



Stable isotopes as indicators of water and salinity sources in a southeast Australian coastal wetland: identifying relict marine water, and implications for future change

Matthew J Currell · Peter Dahlhaus · Hiroyuki Ii

Abstract The Lake Connewarre Complex is an internationally protected wetland in southeast Australia, undergoing increasing environmental change due to urbanisation. Stable isotopes of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and other geochemical indicators were used to assess sources of water and salinity in the shallow groundwater and surface-water systems, and to better understand groundwater/surface-water interactions. While much of the shallow groundwater is saline (from 1.27 to 50.3 g/L TDS) with overlapping salinities across water groups, stable isotopes allow clear delineation of two distinct sources of water and salinity: marine water with $\delta^{18}\text{O}$ between -1.4 and $+1.3$ ‰ and ion ratios characteristic of seawater; and meteoric water with $\delta^{18}\text{O}$ between -6.1 and -3.6 ‰ containing cyclic salts, probably concentrated by plant transpiration. Groundwater bodies in shallow sediments beneath the wetlands have salinities and stable isotopic compositions intermediate between fresh wetland surface water and a marine water end-member. This marine-type water is likely relict seawater emplaced when the wetlands were connected to the estuary, prior to modern river regulation. Freshwater input to underlying groundwater is a recent consequence of this regulation. Future predicted changes such as increased stormwater inflow, will increase rates of freshwater leakage to shallow

groundwater, favouring the proliferation of exotic reed species.

Keywords Stable isotopes · Salinity · Groundwater/surface-water relations · Wetlands · Australia

Introduction

There is increasing pressure on wetlands in many areas globally due to encroaching urban growth, among other threats (Lee et al. 2006; Azous and Horner 2010). Urbanisation creates major hydrological changes such as increased managed and unmanaged stormwater runoff, leakage of imported water into shallow aquifers (Lerner 2002) and changes to nutrient and other solute loads (Baker 2003; Hatt et al. 2004). These changes can have major effects on groundwater and surface-water hydrology, upon which wetland ecosystem structure and function depend (e.g. Bellio and Kingsford 2013). Coastal wetlands are typically some of the most complex hydrological environments, as they represent the meeting of fresh and saline systems, and are points of converging groundwater flow (Toth 1999; Fan et al. 2013). Understanding the hydrological dynamics of these systems, including the role of groundwater/surface water-interaction, saltwater–freshwater mixing and eco-hydrological relationships, is vital for predicting and assessing future changes to coastal wetlands under increasing pressure from urbanisation (e.g., Gattacceca et al. 2009).

In this paper, geochemical indicators are used to better understand hydrological conditions and processes in the Lake Connewarre Complex on the lower Barwon River, a Ramsar-listed coastal wetland in southeast Australia. The wetland complex is located in the City of Greater Geelong—an area set to experience substantial urban population growth in the coming decade (Fig. 1). The main objectives were to determine the major sources of water and salinity in the groundwater and surface water; investigate evidence for mixing and exchange between these waters, and document relationships between vegetation and water chemistry. Stable isotopes of water, used in conjunction with other hydrochemical indicators, are recognised as a powerful tool in the determination of salinity sources in groundwater and surface-water systems in coastal environments (e.g., Vengosh et al. 1999, 2005;

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M. J. Currell (✉)
School of Civil, Environmental and Chemical Engineering,
RMIT University, GPO Box 2476, Melbourne, 3001, Australia
e-mail: matthew.currell@rmit.edu.au
Tel.: +61 3 99250402

P. Dahlhaus
Centre for Environmental Management,
Federation University Australia, Mt Helen, Australia

H. Ii
Faculty of Systems Engineering,
Wakayama University, Wakayama, Japan

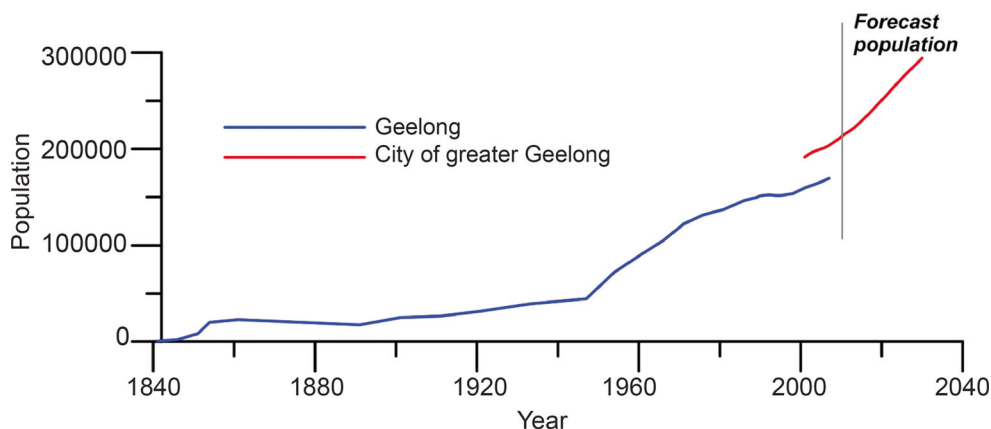


Fig. 1 Historical and projected population growth in the City of Greater Geelong, Australia. Data from .id (2013)

Carreira et al. 2014), including estuaries (Price et al. 2012). The hydrological balance of this system and others like it is a central determinant on ecosystem function (Lloyd et al. 2012). However, at present, detailed characterisation of these eco-hydrological relationships is hampered by a lack of understanding of groundwater and surface-water sources and interactions. The results of this study will allow future water management (e.g. water planning in new urban developments; wetland environmental watering plans) to make more informed judgements about the impacts of proposed actions on the future ecological health of these and other sensitive coastal wetland systems.

Background and setting

The Lake Connewarre Complex (LCC) is a ~20 km long, tidal shallow lake and estuarine system on the lower reaches of the Barwon River, located between Geelong and Barwon Heads on the southeast Australian coast (Fig. 2). The wetlands comprise Lake Connewarre, Reedy Lake, Hospital Swamps and Salt Swamp (Fig. 2). The system is protected as a Wetland of International Importance under the Convention on Wetlands (Ramsar Convention). It is home to a diverse range of flora and fauna, particularly birds, of which up to 199 species have been identified (Dept. of Environment and Primary Industries Victoria 2013)—this includes 20 species listed under the Japan–Australia Migratory Birds Agreement (JAMBA); 25 under the China–Australia Migratory Birds Agreement (CAMBA) and one listed as endangered under the Commonwealth of Australia’s Environment Protection and Biodiversity Conservation Act (1999).

Wetland hydrology

The LCC is already a highly modified and managed hydrological system. River regulation began in the late 19th century, with construction of a breakwater (weir) in 1898 to limit tidal ingress along the Barwon River to the establishing city of Geelong. Prior to this, Reedy Lake and

Hospital Swamps would have been connected to the estuary and subject to direct tidal inflow of marine water. In the late 1950s, the breakwater was replaced with a floating barrage structure, to regulate river levels (Fig. 2). Additionally, a set of channels (inflow and outflow from different parts of the wetlands) were cut to allow greater control of lake water levels. As a result of these actions, Reedy Lake and Hospital Swamps have been essentially cut off from the tidal estuary for over a century, now receiving water almost exclusively from freshwater inflows from the Barwon River (Fig. 2). In contrast, Lake Connewarre has remained connected to the estuary. Over recent years, managed watering regimes have been implemented by means of carefully regulating the inflows from the Barwon River, and outflows from Reedy Lake and Hospital Swamps, with the aim of improving or maintaining ecological, recreational and commercial values (Ecological Associates 2006; Lloyd et al. 2012; Corangamite Catchment Management 2013).

Geology, terrain and hydrogeology

The area surrounding Reedy Lake and Hospital Swamps is planar and low-elevation; Fig. 3 shows a digital elevation model (DEM). Much of the area occupied by and surrounding the wetlands is less than 2.5 m above current sea level—0 m relative to Australian Height Datum (AHD)—and parts of the area were inundated during the mid-Holocene maximum, when sea level was approximately 2 m above present levels approximately 6,000 years BP (Gill and Lane 1985; Marsden 1988; Belperio et al. 2002; Sloss et al. 2007).

