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Water and salt balance of a saline water disposal basin during an experimental flooding and drying cycle (Loveday Disposal Basin, Australia)

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Abstract:

Saline irrigation drainage water along the semi-arid lower River Murray is often disposed of into evaporation basins to prevent contamination of downstream water supplies. These evaporation basins are often former ephemeral floodplain wetlands that have now become extremely ecologically degraded due to high soil and water salinity. An experimental flooding with freshwater was conducted at Loveday Disposal Basin in 2006 to evaluate the environmental benefits of periodic flooding with freshwater. The water and salt balances of the permanent North Basin and ephemeral South Basin during the experiment were evaluated using a combination of hydrometric techniques and trends for salinity and the stable isotopes of water. Filling of the basins (with freshwater from the River Murray) decreased salinity (as total dissolved solids) from approximately 60 to 9 g l^{-1}. Once flooding was completed, water level in both basins receded rapidly and then within 5 months they had re-salinised to pre-treatment levels. The main re-salinisation mechanism was greater evaporative loss induced by the large increase in wetted surface area after flooding, especially in the shallower South Basin. Dissolution of evaporites was not a source of salt to the basins because halite remained undersaturated at all times, but minor quantities of Ca^{2+} and $SO_4{}^{2-}$ were gained from gypsum and carbonate dissolution. The salt mass stored in South Basin surface water increased during flooding and early after flooding, suggesting a significant salt input from the flooded soils. Because of large salt stores in surrounding soils and groundwater, ongoing saline groundwater discharge, and large evaporative losses, periodic flooding alone brings limited environmental benefits (that is, conditions favourable to freshwater organisms) to floodplain disposal basins. However, flooding deeper disposal basins during winter will minimise evaporative losses and increase the length of the freshening period. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS groundwater-surface water interactions; salinity; River Murray; floodplain; wetlands

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INTRODUCTION

In the lower River Murray region (South Australia), a number of floodplain wetlands were converted into disposal basins during the 20th century to store and evaporate excess irrigation drainage (Hostetler and Radke, 1995; Jolly, 1996; Simmons *et al.*, 2002). The aim of these disposal basins was to prevent saline irrigation drainage from discharging into the river, at least outside of major flood events. However, recent management policies aim to remove disposal basins from River Murray floodplains and to return these wetlands to a more natural state when feasible. The remediation of these highly salinized wetlands will be a challenge for environmental managers (Lamontagne *et al.*, 2006).

There appears to be strong mechanisms to re-salinize disposal basins after freshening events. For example, between 1970 and 2000 at Loveday Disposal Basin (Figure 1), following flushing by overbank flow events, water salinity returned within less than a year to previous levels (Figure 2). Reduced irrigation drainage disposal and a lack of overbank flow events have also seen a further increase in salinity in this disposal basin since 2000. A number of mechanisms can be proposed to explain the rapid re-salinisation of disposal basins following freshening events (Jolly *et al.*, 2008). These would include: (i) evapoconcentration; (ii) dissolution of evaporites; (iii) mixing of ponded water with saline vadose water and shallow groundwater; and (iv) ongoing saline groundwater discharge.

Possible re-salinisation mechanisms for floodplain disposal basins were evaluated during a wetting and drying experiment at Loveday Disposal Basin. The water balance during the flooding experiment was evaluated using a combination of hydrometric techniques and trends in salinity and the stable isotope of water. Groundwater–surface water interactions during the experiment were evaluated using piezometer transects spanning the study area. As the North and the South basins of Loveday were isolated and flooded independently, the experiment also enabled to evaluate the impact of flooding on basins with different morphometry.

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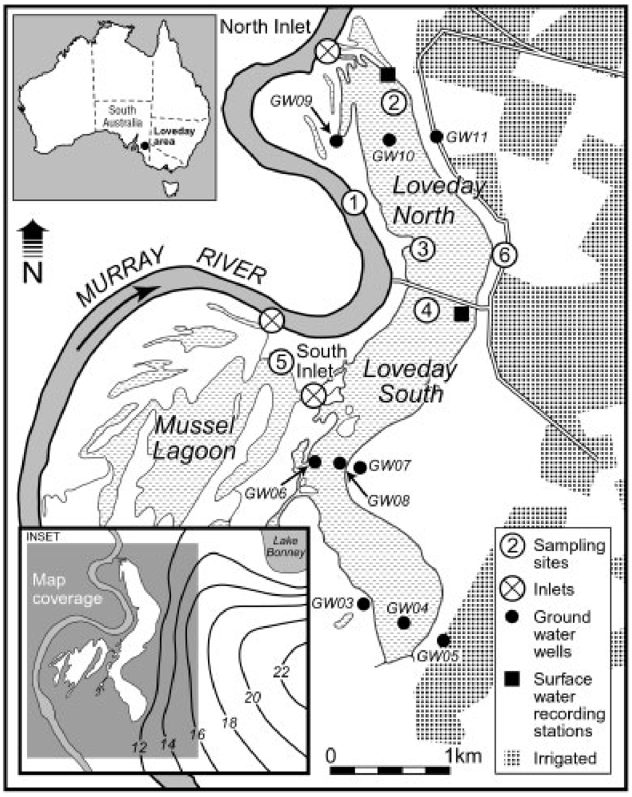

