake volumes during the drought is primarily due to the decline in the rainfall component (Fig. 7). The maximum decrease in mean rainfall input to Lake Colac is a decrease by 50% from 1992 to 2006, and a decrease by 60% from 1992 to 1999 to Lake Corangamite. During the drought, both Lakes Corangamite and Colac show no increase in the volume evaporated. For Lake Colac, the groundwater component only begins to decline in 2004, and for Lake Corangamite, the groundwater component only declines between 1997 and 1999 (Fig. 7). Therefore, although hydrochemistry data (Cl/Br ratios and stable isotopes) indicate the lakes are groundwater-fed and subject to evaporation (Turnbull, 2006), the declines in lake levels are primarily controlled by the decline in rainfall inputs to the lakes.

The large uncertainty in the water budget, linked to estimates of rainfall and evaporation components (Fig. 7), does not allow a determination of changes in lakes from recharge to discharge systems based on the net groundwater components of the water budget. However the patterns in the groundwater component values are useful for observing rates of change and defining hydrodynamic changes during the drought. The total annual groundwater/average annual lake volume ratios highlight the varied patterns in lake–groundwater dynamics for each lake during pre-drought and drought conditions (Figs. 4c and 5c). During the drought, net mean groundwater discharge to Lake Colac increased by 30% from 1999 to 2002, and then decreased from 2004 to 2006 by 20% (Fig. 5c). These patterns are consistent with the hydrograph data and lake level patterns shown in Fig. 5a, and therefore indicate a hydraulically well-connected groundwater and lake system. In comparison, at Lake Corangamite the groundwater discharge decreases by 10% from 1997 to 1999, and then remains relatively stable for the rest of the drought period (Fig. 4c). Therefore, although the lake levels at Lake Corangamite have rapidly declined relative to groundwater levels (Fig. 4a), this has not resulted in increased flow of groundwater into the lake, and therefore indicates a low hydraulic connection between the lake and the surrounding shallow groundwater system.

Changes in lakes EC and solute loads

The time series data for EC values at Lakes Corangamite and Colac are presented in Figs. 4d and 5d, respectively. Results for both lakes show a corresponding rise in lake EC values, particularly from 1997 onwards with the decline in lake water levels. For Lake Colac, EC values from April-1998 to April-2006 have increased from 3750 to 8150 μS/cm. For Lake Corangamite, from April-1998 to April-2006 the EC values have increased from 73.7 to a maximum value of 206 mS/cm.

The solute loads for Lakes Colac and Corangamite were calculated to determine whether this 2–3 times increase in lakes salinity values were just due to on-going evaporation, or whether any increase in groundwater discharge also resulted in increased salinity. The EC of groundwater up-gradient from the lakes ranges from ~1 to 50 mS/cm at Lake Corangamite, and ~0.8 to 4 mS/cm at Lake Colac (Figs. 4d and 5d). Therefore, an increase in groundwater inflow would result in a rise of the lake solute loads.

Results of solute load calculations for Lake Corangamite show that the pre-drought and drought values are within similar ranges (Fig. 4e). The major ion chemistry for Lake Corangamite shows that it is a Na–Cl dominated brine, for example in November 2006 the Na and Cl concentrations form 94% of the TDS content. Therefore precipitation of halite is the only evaporite that will significantly affect the solute load. For all TDS measurements used to calculate the solute load in Fig. 4e, the lake is undersaturated with respect to halite. Geochemical modelling (using PHREEQC; Parkhurst and Appelo, 1999) indicate halite saturation for Lake Corangamite occurs when the lake is evaporated to a TDS value of ~300,000 mg/L, which is over twice the value observed (Fig. 4e). Therefore, since no significant halite precipitation occurs and the increase in lake TDS is generally proportional to the decrease in lake volume, evaporation is a dominant control on this lake's increase in salinity. These results are consistent with the water budget results that indicate there is no significant increase in groundwater discharge to lake Corangamite during the drought (Fig. 4c).

Lake Colac is also dominated by Na–Cl (82% of TDS content in November 2006), and undersaturated with respect to halite (saturation index = −4.0, November 2006); therefore evaporite precipitation is not affecting the solute load. During the drought Lake Colac has increasing salt load values from 1.2×10^5 tonnes in December 1996, to 2.1×10^5 tonnes in December 2006 (Fig. 5e), which is consistent with the water budget results that indicate an increase in groundwater discharge up until 2004 (Fig. 5c). These results show that during the drought (1) Lake Colac salinity values increased due to evaporation and increased groundwater discharge, whilst (2) Lake Corangamite salinity values increased due to evaporation only.

Lake inundation and evaporite mapping

Lakes inundated areas were mapped over the period 1989–2006 (Table 2), and results for December 2006 are shown in Fig. 8. The deeper volcanic crator lakes (lake numbers 1–3; average depths 15–66 m) only show 1–3% decreases in inundated areas between 1998 and 2006. All other lakes (lake numbers 4–28; average depths 0.5–6 m) show a rapid decrease in water surface area during the drought between January 1998 and December 2006 (Table 2). By December 2006 these lakes are on average 15% of their total lake area under 'normal' conditions, whereas pre-drought (1989–1998) the average lake water area covers 92% of the lake area. The first lake to dry out (lake number 4) is located highest in the landscape (by 33.4 m compared with other lakes).