The surface and shallow geology of the region is shown in Figs. 4 and 5, which also indicate the location of groundwater and surface water monitoring sites for this study. Various interpretations of the geology and geomorphological evolution have been previously documented (e.g. Rosengren 1973; Bird 1993; Holdgate et al. 2001; Holdgate and Gallagher 2003; Dahlhaus et al. 2007). The basement rock comprises Otway Group mudstones and sandstones of Cretaceous age. Overlying the basement are a series of Palaeogene and Neogene sediments of terrestrial and marine origins, with sands associated with

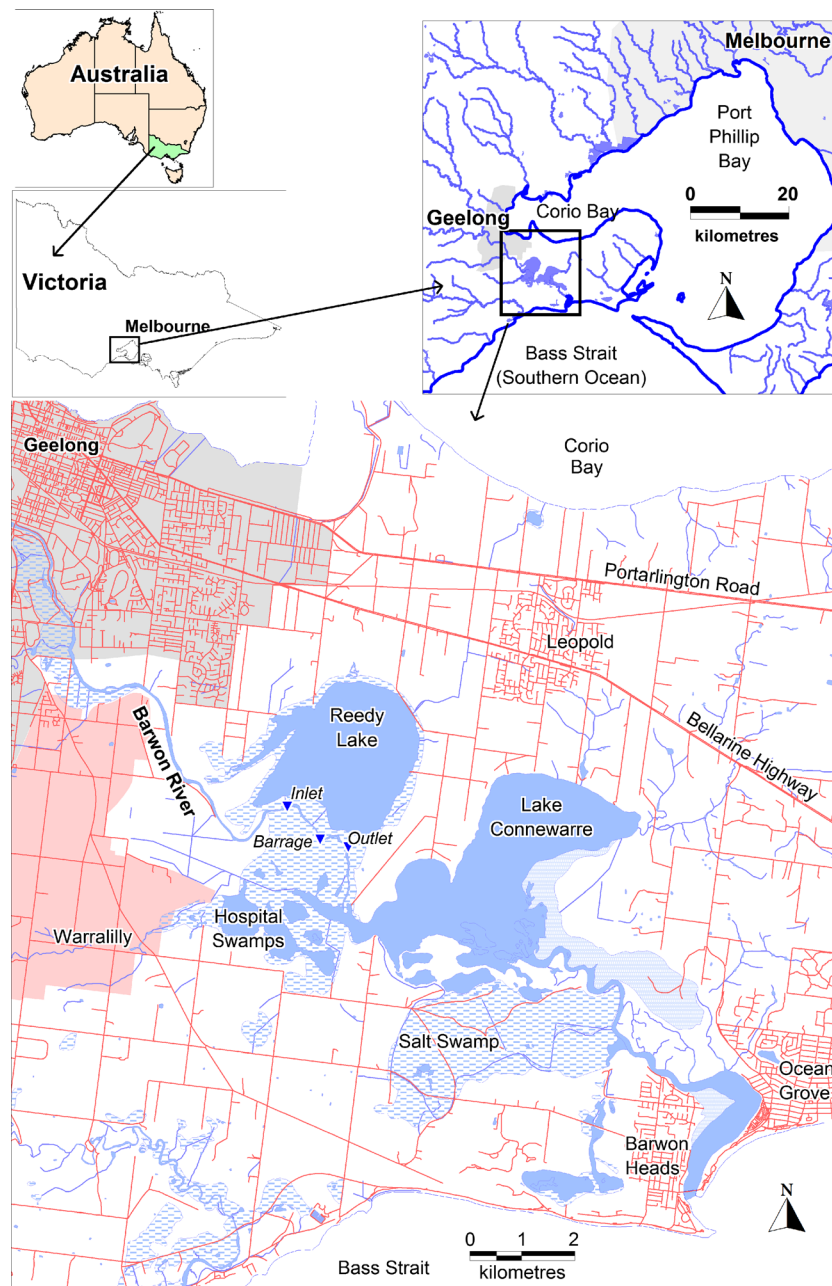


Fig. 2 Location of the *Lake Connearre Complex* and surrounding land uses. *Grey shading* is existing urban area of the City of Greater Geelong; *pink shading* is designated new development area

the Pliocene marine transgression (Moorabool Viaduct Formation), and basalts of the Plio-Pleistocene Newer Volcanic Formation prominent at the surface. Many of the Quaternary sediments in the immediate vicinity of the wetlands and in the bed of the lakes have formed since the most recent sea-level maximum at ca. 6,000 years BP.

Groundwater in the region is generally characterised by low hydraulic gradients, reflecting the flat topography, but regionally it flows south-eastwards towards Reedy Lake and the mouth of the Barwon River. The major regional shallow aquifers are the Newer Volcanics, consisting of fractured basalt and occurring on the southern side of the wetlands; and sedimentary aquifers on the northern side, including the

Fyansford Formation and Moorabool Viaduct Formation (Neogene) and Quaternary alluvial terraces (Fig. 4). Above this sits a local groundwater system comprising the Holocene aged alluvial, lacustrine, paludal and lagoonal sediments in the lakebed of the wetlands (Figs. 4 and 5). Groundwater flow on the southern side of the wetlands is controlled by presence and morphology of the basalt, which in-filled a prior valley in the historic topography (Rosengren 1973), and may act as a kind of palaeo-channel conduit for groundwater flow. Groundwater monitoring wells have been constructed surrounding the LCC in these aquifers, including in the top ~3 m of sediment in the beds of Reedy Lake, Hospital Swamps and the banks of the Barwon River (Figs. 4 and 5).

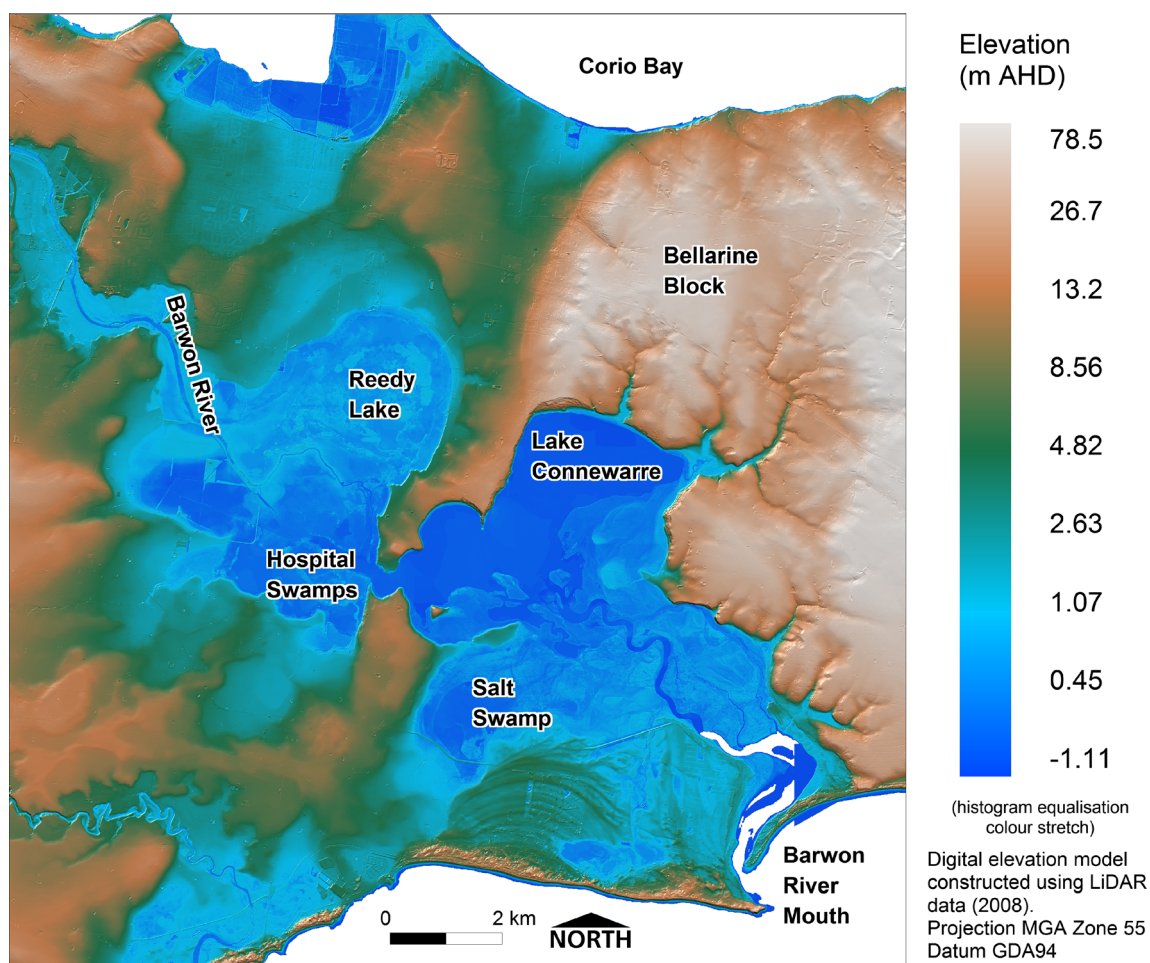


Fig. 3 Digital elevation model of the study region constructed from airborne light detection and ranging (LiDAR) surveys