Figure 1. Location of sampling sites, piezometers, and surface water level monitoring stations at Loveday Disposal Basin. Site 1—River Murray; Site 2—Northern end of North Basin; Site 3—Southern end of North Basin; Site 4—South Basin; Site 5—Mussel Lagoon; Site 6—drain outlet. The inset shows the piezometric surface (in m AHD) for the groundwater mound underneath the irrigation district. Groundwater mounds are common under irrigated areas in this region because of significantly larger recharge rates relative to nearby areas under native vegetation

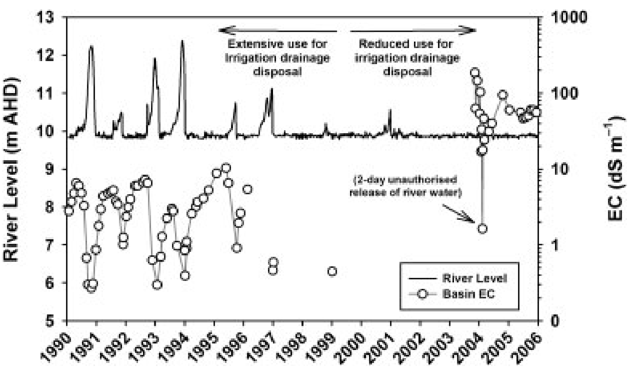

Figure 2. Long-term electrical conductivity trends at Loveday Disposal Basin compared with River Murray water level. Overbank flow occurs when river level exceeds ~9·81 m AHD

METHODS

Study site

Loveday Disposal Basin is located near the township of Barmera, in the State of South Australia on the lower reaches of the River Murray (Figure 1). The climate is semi-arid, with potential evapotranspiration (~2,000 mm year^{-1}) well in excess of precipitation (100–500 mm year^{-1}). The primary land-use in the vicinity of Loveday Basin is vineyards irrigated with River Murray water. Prior to the installation of weirs on the River Murray in the 1920s, the area of Loveday Basin would have been a depression supporting an ephemeral lignum swamp. Following the installation of Lock 3 and the corresponding rise in River Murray pool level, this area became permanently inundated. However, control structures were built in the 1970s to isolate the wetland from the river. This enabled the use of the wetland as a disposal area for shallow groundwater collected by a drain system under nearby irrigated crops, as these waters were too saline to be released directly into the river. This drainage system prevents waterlogging in the root zone by rising water tables, a common problem for areas under irrigation in the region. Thus, due to the control structures preventing overland outflow and the high water table when the River Murray remains at pool level, the Loveday Disposal Basin became a system from which the main water loss was evaporative (i.e. endorheic).

Loveday Disposal Basin consists of a North and South basin separated by a causeway but connected through several culverts. Following a reduction in drainage disposal in the 1990s, only a part of the North Basin remained permanently inundated. This water originates in part from leakage from the inlet (TDS = 0·1–0·2 g l^{-1}), discharge from a groundwater mound under the irrigation district (TDS = 3–40 g l^{-1}), and the drain system (TDS ~3 g l^{-1}). The basin sediments have elevated sulfide concentrations and emit noxious odours when exposed (Hicks and Lamontagne, 2006; Lamontagne *et al*., 2006). In order to prevent noxious odours, small releases of River Murray water from the North inlet were made between October 2005 and April 2006 to increase the water cover over the North Basin sediments. In contrast, during the same period, the shallower and slightly more elevated South Basin (Figure 3) was ephemeral, maintaining a small pool of water during winter or for a few weeks following larger rain events in summer. Nearby Mussel Lagoon is a freshwater wetland with a regular input of River Murray water. Excess Mussel Lagoon water is discharged to the South Basin by a surface water outlet (Figure 1).