Evaporite deposits in lakes were also mapped over the period 1989–2006 (Table 3). 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). For 10 of the 28 lakes evaporites are present in December 2006 (Fig. 8) and with the exception of 3 lakes (4, 27 and 28) the evaporites appear only in December 2006, which co-incides with the timing of the sharpest decline in water areas. For these 7 lakes that show an onset of evaporites during the drought, the pre-drought lake TDS content may have been relatively high compared with other lakes, as they were closer to saturation with respect to the dominant evaporite

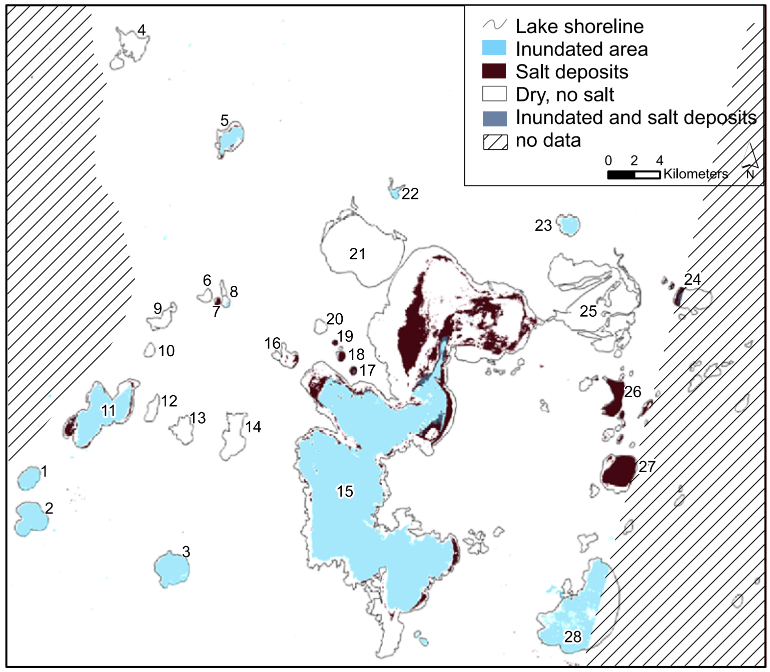

Fig. 8. Lakes water and evaporite mapping for the study area using Landsat-5TM in December 2006. Lake numbers, names and area of water and evaporites are presented in Tables 2 and 3.

minerals, or increases in lake salinity during the drought may have been more severe due to increased evaporation/lake volume ratios or groundwater discharge with high EC. In December 2006 Lake Corangamite has evaporites, and the water in November 2006 was undersaturated with respect to halite and gypsum but saturated with respect to calcite, dolomite and magnesite. Therefore, the evaporites mapped in December 2006 (Fig. 8) are likely to be calcite, dolomite and magnesite, or may be precipitation of halite and gypsum only in areas where the receding main body of water has left behind isolated pools.

Discussion

Dynamic surface water and groundwater interactions

As found by Tague et al. (2008) for stream discharge, spatial variations in the controls on groundwater discharge can often determine the surface water's sensitivity to hydrological change. For groundwater connected lakes, spatial variations in lakes and groundwater interaction will arise from the following factors (1) the hydraulic controls on groundwater flow rates (hydraulic conductivity and gradient) (e.g. Winter and Rosenberry, 1998) and storage (e.g. van Lanen et al., 2004); (2) whether the lake receives shallow (local) or deeper (regional) groundwater discharge (e.g. Tague et al., 2008); (3) location in the landscape and therefore rainfall vs. groundwater input components (e.g. Kratz et al., 1997); and (4) lake bathymetry (e.g. Delalande et al., 2008).

In the Corangamite catchment, during the drought, the groundwater-fed lakes firstly respond to declines in the rainfall component and secondly are impacted by changes in the groundwater system. In this study, the extent of changes in groundwater discharge for each lake varies. Prior to the drought, all of the 28 lakes studied were inundated, and by 2006 16 of these lakes had dried up. In comparison with lakes that did not dry up, these 16 dry lakes either had relatively low groundwater inflow rates, local groundwater discharge, are located high in the landscape or have a shallow bathymetry. For 10 of these dry lakes there were no evaporites present, therefore the principal mechanism of output, after any rainfall, is water leaving via flow through the lake bottom and recharging groundwater, rather than leaving via evaporation and resulting in the precipitation of evaporites (e.g. Cartwright et al., 2009). Therefore the drought has reversed hydraulic gradients resulting in some of these lakes changing from groundwater throughflow or discharge (e.g. Turnbull, 2006) to recharge lakes. A more delayed groundwater discharge response to the drought is observed for Lake Colac. The results from the water budget indicate that groundwater discharge has only begun to decline relative to the lake volume since 2004 (Fig. 5c). This may reflect a 7-year time lag for the drought to result in lowering local groundwater discharge to the lake, and perhaps the full impacts of this drought on Lake Colac are yet to be observed (at the time of publication this lake had dried out during February-2009).