Methods

Groundwater and surface-water sampling were carried out over a series of field campaigns between 2006 and 2013, with most sites sampled and analysed three or more times in that period. The sampling sites are shown in Fig. 4, and incorporate groundwater from the main shallow aquifer units, and surface water both upstream (fresh) and downstream (saline) of the barrage structure in the river. Groundwater samples were collected from monitoring bores made from 50-mm internal diameter PVC, with slotted screens surrounded by a sand filter pack below bentonite seals. The screen intervals in monitoring bores are from 1 to 3 m in length (screen interval depths are indicated in Table 1 and indicated in Fig. 5) using portable electric submersible pumps; in general, bores were fully purged and allowed to recover at least once prior to sampling, or in cases where drawdown was limited, sampling occurred after stabilisation of physio-chemical parameters—pH, electrical conductivity (EC) and oxygen-reduction potential (ORP). Surface-water samples were collected using a bucket; lake and river depths at the sampled sites were all relatively shallow (<2 m) and, hence, salinity stratification with depth is considered unlikely. All samples were filtered in the field with 0.45- μm syringe filters. For cation analysis, the samples were acidified using concentrated distilled nitric acid to pH \sim 2.

Cations and anions were measured at Wakayama University, Japan and CSIRO Land and Water (Adelaide laboratories), using ICP-MS and ion chromatography.

Water stable isotope contents ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) were analysed at Wakayama University, Japan, using a GEO 20–20 dual-inlet mass spectrometer, with preparation unit and water equilibration device (WES) system (SerCon, Limited, UK); 1-ml aliquots of water were added to glass vessels and equilibrated with CO_2 for $\delta^{18}\text{O}$ or H_2 for $\delta^2\text{H}$, while the equilibration temperature and time were 35 °C and 10 h, respectively. The reproducibility (standard deviation) achieved in the analyses was ± 1.0 ‰ for $\delta^2\text{H}$ and ± 0.05 ‰ for $\delta^{18}\text{O}$. The results are expressed with δ notation (permil deviation [‰]) of the isotopic ratio in a water sample from VSMOW).

Radiocarbon was analysed in four groundwater samples using accelerator mass spectrometry at the SSAMS Radiocarbon Dating Centre at Australian National University, following the procedure outlined in Fallon et al. (2010). The $\delta^{13}\text{C}$ values of these samples were also analysed at CSIRO Land and Water (Adelaide), using Isotope Ratio Mass Spectrometry. A summary of the groundwater quality and isotopic results is presented in Table 1, while a full list of all isotopic and major ion analysis results is presented in Appendix 1 of the (ESM).

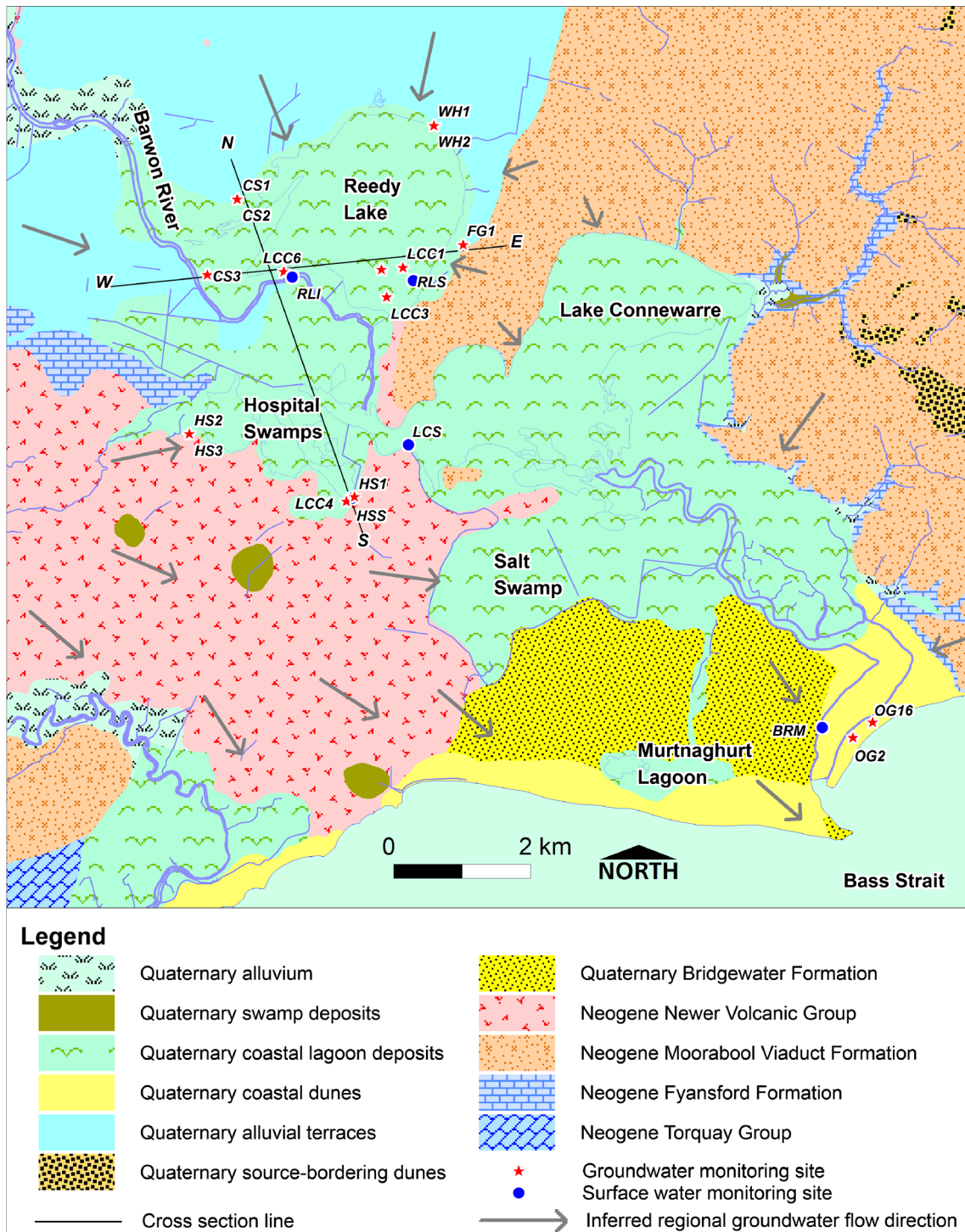


Fig. 4 Map of surface geology and groundwater/surface-water sampling locations

Results

Salinity and stable isotopes

A wide range of salinities—from 1.27 to 50.3 g/L total dissolved solids (TDS)—and stable isotopic compositions ($\delta^{18}\text{O}$ from -4.72 to $+7.46$ ‰; $\delta^2\text{H}$ from -29.4 to $+40.2$ ‰) were observed in the groundwater and surface water (Table 1; Fig. 6), which reflects the wide range of

water compositions present in coastal wetland systems, including fresh and evaporated river water, marine water inputs, and groundwater from different flow systems that converge at the coast. Stable isotopic compositions of waters in the system are shown on Fig. 6, along with the Melbourne local meteoric water line (LMWL), average weighted mean Melbourne rainfall, and standard oceanic water (VSMOW). In some cases, groundwater and