The hydrogeological environment at Loveday is typical of lower River Murray floodplains. The porous media consists of a relatively impervious silty clay cover (or Coonambidgal Clay) generally 2–8 m in thickness (Jolly and Walker, 1995; Doble *et al*., 2006). This clay cover overlies a sandy silt aquifer (or Monoman Formation) which acts as the main aquifer connecting upland irrigated areas to the floodplain (Doble *et al*., 2006). However, the Coonambidgal Clay cover is not continuous and Monoman Formation outcrops can occur in the floodplain (Jolly *et al*., 1994; Lamontagne *et al*., 2005). The water table in the Coonambidgal Clay aquitard is shallow across Loveday Disposal Basin (i.e 0–2 m from the surface). Thus, groundwater discharge by water table evaporation occurs over exposed sediments (that is, evaporation of water in the vadose zone is replenished by groundwater due to capillary rise; Wind, 1955; Coundrain-Ribstein *et al*., 1998). This has resulted in a large accumulation of

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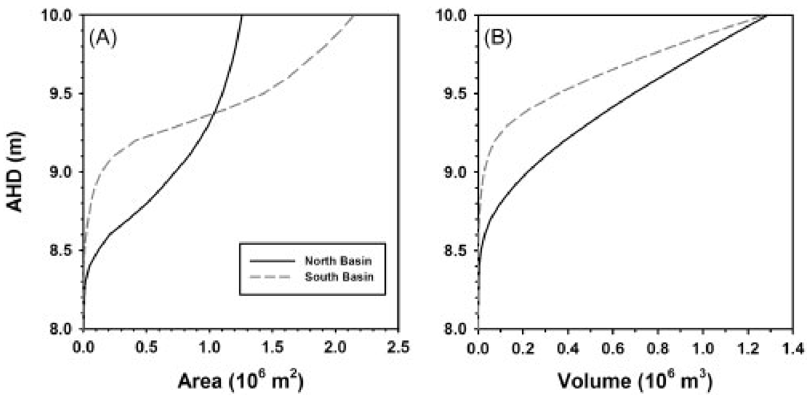

Figure 3. Relationship between elevation (m AHD), and (A) surface area and (B) volume in the North and South basins. Note that the South Basin is flatter than the North one—at full capacity (10 m AHD) the South Basin covers twice the surface area of the North Basin for a similar volume of water

saline water in the vadose zone (1 : 5 soil/water extracts = 0·5–71 dS m^{-1}; Lamontagne *et al.*, 2006) and groundwater (TDS = 3–46 g l^{-1}) in the Coonambidgal Clay (see also Jolly *et al.*, 1994; Slavich *et al.*, 1999). The presence of a groundwater mound under nearby irrigated lands and a permanently raised River Murray level make the floodplain at Loveday a groundwater discharge zone. However, some export of saline groundwater by brine reflux may occur (i.e the 'sinking' of denser brines into fresher parts of the aquifer; Nield *et al.*, 2008).

Flooding experiment

The monitoring program spanned three periods: (i) pre-flooding; (ii) active flooding; and, post-flooding draw-down (Table I). Prior to the flooding experiment, the culverts between the North and South basins were closed off, thereby isolating the two basins. Flooding of the North Basin was undertaken by opening the Northern inlet control structure, while the South Basin was flooded using the outlet from Mussel Lagoon. Thus, in both cases River Murray water (TDS ~0·22 g l^{-1}) was used to flood the basins, but it first transited through the Mussel Lagoon in the case of the South Basin.

Hydrological monitoring

Surface water levels were recorded using Solinst LTC dataloggers in both the North and the South basins (Figure 1; Department of Water, Land and Biodiversity Conservation [DWLBC] Station number A4261081 and A4261088, respectively) and for a limited period of time (May—September 2006) at Mussel Lagoon (Station 6029-00 956). However, recording in the South Basin was only initiated from late May 2006 onward. Three piezometer transects were installed across the basins prior to flooding. They consisted of 80 mm diameter PVC with 3 m long PVC screens [construction details in Lamontagne *et al.* (2008)]. The piezometer screens were installed to be open to the Monoman Formation. In areas already covered with water (GW8 and GW10) shallow piezometers were installed by hand but were not surveyed or monitored during flooding because of accessibility problems (they were sampled for water quality prior to flooding). Water level and electrical conductivity (EC) were monitored in the piezometers GW3, GW4, GW5, GW9, and GW11 using Solinst LTC dataloggers. Pressure readings from the loggers were calibrated for variations in barometric pressure using a Solinst Barologger suspended above the water in one of the piezometers, and against bi-monthly manual water level readings.