Combined impact of drought and land use change

Changes in land use can have significant impacts on groundwater and surface water resources (e.g. Scanlon et al., 2005, 2007). In agriculturally productive regions, the impacts of climate variability on lake systems can often be difficult to discern from the impact of land use change. Studies elsewhere have found varying magnitudes of drought vs. land use impacts on the hydrologic budget. For example, in West Africa, the impacts of land clearance overrode the effects of prolonged droughts, resulting in a ∼2.5 increase of the drainage density and a 4 m rise in groundwater levels in the second part of the 20th century (Leblanc et al., 2008; Favreau et al., 2009). In Australia, the land clearing during European settlement has had significant impacts on the hydrologic budget. In regions of South-East Australia where native vegetation included deep-rooted trees, land clearance resulted in rising groundwater levels due to increased groundwater recharge (Allison et al., 1990). In these areas, rising groundwater levels due to land clearing resulted in increased lake water levels and salinity (secondary salinity) of groundwater-fed lakes (Williams, 2001). The recent multi-year drought has reversed this groundwater level rising trend inherited from land clearing, with observations in the Murray-Darling Basin showing that on average the water table has declined by ~1 m between 2001 and 2008 (Leblanc et al., 2009).

In comparison, for the Corangamite region the shift from native grasslands to pastures and crops during European settlement did not have as significant impact on the groundwater levels, and during the Quaternary period, saline groundwater and lake water was already a feature of the region (e.g. Dahlhaus et al., 2008). Therefore unlike in other regions of South-East Australia, land use change did not impact storage and water quality in the Corangamite lake system and the impact of the on-going drought can be isolated. Previous investigations within the study area have also highlighted that before the drought the lakes water quality (1984–2000; Tibby and Tiller, 2007) and across longer-term monitoring periods the lake levels (1840–1990; Jones et al., 2001) have been more strongly impacted by changes in the climate rather than land use. For example, the drought has already had a greater impact on Lake Corangamite compared with a major water diversion from ~1960 to 1986. The surface water diversion resulted in a decline in water levels by 2.3 m and doubled the lake salinity values over the 26 year period (Williams, 1995; Timms, 2005). In comparison, as a result of the drought the lake salinity values at Lake Corangamite were already ~2.8 times greater over just a 9 year period to 2006.

Vulnerability of groundwater connected lakes to climate variability

Identifying the temporal and spatial variations in the sensitivity of lakes to climate variability is essential in managing catchments (e.g. Gustard et al., 2004). As observed in this study, local variations in hydraulic connectivity and bathymetry can result in some groundwater-fed lakes that are more immediately vulnerable to drying up in the event of droughts. The more drought-resistant lakes (in 2006 43% of lakes studied) offer essential refuge areas to water birds, however increases in salinity as observed during the drought can have detrimental impacts on lakes biota (e.g. Williams, 2002), which means these drought-resistant lakes may no longer support all dependent ecosystems.

Determining whether the current drought in South-East Australia is due to natural climate variability or climate change is also critical for effective management of the lakes and associated ecosystems. Enhanced greenhouse gas concentrations are likely to be an influence on rising temperatures in South-East Australia and exacerbate the dry conditions – a phenomenon not observed during previous prolonged droughts (Murphy and Timbal, 2008). Using a statistical downscaling technique, Timbal and Jones (2008) showed that the recent rainfall decline in South-East Australia may be explained by a shift to higher pressures and lower atmospheric precipitable water in the region. Applying the same downscaling technique to five global climate models, suggest that winter rainfall in the region is likely to decline in the future as greenhouse gas concentrations increase (Timbal and Jones, 2008). The severe impact of the multi-year drought described in this paper gives an indication of the vulnerability of the Corangamite lakes system to climatic change and confirms the urgent need to reconsider the full impact of climate change on the regional water resources and associated ecosystems (e.g. Milly et al., 2008).

Conclusions

In this study, the observations of drought impacts on lakes–groundwater interactions and lakes salinity are presented for a large catchment in South-East Australia. Integrating satellite remote sensing with on-ground field monitoring data to perform mapping, water budget and solute budget analysis provided the spatial and temporal datasets required for the determination of historical dynamics between lakes and groundwater interaction. The loss of water during the drought for the 28 lakes studied amounts to a decrease in inundated surface area of 220×10^6 m^2 (from 1993 to 2006), which is a 60% decrease. For 2 lakes where volumes were calculated, the drought has resulted in a total loss of 714×10^6 m^3 (1993 to 2006), which is an 80% decrease. The drought-induced changes on the hydrologic budget have resulted in hydraulic gradient reversals in some of the lakes; where 36% of the lakes monitored changed from throughflow or discharge to recharge lakes. Additionally, the increased salinization during the drought is characterized in this study by lakes with evaporite deposits, and for 25% of these lakes remote sensing data highlights that pre-drought they were previously evaporite free. This study also highlights the spatial variability on the rate of change for different lakes within the catchment, and the non-uniform vulnerability of lakes to a regional stressor such as the drought.

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