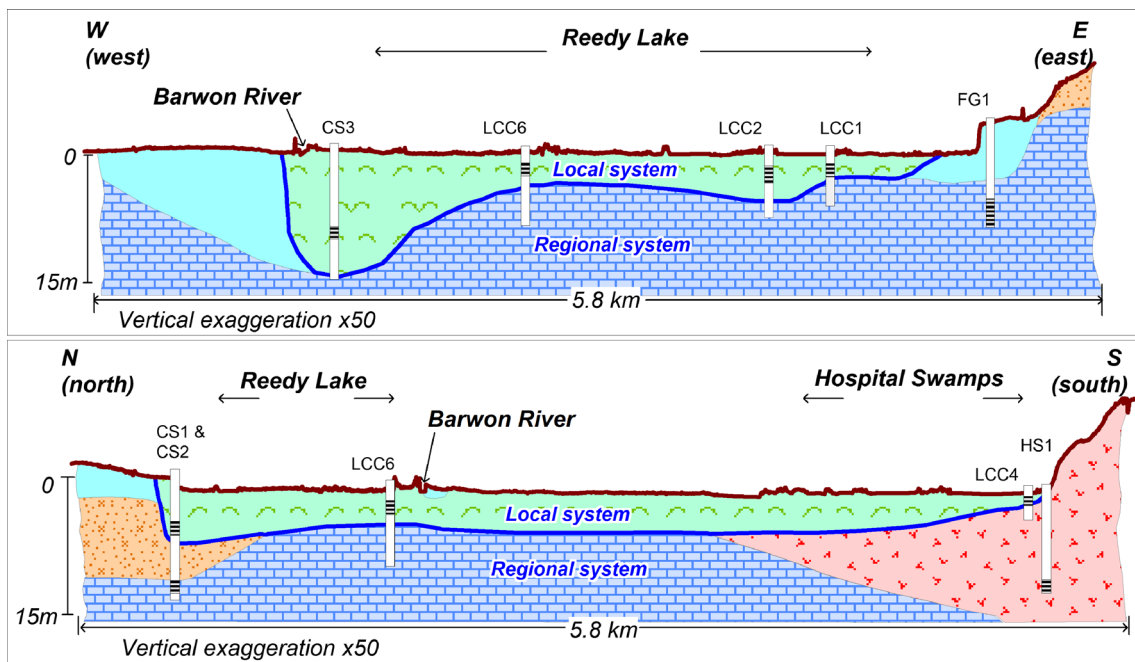


Fig. 5 Cross sections of the shallow geology below the wetlands. Grey shading indicates monitoring bore screen intervals. For groundwater salinity data, refer to Table 1. Lines of section indicated on Fig. 4. Legend as for Fig. 4

surface-water isotope values group near these two end-members (rainfall and ocean water); in other cases they have intermediate compositions between the two, while in others they plot outside the range of rainfall and oceanic water along an evaporation trend line, with a slope of ~ 5.2 (Fig. 6).

Surface water

Surface water exhibits a range of salinities, from freshwater sampled in the river and lakes upstream of the barrage (0.72–6.92 g/L), to estuarine water (6.07–39.4 g/L) downstream of the barrage in Lake Connewarre and at the mouth of the river. On some occasions, salinities in Lake Connewarre or immediately downstream of the barrage are relatively fresh (one sample = 6.07 g/L TDS), indicating that following river floods, freshwater temporarily dilutes the normally saline lake. The stable isotope compositions of the fresh surface water in Reedy Lake and Hospital Swamps are strong evidence of evaporative concentration—e.g., $\delta^{18}\text{O}$ values from +3.4 to 7.5 ‰ in Hospital Swamps and -0.1 to +1.1 ‰ in Reedy Lake; this is most pronounced in summer when surface-water levels are relatively low (e.g. <0.7 m AHD). The evaporative concentration results in only relatively minor increases in salinity of these surface waters, from typical river-water compositions of ~ 1.5 g/L up to salinities of 3.1 g/L in Reedy Lake and 6.9 g/L in Hospital Swamps. These waters are still much less saline than surface water downstream of the tidal barrage (salinities of up to 39.4 g/L), which consistently has $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values near standard marine water (e.g. $\delta^{18}\text{O}$ between +0.1 and 1.3 ‰).

Lakebed groundwater

Groundwater sampled from a series of shallow bores along the channel of the Barwon River and in the beds of Reedy Lake and Hospital Swamps (sample codes LCC) exhibit a wide range of salinities, from 2.15 to 50.3 g/L TDS. Near the inlet of the Barwon River into Reedy Lake, shallow groundwater is fresh (2.15–4.94 g/L), with moderate evaporative concentration indicated by elevated stable isotopic compositions (e.g., $\delta^{18}\text{O}$: -1.8 to -0.3 ‰). Near the outlet of Reedy Lake (near Lake Connewarre) hyper-saline groundwater was found in bore LCC3, with TDS values between 39.0 and 50.3 g/L. This water has stable isotopic compositions similar to but slightly lower than standard seawater ($\delta^{18}\text{O} = -2.0$ to -0.8 ‰, $n=3$).

The groundwater sampled in three bores (LCC1, LCC2 and LCC4) that are screened in the lakebed sediments of Reedy Lake and Hospital Swamps (below permanent surface water), has TDS contents between 9.1 and 29.2 g/L, with stable isotopic values between -0.2 and $+4.9$ ‰ for $\delta^{18}\text{O}$ and -1.1 to 25.1 ‰ for $\delta^2\text{H}$. The salinity and stable isotopic compositions are generally intermediate between the evaporated surface water sampled in the wetlands, and a marine water end-member similar to standard oceanic water (Fig. 6; see further discussion in “Salinity and water sources”).

Regional groundwater

Groundwater in the sedimentary aquifers (the Fyansford and Moorabool Viaduct formations, sites CS1, CS2, WH1, FG1) located on the northern side of the wetlands has TDS contents ranging between 14.3 and 34.8 g/L, and stable isotopic values from -5.9 to -3.7 ‰ for $\delta^{18}\text{O}$ and -29.4 to -20.9 ‰ for $\delta^2\text{H}$. In contrast with the other

Table 1 Site details, field parameters and selected isotopic data, from samples taken 2006–2013. Full data are available in Table S1 of the electronic supplementary material (ESM)

Bore ID	Sample location (map grid of Australia zone 55 coordinates)		Screen interval (depth in m below surface as Australian height datum)	Total samples (2006 to 2013)	Sample type	EC (mS/cm)		pH		Stable isotopes of water		Carbon isotopes	
	Easting	Northing				Min	Max	Min	Max	$\delta^{18}\text{O}$ (‰) (min; max)	$\delta^2\text{H}$ (‰) (min; max)	$\delta^{13}\text{C}$ (‰)	$\delta^{14}\text{C}$ (pMC ^a)
LCC1	274927	5767402	1.5–3.0	5	Lakebed groundwater	15.1	18.5	6.8	7.2	0.1; 0.4	2.3; 4.6	–	–
LCC2	274616	5767373	1.5–2.5	5	Lakebed groundwater	18.1	25	7.3	7.8	–0.2; 1.4	–1.1; 4.5	–	–
LCC3	274692	5766968	2.0–3.5	4	Lakebed groundwater	60	77	6.8	7.2	–2.0; –0.8	–11.4; –2.3	–	–
LCC4	274102	5763977	0.5–1.5	5	Lakebed groundwater	14	45	6.6	7.7	0.1; 4.9	3.8; 16.7	–	–
LCC6	273187	5767341	1.2–2.7	4	Lakebed groundwater	3.3	7.6	6.6	7.4	–1.8; –0.3	–12.6; –2.2	–	–
CS3	272070	5767295	8.55–10.05	2	Quaternary sediments	35.2	40.9	7.3	7.7	–1.3; –0.6	–5.5; –4.2	–7.5	33.7
OG16	281795	5760737	2.0–5.0	2	Quaternary sediments	0.63	2.2	7.1	7.1	–6.1; –4.8	–30.9; –26.2	–	–
WH2	275383	5769481	2.5–4.0	3	Quaternary sediments	53.4	58.7	7.4	31.8	–4.4; –3.6	–25.2; –20.6	–	–
CS1	272508	5768399	11.2–12.7	3	Regional groundwater (Fyansford)	34	37.2	7.0	7.2	–4.4; –3.6	–24.6; –22.4	–	–
CS2	272506	5768401	4.75–6.25	3	Regional groundwater (Moorabool Viaduct)	24	29.1	7.0	7.2	–4.6; –4.2	–26.3; 25	–	–
FG1	275810	5767736	8.6–11.6	3	Regional groundwater (Fyansford)	22.3	31.9	7.0	7.1	–5.9; –4.9	–29.4; –26.7	–	–
WH1	275383	5769482	6.5–8.0	3	Regional groundwater (Moorabool Viaduct)	25	34.4	7.0	7.2	–4.7; –3.7	–29.4; –20.9	–9.8	73.5
OG2	281506	5760514	16.7–19.7	2	Regional groundwater (Newer Volcanics)	47	58.6	7.4	7.4	0.5; 0.6	2.9; 3.4	–	–
HS1	274220	5764045	9.55–11.05	3	Regional groundwater (Newer Volcanics)	49.9	57.5	7.5	8.1	–1.2; –0.4	–11.1; –2.9	–18.6	49.45
HS2	271805	5764967	13.5–15	3	Regional groundwater (Newer Volcanics)	14.0	19.4	7.2	7.7	–4.4; –4	–27.8; –25.3	–15.4	77.6
HS3	271806	5764967	4.5–6.0	3	Regional groundwater (Newer Volcanics)	12.0	17.0	7.3	7.6	–4.6; –4.5	–28.8; –26.5	–	–
Hospital Swamps Surface (HSS)	274188	5764024	–	3	Surface water	10.6	40.1	9.0	9.9	3.4; 7.5	15.4; 40.2	–	–
Reedy Lake Inlet (RLI)	237311	5767261	–	3	Surface water	1.95	2.50	8.1	8.4	–3.4; –2.8	–18.6; –16.2	–	–
Reedy Lake Surface (RLS)	275079	5767212	–	2	Surface water	2.94	4.8	7.0	8.4	–0.1; 1.1	–0.8; 6.7	–	–
Lake Connewarre Surface (LCS)	275009	5764806	–	4	Surface water	9.34	62.5	8.3	8.5	0.2; 1.3	1.5; 12	–	–
Barwon River Mouth (BRM)	281059	5760662	–	5	Surface water	53	55	8.2	8.3	0.3; 0.9	4.6; 8.3	–	–