Daily precipitation and pan evaporation measurements were obtained from the Bureau of Meteorology Loxton Research Centre Station (Station Number 24 024), located approximately 25 km away from Loveday. Daily drain discharge to the North Basin was gauged at the drain outlet using a triple-crested V-notch weir (DWLBC Station Number A4260698). The weir discharge estimates are not believed to be accurate (B. Porter, DWLBC, *personal communication*), but it will be demonstrated later that this is unlikely to have had a significant effect on the estimates of the water balance. When open, discharge from the North and South basin inlets could not be gauged accurately. However, the times when the inlets were open or closed were recorded. Water level in the River Murray was obtained from a nearby monitoring station (DWLBC Station Number A4260516) but remained at ~9·8 m Australian Height Datum (AHD) throughout the study (AHD ~ mean sea level).

Table I. Dates for the different periods of the monitoring program in Loveday North and South Basin

Period	Loveday—North	Loveday—South
Pre-flooding	31 May 05–24 May 06	31 May 05–8 June 06[a]
Flooding	25 May 06–11 August 06	9 June 06–1 September 06
Post-flooding	12 August 06–7 March 07	2 September 06–7 March 07

The inlet from the River Murray to Mussel Lagoon was also closed on 1 October 2006.
[a] Only water quality was monitored during this period in the South Basin.

Water quality monitoring

Six sites were sampled on an approximately monthly basis from May 2005 to March 2007. Sites included

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the River Murray, both ends of the North Basin, the South Basin near the causeway, the outlet of the irrigation drainage system, and Mussel Lagoon (Figure 1). Surface water was collected by submerging a well-rinsed 1-L bottle below the surface by wading from the shoreline up to ~50 cm water depth, or as far as practicable. Drain discharge samples were collected from the weir pool. At two of the sites (southern end of North Basin and South Basin) when surface water was not present, a pit was dug and shallow groundwater collected. During the flooding period the North Basin was temporarily density-stratified (see Section on *Results*). During the stratification period, integrated samples of the water column at sites 2 and 3 were collected by inserting a tube vertically up to the sediment surface, capping the top, and rapidly emptying the contents in a well rinsed 1-l bottle. In addition, at Site 2, an inflatable raft was used to collect offshore samples and salinity profiles.

Temperature, EC, and pH were measured on site using probes (TPS). The EC and pH probes were calibrated daily with standard solutions. Unfiltered alkalinity was measured with a field titration system (Hach) using the bromocresol green-methyl red indicator method (using a pH 4·5 titration end-point). A sample for the analysis of the stable isotopes of the water molecule was preserved using gas-tight bottles (McCartney bottles). The remaining subsamples were filtered with disposable 0·45 µm Supor membrane filters (Pall) using a syringe and three-way valve system that minimizes sample contact with the atmosphere. One filtered 100 ml sample was acidified to pH <2 using high purity HCl for analysis of major cations and anions. Another 100 ml sample remained unacidified and was used for laboratory EC, pH, chloride and alkalinity measurements. All samples were kept on ice in the field and stored at 4 °C in the laboratory. To prevent contamination, freshwater samples (River Murray and Mussel) were collected first during the sampling trips and filtered using separate equipment. At the end of each sampling trip a field blank was processed in a similar manner to the samples, using deionised water. All analyses were performed at the CSIRO Waite Campus Analytical and Environmental Isotopes laboratories. Details of the analytical methods are outlined in Lamontagne *et al*. (2008).

Water balance

The water balance for Loveday Disposal Basin can be described as follows:

$$\frac{dV}{dt} = P - E + S + D + G + R + \varepsilon, \quad (1)$$

where, dV/dt is change in wetland volume over time, P precipitation, E evaporation, S surface water input from the river (or from Mussel Lagoon for the South Basin), D input from the drainage system (for the North Basin only), G groundwater discharge (or recharge), R storm runoff, and ε the error (all units in m^3 per unit time). Changes in area and in volume over time in each basin were estimated by using depth to area and depth to volume relationships determined by surveying the basins prior to flooding (Figure 3). Daily precipitation (p_d; m day^{-1}) and pan evaporation (e_d; m day^{-1}) measurements from the Loxton meteorological station were converted into daily P and E for each basin using the following expressions:

$$P = p_d \cdot A \quad (2)$$

and

$$E = e_d \cdot F \cdot A \quad (3)$$

where, A is the wetland surface area on a given day and F a pan correction factor that takes into account the 'oasis' effect associated with small water bodies in arid landscapes (Turk, 1970; Jolly *et al*., 2000).

Due to poorly formed channels, backing-up of water during in-filling, and the periodic growth of vegetation within the channels, the inputs of water from the Northern inlet to the North Basin or from the Mussel Lagoon outlet to the South Basin could not be gauged accurately. The periods over which the gates were open were known but the North Inlet had some leakage when closed. Groundwater loading rates were not estimated either but the potential direction of groundwater flow in each basin was monitored using the piezometer transects.

Thus, not all potential sources (or losses) of water to the basins could be measured during the monitoring program, so the water balance was simplified as follows:

$$\frac{dV}{dt} = P - E + D + I + \varepsilon \quad (4)$$

Thus, I includes the potential contributions from S, G, and R, which could not be individually measured. Based on the local topography, only the South Basin is expected to receive significant storm runoff.

RESULTS

Surface water trends

Loveday North was partially dry and Loveday South was ephemeral during the pre-flooding period. During this period, occasional releases of water from the North Inlet were made (usually over a day or two) to maintain a minimum water level in the North Basin as a measure to prevent the emission of noxious odours (Figure 4a). Upon initiation of the flooding experiment, both basins filled by about 1 m over approximately 6 weeks. Water levels in both basins started to recede once the inlets were closed. Two small temporary rises in water level in the North Basin in the post-flooding period were associated with temporary openings of the North inlet (Figure 4a). A smaller temporary water level increase in both basins was also associated with a rain event in January 2007 (Figure 4b). However, both basins had returned close to their original water level by March 2007. For a similar change in volume, the South Basin had a larger increase in surface area (from 0·1 to $1·8·10^6$ m^2) than the North Basin (from 0·7 to $1·2·10^6$ m^2) because it is shallower

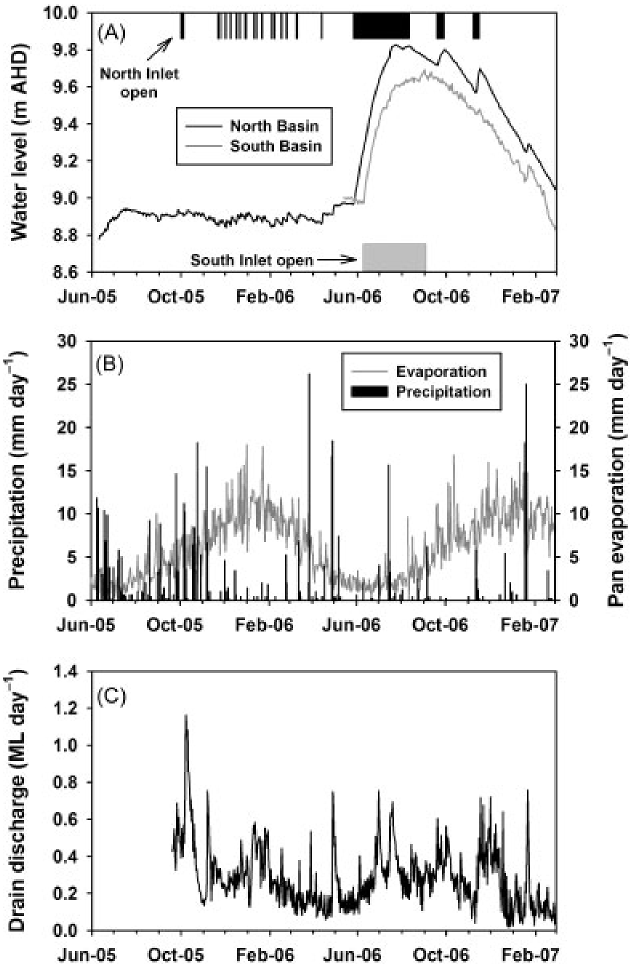

Figure 4. Basic hydrological parameters for Loveday Disposal Basin during the monitoring program. (A) water level and inlet opening periods; (B) precipitation and pan evaporation; (C) drainage disposal. Note that water level monitoring was only initiated in May 2006 in the South Basin