^a $\delta^{14}\text{C}$ is radiocarbon activity, expressed as percent modern carbon (pMC)

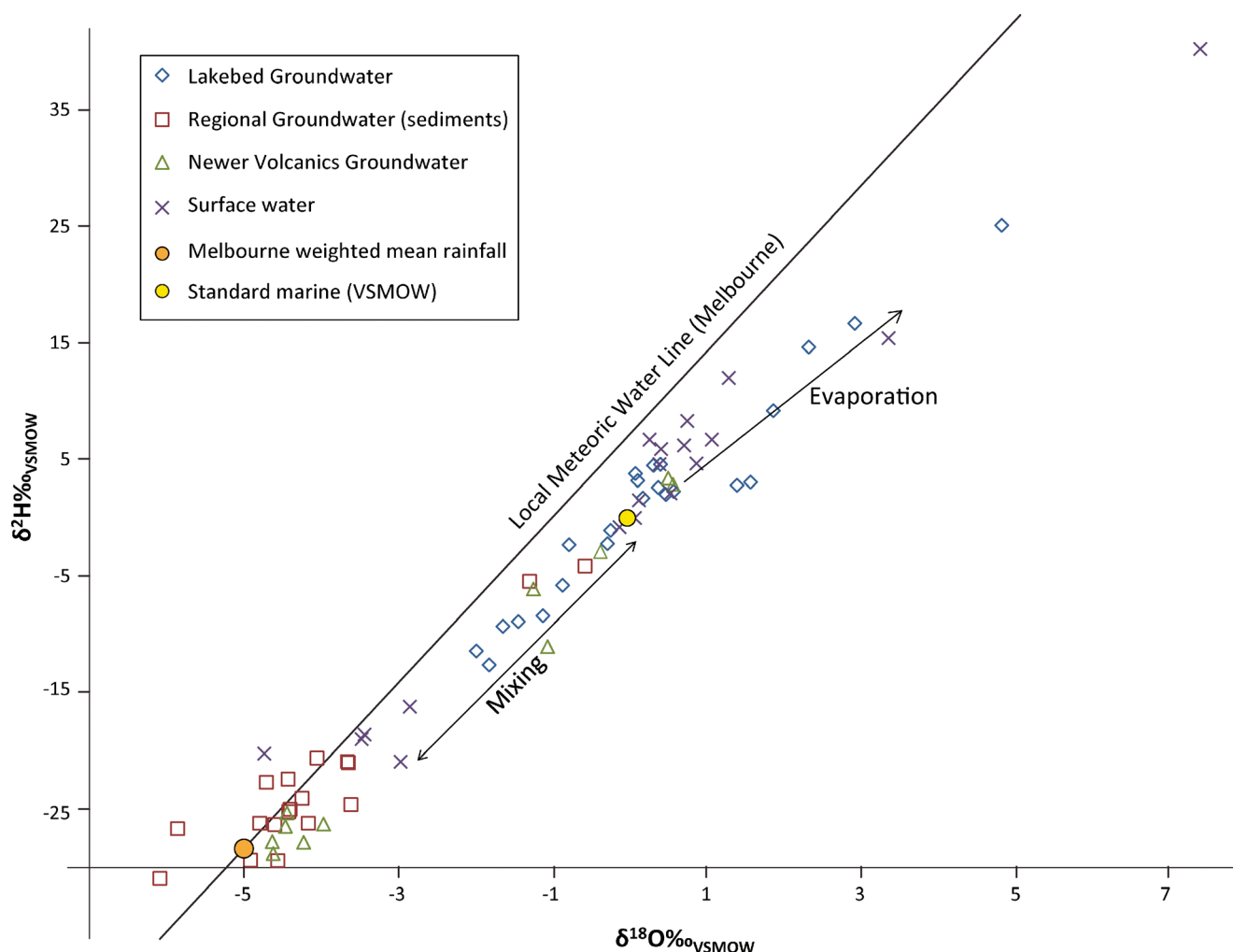


Fig. 6 Stable isotope compositions of groundwater and surface-water samples from the LCC collected between 2006 and 2013. *LMWL* local meteoric water line; data from IAEA-WMO Global Network for Isotopes in Precipitation

groundwater samples in the system, these isotopic compositions are more depleted, and are similar to weighted mean Melbourne precipitation ($\delta^{18}\text{O} = -5.0\text{‰}$ and $\delta^2\text{H} = -28\text{‰}$; Fig. 5). In the Newer Volcanics aquifer, located on the southern side of the wetlands (sites HS1, HS2 and HS3), salinities range from 7.74 to 34.2 g/L, and stable isotopic values from -4.6 to -0.35‰ for $\delta^{18}\text{O}$ and -28.8 to -2.9‰ for $\delta^2\text{H}$, with one sampling location in particular (HS1) showing a stable isotope composition and salinity that is similar to standard seawater (mean: $\delta^{18}\text{O} = -0.87\text{‰}$; $\delta^2\text{H} = -6.70$, $n=3$)

Major ion chemistry

The key major ion compositions of the groundwater and surface water are shown in Fig. 7. Much of the saline water has ion compositions similar to ocean water, with sodium–chloride dominance; freshwater also tends to have chemistry resembling dilute marine water (Na–Cl dominated), with locally increased bicarbonate concentrations, Ca/Cl and Mg/Cl ratios, particularly in the lakebed groundwater.

Molar Na/Cl ratios (Fig. 7a) range from 0.62 to 0.98 overall, with the majority of samples close to the typical oceanic ratio of 0.8. The general lack of variability in the cation/chloride ratios across a wide range of salinities in both groundwater and surface water (Fig. 7) are consistent with most water consisting of marine derived solutes—either marine aerosol delivered in rainfall, or the primary water source being ocean water. Some minor depletion of Na relative to Cl is apparent in the most saline regional groundwater (Fig. 7a; Na/Cl ratios <0.7), while enrichment of Mg, and particularly Ca relative to standard marine water is evident, particularly in the lakebed groundwater (e.g., molar Mg/Cl ratios up to 0.2 and Ca/Cl ratios up to 0.13). This probably reflects inputs from carbonate mineral weathering in the sedimentary aquifers (where shell deposits are notably abundant), and minor vein calcite in the basaltic aquifer. The molar Cl/Br ratios in the groundwater and surface water (Fig. 7d) are similar to oceanic water ratios across the full range of salinities, ranging between 600 to 1,200 (Herczeg and Edmunds 2000).