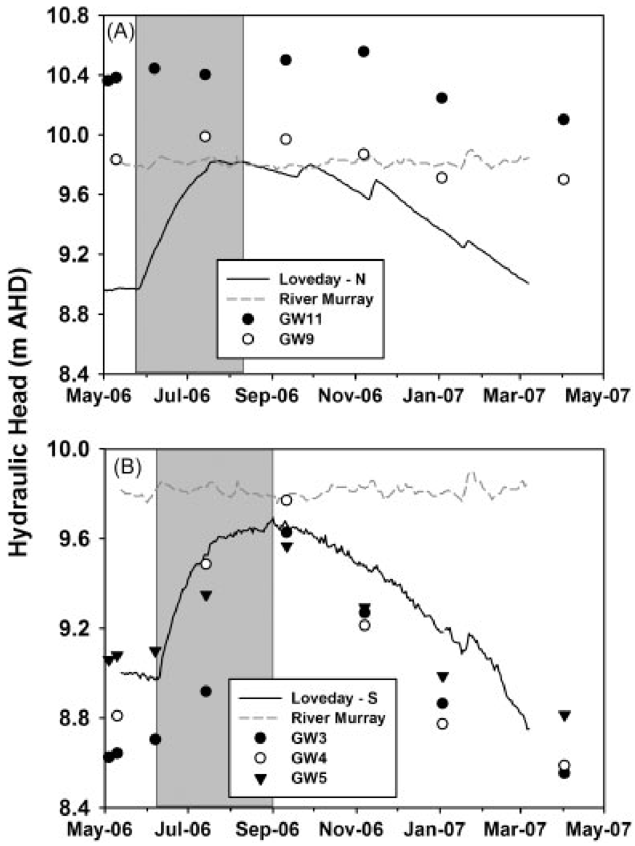

Figure 5. Hydraulic head variations in two piezometer transects (as freshwater head equivalents) obtained from manual water level readings. Density correction made using measured groundwater TDS prior to flooding following Post *et al*. (2007). (A) North Basin; (B) Southern end of South Basin. Shaded areas represent the flooding periods. Groundwater salinity did not vary noticeably in the Monoman Formation during flooding (Lamontagne *et al*., 2008)

(Figure 3). The South Basin surface area receded rapidly once the South inlet was closed and this basin was dry by March 2007.

As a result of a drought across the Murray—Darling Basin (CSIRO, 2008), precipitation inputs to the Loveday basins were relatively small during the study period. As expected for a semi-arid climate, pan evaporation rates varied from a few mm day^{-1} during winter to in excess of 15 mm day^{-1} during summer (Figure 4b). Drain discharge to the North Basin was variable but had a decreasing trend over time (Figure 4c), consistent with lowered water tables in the region due to the regional drought.

Groundwater trends

Significant changes in groundwater—surface water interactions in the basins were found during the flooding and drying cycle at Loveday Basin. However, because groundwater has a large range in salinity in this environment, the interpretation of hydraulic head data to infer groundwater flow patterns is not always straightforward. For brevity and clarity, only the manual water level readings reported as freshwater head equivalents are reported here. Density corrections were made following the protocol proposed by Post *et al*. (2007).

Prior to flooding, the North Basin appeared to be a groundwater sink (Figure 5a). The piezometric surface in the Monoman Formation indicated a general flow direction from the irrigated uplands towards the basin and, to a lesser extent, from the floodplain towards the basin. At the southern end of the South Basin, the hydraulic gradient suggests that the basin was a groundwater flow-through zone (Figure 5b), with hydraulic head in Loveday intermediate between those of the inland and floodplain piezometers. As this end of the South Basin was dry at all times prior to flooding, groundwater discharge could have only occurred as water table evaporation. The differences in groundwater—surface water interactions between basins are due, in part, to a more elevated water table on the landward side of the North Basin (GW11 on Figure 5a). The North Basin is also more incised in the Coonambidgal Clay than the South Basin (Figure 3), which should also favour a better connection with the Monoman Formation.

Hydraulic heads increased in both basins following flooding, indicating that the Monoman Formation is hydraulically connected to them. The North Basin remained a groundwater sink during flooding (Figure 5a), whereas the South Basin became a groundwater recharge area (Figure 5b). Because of the semi-confined nature of the Monoman Formation, these hydraulic head responses probably primarily represented changes in pressure in the aquifer. However, some groundwater recharge likely occurred in both basins in the overlying Coonambigdal Clay aquitard. In particular, some of the sediments in dried areas of the basins had extensive dessication features (that is, cracks up to 50 cm deep; Lamontagne *et al.*, 2006) which would have facilitated recharge. These dessication features gradually disappeared once sediments were flooded.