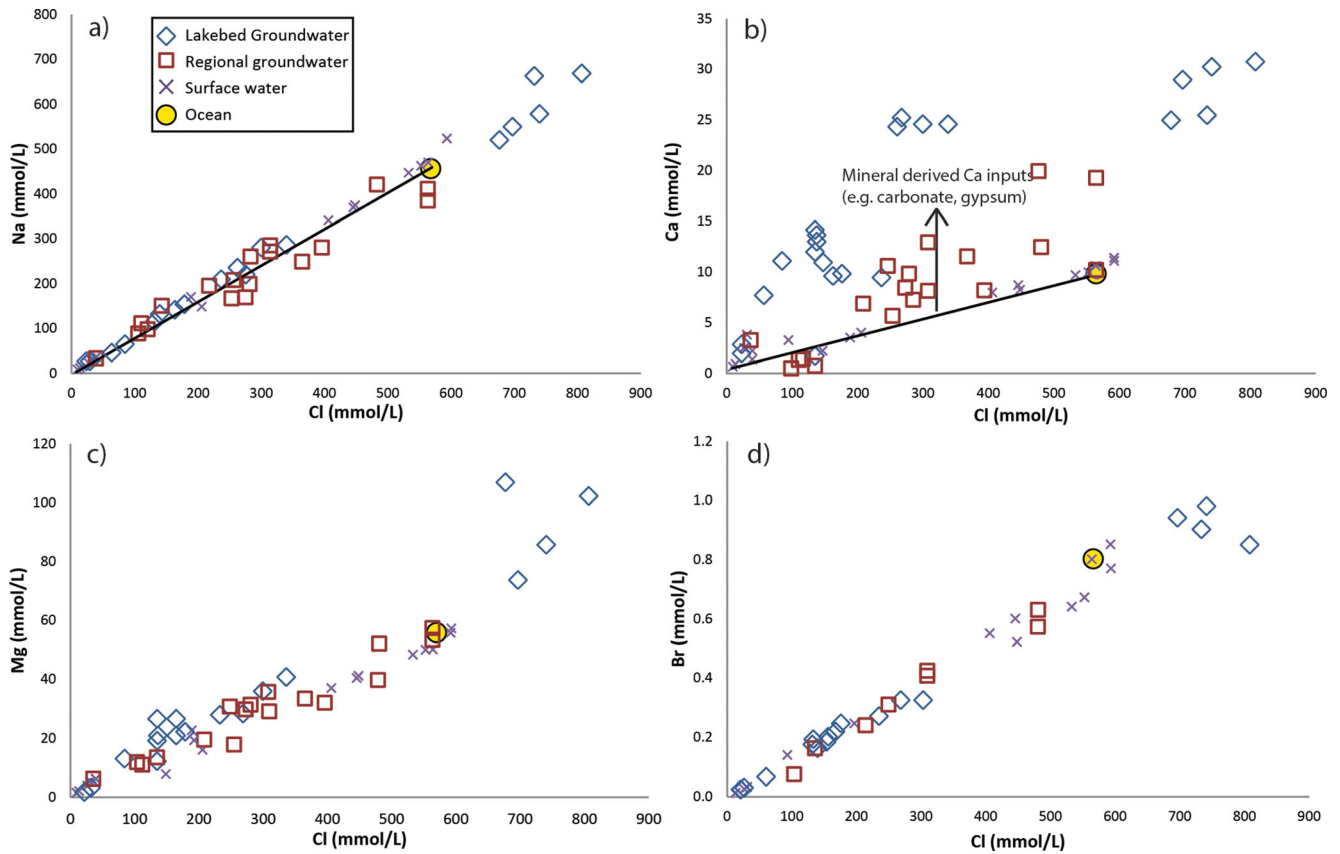


Fig. 7 Ion ratios in sampled groundwater and surface water: **a** Na/Cl; **b** Ca/Cl; **c** Mg/Cl; **d** Cl/Br. Standard marine water compositions taken from Appelo and Postma (2005)

Discussion

Salinity and water sources

Combined examination of the stable isotope and salinity data from surface and groundwater (Fig. 8) allows delineation of the sources of water and solutes throughout the wetland system, and illustrates major processes controlling salinity in each major group of water, as described in the following section.

Lakebed groundwater

The strong similarity between salinities and isotopic compositions of the river water and groundwater near the river inlet to Reedy Lake (at site LCC6) suggest a strong river–groundwater connection in this location. This is supported by pumping data during sampling, which showed no measurable drawdown while pumping at ~ 5 L/min. In groundwater from the lakebeds of Reedy Lake and Hospital Swamps (e.g. sites LCC1, LCC2 and LCC4), both the salinities and stable isotopic compositions are intermediate between fresh surface water from the wetlands, and marine water (Fig. 8), which implies that the shallow groundwater in the lakebeds constitutes a mixture of these two sources. The combined salinity/stable isotopic values observed cannot be explained by evaporation (which would increase stable isotope values much

more substantially), water–rock interaction (which should systematically enrich certain major ions), or plant transpiration (which would increase salinities but leave stable isotope values unchanged) alone. The position of paired groundwater and surface-water sample sets in Fig. 8 are consistent with mixing between wetland freshwater that has undergone some evaporative concentration, and a marine water end-member. For example, lakebed groundwater in Hospital Swamps (LCC4) plots on a mixing trajectory between surface water in Hospital Swamps and marine water, while lakebed groundwater in Reedy Lake (LCC1 and LCC2) plots on a mixing trajectory between the Reedy Lake surface water and typical marine water.

Because there is currently no surface pathway linking these parts of the wetlands to the ocean (due to the presence of the barrage structure), the marine mixing component in the upper shallow groundwater must constitute water that was emplaced in the bed and banks of the wetlands prior to river regulation, probably by surface leakage when Reedy Lake and Hospital swamps were still connected to the estuary. Another observation that is consistent with this mechanism is the presence of water that has a marine-like isotopic composition ($\delta^{18}\text{O} = -1.3$ to -0.6 ‰) and high salinity (EC = 35.2 to 40.9 mS/cm) in shallow Quaternary sediments just outside the current extent of the inundated wetland (bore CS3). This bore is screened within Quaternary lake sediments,

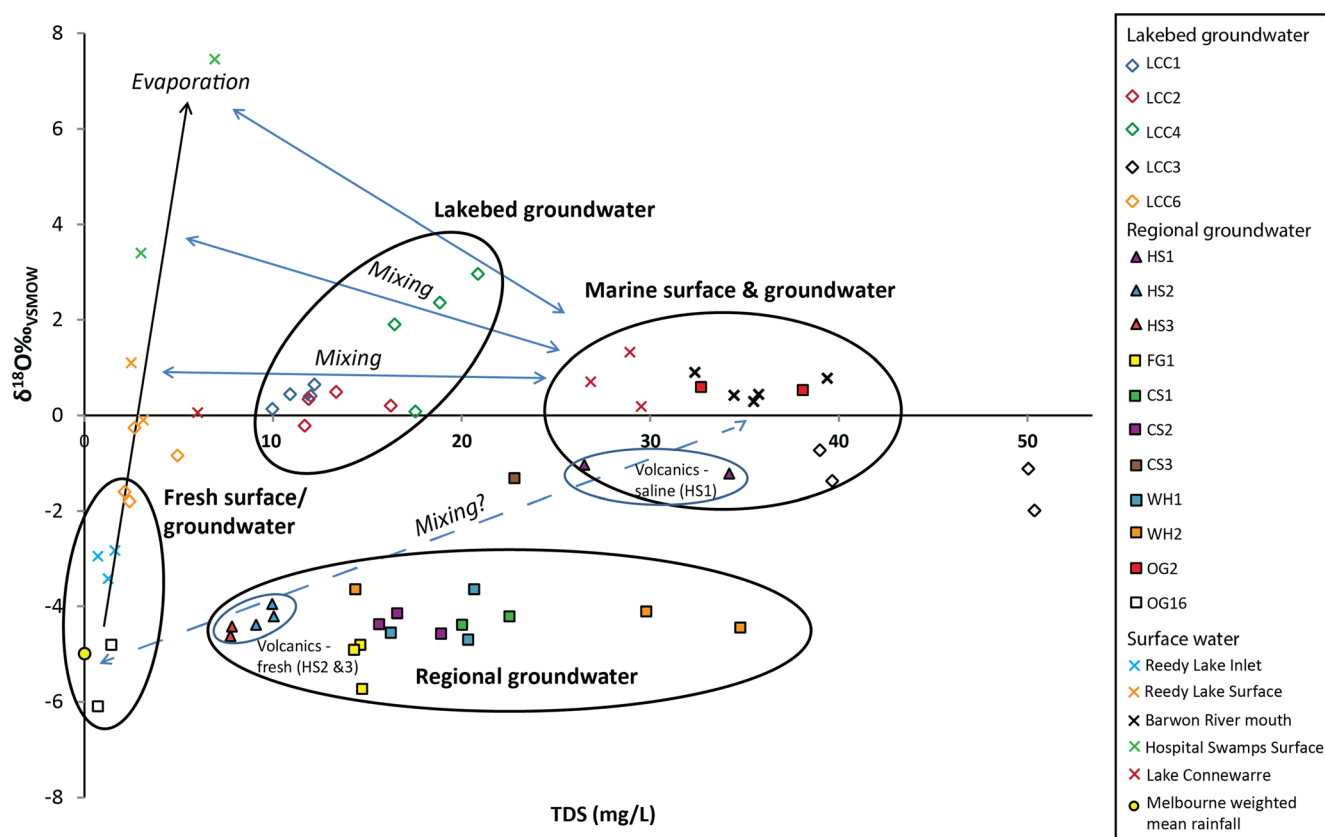


Fig. 8 Stable isotopic compositions and salinities of major groups of groundwater and surface water, indicating water and salinity sources throughout the wetlands. Inferred mixing relationships shown as lines

similar to those in the lakebeds, but currently it is not below any permanent surface water. Hence, the groundwater at this location was probably subject to surface inundation when the system was connected to the estuary, but unlike the other lakebed groundwater (now under permanent surface water: sites LCC1, LCC2 and LCC4), it has not received modern leakage of freshwater, and thus retains oceanic-like chemistry.