During the drying phase, hydraulic heads fell in all piezometers and were lower at the end than at the beginning of the monitoring. Locally, the loss of hydraulic head is consistent with the gradual loss of the water column in both basins. However, the loss of hydraulic head in the Monoman Formation during the drying phase could also have been, in part, a regional effect fostered by lower groundwater recharge rates in the region (because of lower rainfall and irrigation rates at the time of the study).

Trends in volumetric gains and losses

The trends in volumetric gains and losses for Loveday North and South suggest that surface water input and evaporation were the two largest components of the water balance (Figure 6). While surface inputs could not be independently estimated from storm runoff and groundwater discharge, the largest influx of water to Loveday (I) were clearly during periods when the inlets to either basins were open (Figure 6). Evaporative losses increased markedly following flooding owing to the large increase in wetted surface area in the North Basin (72%) and especially the South Basin (1250%). In the South Basin, after the inlet was closed, I was initially positive but decreased to become negative by the end of the monitoring period. Thus, an additional source of water contributed to the water balance of the South Basin post-flooding.

Salinity and stable isotopes of water

Prior to flooding, the North Basin was saline (>40 g l^{-1}) and alkaline (Lamontagne *et al.*, 2008). The brine was NaCl dominated and depleted in Ca^{2+}, K^+, and carbonates relative to what would be expected from the evaporation of River Murray water (Herczeg *et al.*, 2001; also detailed in Lamontagne *et al.*, 2008). Drain discharge to the North Basin was brackish to saline (TDS = 1·4–4·0 g l^{-1}) and very alkaline (up to 9·6 meq l^{-1}). Groundwater surrounding Loveday was saline and had a similar ionic composition to Loveday surface water (Table II; Lamontagne *et al.*, 2008). During summer 2005, salinity in the southern end of the North Basin was higher than that at the other end because this site became separated from the main water body by low water levels and nearly dried out (Figure 7). Groundwater, occasionally collected from the shallow pits at sites 3 and 4, was also saline (Lamontagne *et al.*, 2008).

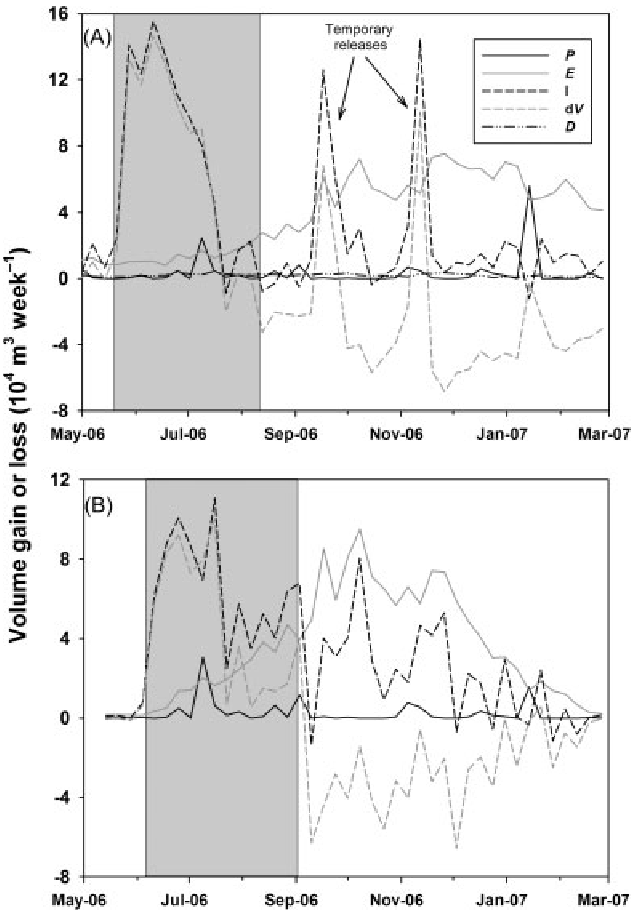

Figure 6. Estimated weekly volumetric gains and losses at Loveday Basin during the monitoring program. (A) North Basin; (B) South Basin. Flooding periods highlighted in grey

Table II. TDS and stable isotope composition for groundwater in the Monoman Formation in the vicinity of Loveday Disposal Basin prior to flooding