The shallow groundwater near the outlet of Reedy Lake (nearer Lake Connewarre) is the most saline water sampled in the system; this water has major ion ratios (e.g. Cl/Br ~750; Na/Cl ~0.8) and stable isotopic values ($\delta^{18}\text{O}$ from -1.9 to -1.1 ‰) indicative of marine water; however, the solutes have been subject to further concentration (e.g., up to salinities exceeding typical marine water). The additional concentration must have occurred via a non-fractionating process for ^{18}O and ^2H , as stable isotopic values are no higher than typical marine water; in fact, they are slightly below VSMOW. This could either have occurred due to water–rock interaction and/or transpiration by halophytic vegetation. The latter is supported by the marine-like ion ratios in the water (Cl/Br ~800; Na/Cl ~0.8; Mg/Cl ~0.12), which would imply that halophytic vegetation in the region is capable of concentrating groundwater solutes by ion exclusion, even where salinities are high to begin with (e.g. Dawson and Ehleringer 1998).

The predominantly ‘losing’ conditions in these wetlands (surface water leaking into lakebed groundwater)

that are implied by the geochemical data are generally not typical of the lower reaches of rivers, which are normally groundwater discharge areas (e.g. Fan et al. 2013). This can be explained as a result of river regulation, which has artificially raised the surface-water levels in the lakes relative to natural conditions, and provided a permanent source of fresh surface water that is gradually leaking into the underlying sediments. While regional groundwater discharge from the aquifers to the wetlands might be expected to occur under natural conditions, and may still occur when surface water levels are low (water level time series indicate periodic ‘gaining’ conditions (P. Dahlhaus, Federation University, unpublished data, 2014), this is likely to be masked by the introduction of the artificially raised surface water levels in the freshwater parts of the wetlands.

Regional groundwater

Relatively high salinities (>15 g/L TDS) also occur in most of the groundwater from the regional sedimentary and volcanic aquifers (sites CS1, CS2, FG1, WH1, OG2, HS1, HS2, Fig. 8). However, the rainfall-like stable isotope values observed in groundwater samples preclude marine water as a direct salinity source (e.g. via seawater intrusion or relict seawater). Rather, the salinity in these waters must result due to water–rock interaction and/or concentration of dissolved cyclic salts via plant

transpiration, which is characteristic of many saline regional groundwater systems in Australia, which generally only show indications of major evaporative enrichment at groundwater discharge areas such as salt lakes, and otherwise retain ‘meteoric-like’ stable isotope compositions (Herczeg et al. 2001; Cartwright et al. 2006). In general, the observed ion ratios are similar to typical rainfall (i.e. marine aerosol) for Australia (e.g. Ca/Cl 0.02–0.03; Mg/Cl 0.07–0.12; K/Cl 0.02; Herczeg and Edmunds 2000) with some depletion of sodium (Na/Cl 0.62–0.72) and enrichment of Ca (Ca/Cl up to 0.12) that could be explained by cation exchange and/or minor contributions from carbonate mineral weathering. These major ion and stable isotopic data imply that like in the Murray Basin and other southeast Australian systems, water–rock interaction is a limited source of groundwater salinity, as typical water–rock reactions (e.g. carbonate, evaporate or feldspar mineral weathering) lead to systematic enrichment of particular ions in solution relative to marine and rainfall ratios (Herczeg and Edmunds 2000). This again implies an important role being played by plant transpiration, concentrating the solutes in regional groundwater systems of Australia (Herczeg et al. 2001).

In the Newer Volcanics groundwater, the fresher groundwater samples (HS2 and HS3, TDS = 7.7–10.4 g/L) exhibit stable isotope compositions similar to meteoric water (e.g., $\delta^{18}\text{O}$ of –3.96 to –4.62 ‰); however, the more saline water (HS1, TDS = 26.5–34.2 g/L) has stable isotopic compositions similar to marine water (in contrast to the rest of the regional groundwater). The radiocarbon activity in this sample of 49.5 pMC (uncorrected age ~5.7 ka) and the seaward hydraulic gradients, which would likely prevent ingress of ocean water in the present day, suggest that this water is also trapped marine water. This may have been emplaced via surface flooding when sea levels were higher than at present, (e.g. during the middle-Holocene). According to the digital elevation model, a significantly expanded area of the wetlands, including the location of HS1, would have been covered by shallow sea at this time (Fig. 3). The fresher groundwater in the Newer Volcanics plots relatively close to a mixing line between Melbourne weighted mean rainfall and marine water (Fig. 8), which can be explained as a mixture of the emplaced marine water (observed in HS1), and more recent freshening with meteoric recharge. These data are again consistent with the proposed marine origin of water in the shallow lakebed system underlying the wetlands. In contrast, the stable isotopic signatures in groundwater on the northern side of the wetlands (Neogene and Quaternary sediments: samples CS1 and CS2, WH1 and WH2, FG1) strongly resemble meteoric water, indicating that no such trapping of marine water occurred, which is probably due to slightly higher elevations (Fig. 3) and, possibly, a greater degree of confinement compared to the fractured volcanic rocks.

Vegetation–salinity relationships

The wetlands are characterised by diverse vegetation communities, which are generally distributed in distinct zones; these are related primarily to the salinity and

availability of different water types in the system (e.g. Fig. 9; Lloyd et al. 2012). Areas of permanent or periodic inundation with fresh surface water are dominated by reed species, particularly *Typha Orientalis* (Cumbungi or Bullrush) and *Phragmites Australis* (Common Reed). Areas that are generally not inundated, and which are underlain by the saline groundwater with meteoric origin, tend to be characterised by zones of halophyte vegetation, including *Sarcocornia quinqueflora* (Beaded Samphire) and *Muehlenbeckia florulenta* (Lignum). There is generally a consistent relationship around the wetlands between the distance to permanent or semi-permanent surface water, and vegetation type (Fig. 9). In areas where fresh surface water is either permanent or periodically available, the reed species are prolific and out-compete other types of vegetation. In areas that are only rarely inundated, for example on the banks of the lakes away from permanent water, the native halophytes out-compete less salt-tolerant species, as they are able to survive in proximity to the shallow saline groundwater. As a result of the close relationship between access to water of particular salinities and vegetation type, the vegetation patterns are likely to be subject to rapid changes in distribution in response to any major hydrological changes. This is supported by periodic vegetation mapping from the last 30 years, which reveals substantial changes in the distribution of vegetation since 1983—particularly reed distributions—accompanying the evolving hydrological conditions (Yugovic 1985; Ecological Associates 2006; Lloyd et al. 2012).

Implications for future vulnerability

The hydrological data and processes described in this paper allow a qualitative assessment of potential impacts of future hydrological changes that are likely to occur because of increased urban development near the wetlands in the next two decades. The new Armstrong Creek urban growth area will bring residential suburbs within close proximity (less than 1 km) of the wetlands on the southwest side (Fig. 2). Further development to the north of Reedy Lake near Leopold is also planned. Likely scenarios that will occur as a result of this growth are: (1) increases in managed and unmanaged stormwater runoff into the freshwater parts of the wetlands, e.g., Hospital Swamps and Reedy Lake; (2) changed amount, location and quality of groundwater recharge in the area of the developments, due to leakage of imported water and hard-paving the natural landscape (Lerner 2002). Possible hydrological impacts and potential ecosystem flow-on effects of these scenarios are discussed in the following.

Scenario 1: increased stormwater inflow into freshwater wetlands

Under this scenario, which is currently being considered as a stormwater management strategy for the new suburbs, there is likely to be an increase in the frequency and amplitude of minor episodic flood events, an increase in the length of time that the wetlands will retain freshwater,

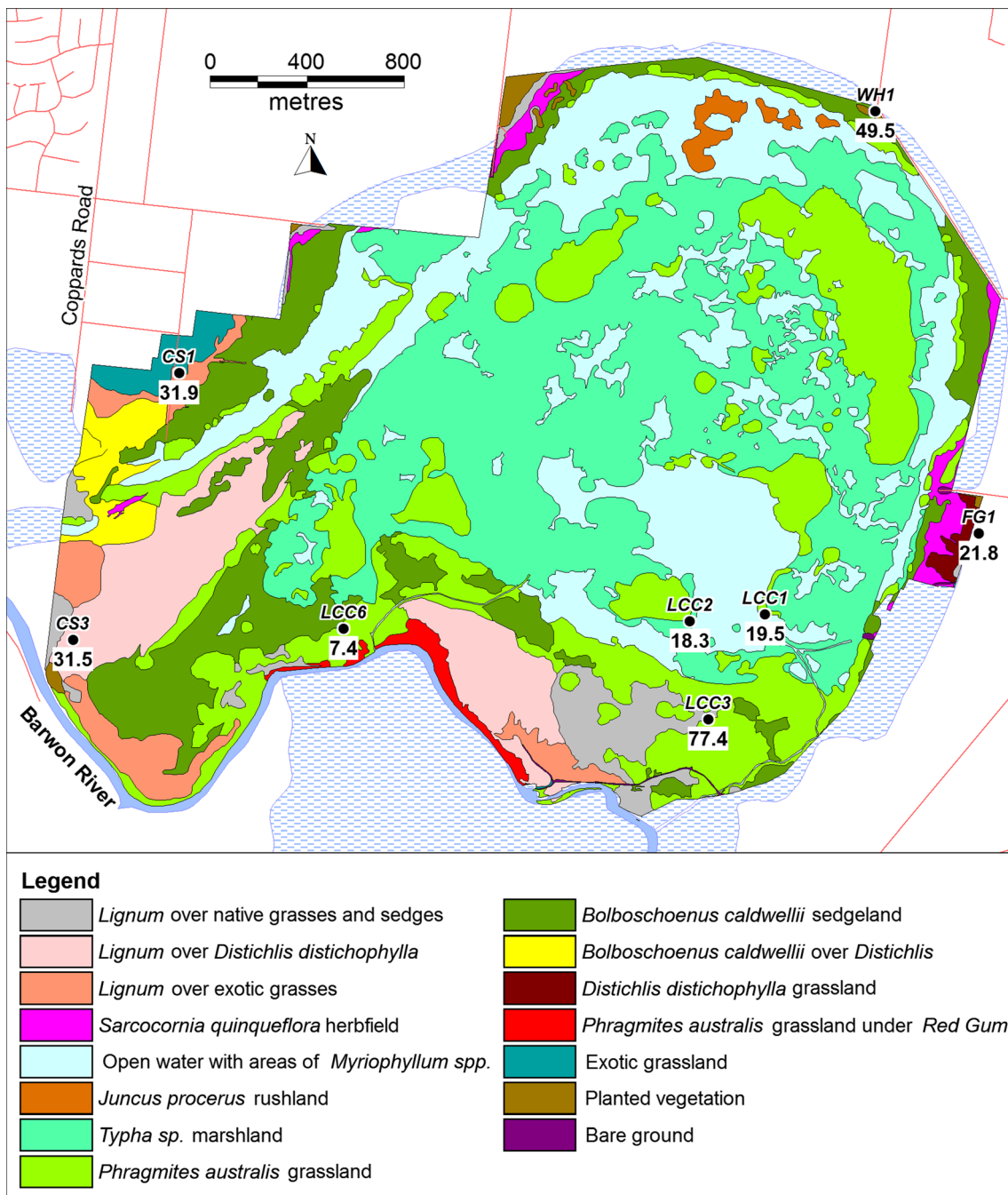


Fig. 9 Map of major vegetation classes and shallow groundwater salinity (as EC, mS/cm) at Reedy Lake. Data courtesy of M. Cooling, Ecological Associates Australia, unpublished data, 2014

and an increase in the area of permanent surface water in the wetlands. The result will be longer periods of ‘losing’ hydraulic gradients, and increased magnitude of these gradients, in Hospital Swamps and Reedy Lake. This will probably lead to increased leakage of surface water into the shallow lakebed aquifer, which in the short term may lower the salinity of both surface and shallow groundwater. These new hydrological conditions might be expected to favour plant species of relatively low salinity tolerance that thrive in areas of permanent water or regular inundation—the reeds *T. Orientalis* and *P. Australis* in

particular (e.g., Lloyd et al. 2012). As discussed in the following, in the long term, rising water tables from increased leakage may, however, lead to salinisation of the upper soil profile and water-table aquifers.

Scenario 2: changed groundwater recharge

Hard-paving of surfaces will locally restrict recharge and increase the volume of stormwater runoff; however, this will be offset to some degree by the leakage of pressurised urban water for household and irrigation use (Lerner

2002). This will in some places cause already shallow saline water tables to mound closer to the surface. In addition, the irrigation of domestic gardens, parks and sports reserves and construction of artificial water features are likely to increase accessions to the water table. The net result is likely to be a local redistribution of groundwater flow with a regional rise in groundwater levels (Foster et al. 1998; Chilton 1999). While the new recharge associated with urbanisation will be predominantly fresh water, the low hydraulic gradients and high natural evapotranspiration rates characteristic of the area may lead to salinisation of the upper soil profile (Ghassemi et al. 1995). In the long term, this may affect the structural integrity of buildings and urban infrastructure as well as the vegetation, favouring species which prefer permanent access to saline groundwater in areas where permanent surface water is absent. In the long term, the raised water tables may also lead to increased groundwater hydraulic gradients towards the wetlands, and therefore higher rates of saline groundwater discharge. However, the relative effect of any increased groundwater discharge is likely to be small compared to the increased fluxes of stormwater runoff into the wetlands, in terms of the surface-water balance. The likely overall outcomes of urbanisation in the long term will thus be increases in water-table heights, salinisation of the upper soil profile, and increased areas of the wetlands influenced by inundation with stormwater.

Conclusions

The geochemical data in this study provide new insights into the sources of water and salinity in the groundwater and surface-water systems of the Lake Connemara Complex, and modified coastal wetland systems that are subject to river regulation generally. In particular, the stable isotope compositions indicate two distinct salinity/water sources: (1) marine water in the estuarine surface water system and trapped as shallow groundwater in the aquifers below and immediately surrounding the wetlands; (2) meteoric water containing cyclic salts concentrated by plant transpiration and affected by water–rock interaction (much of the regional groundwater). The different water sources would probably not be distinguishable without the aid of the stable isotopic data, which clearly delineate distinct groups of water and salinity type. Groundwater in the lakebed of the freshwater parts of the wetlands constitutes a mixture of marine water, that must have been emplaced prior to river regulation, and fresh surface water that has been introduced by the present-day river regulation regime. River regulation has created a predominantly losing ground-surface water system—with downwards leakage of fresh surface water into the underlying saline shallow aquifer(s) in the lakebed. This is likely a relatively recent phenomenon; prior to river regulation the region would have constituted a typical estuarine environment with brackish and saline surface-water mixing controlled by tide–river runoff interplay. The region would likely have also been a groundwater discharge area for the

regional aquifers (as a regional topographic low); however, at present any such discharge of saline regional groundwater is masked by the constant input of freshwater to the wetlands from the Barwon River.

Marine-type water was also found in the Newer Volcanics; however, this water has a radiocarbon age indicating pre-modern recharge; this is probably relict seawater emplaced in the aquifer during a period of higher sea level in the middle Holocene. The presence of trapped marine water in aquifers beneath low-lying areas that would have been subject to inundation in the mid-Holocene sea-level maximum is a generally unexplored phenomenon in the literature, and warrants further investigation.

The distribution of different vegetation types in this and other coastal wetland systems is controlled by access to fresh and/or saline groundwater and surface water. Future increases in the amounts of managed or unmanaged stormwater runoff to the wetlands will likely favour exotic reed species, which out-compete the more salt-tolerant coastal native species in areas of frequent inundation with fresh surface water, and fresher shallow groundwater.

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