Piezometer	TDS (g l^{-1})	δ^{18}O (‰–VSMOW)	δ^{2}H (‰–VSMOW)
GW3	44	−1·83	−13·1
GW4	18	−3·26	−21·2
GW5	2·9	−2·64	−18·9
GW6	39	−2·45	−19·9
GW7	34	−2·23	−20·9
GW8	41	−2·95	−23·0
GW9	46	−2·75	−19·2
GW10	27	−3·02	−21·2
GW11	27	−3·03	−23·5

Upon flooding of the North Basin, a strong density stratification developed, where the freshwater inputs overlayed the more saline resident water (Figure 8). Despite the shallow maximum depth (~1·2 m) of the North Basin, the density stratification persisted for over a month. No evidence of density stratification was observed in the shallower South Basin. Average salinity in the North and South basins decreased rapidly upon flooding (Figure 7) and reached 9–12 g l^{-1} by August 2006. However, salinity in both basins increased rapidly once

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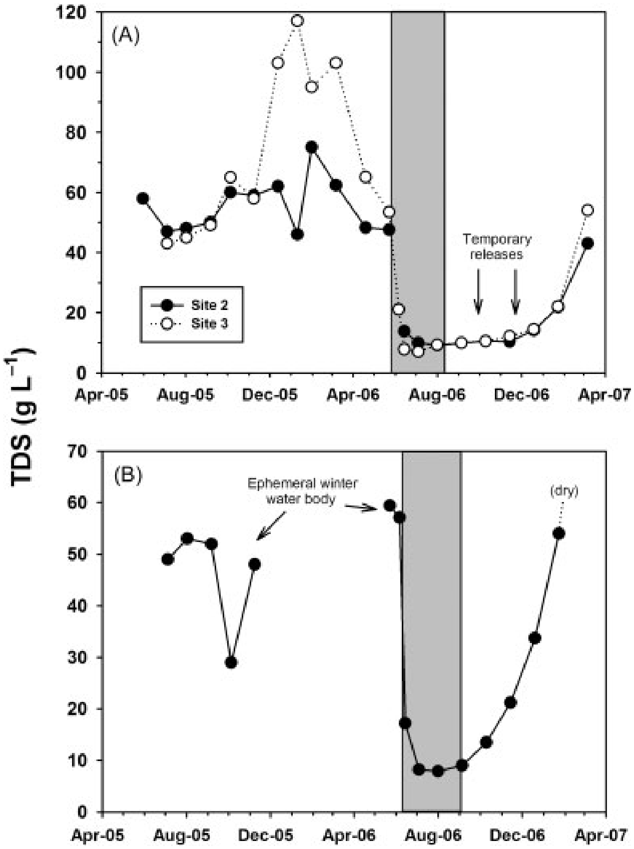

Figure 7. Change in Total Dissolved Solids concentrations in Loveday Disposal Basin North (sites 2 and 3) and South (site 4)

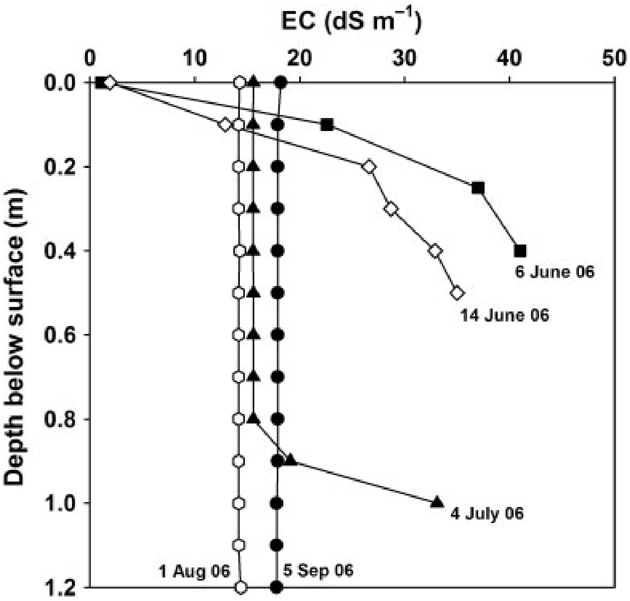

Figure 8. Density stratification at Loveday North (site 2) during the flooding period

the inlets were closed and had returned to pre-flooding levels by March 2007, when monitoring was completed.

There was a large range in the concentrations of the stable isotopes of water across the sites (Figure 9). Concentrations were lowest in the River Murray, intermediate in Mussel, and highest at the Loveday sites. This pattern

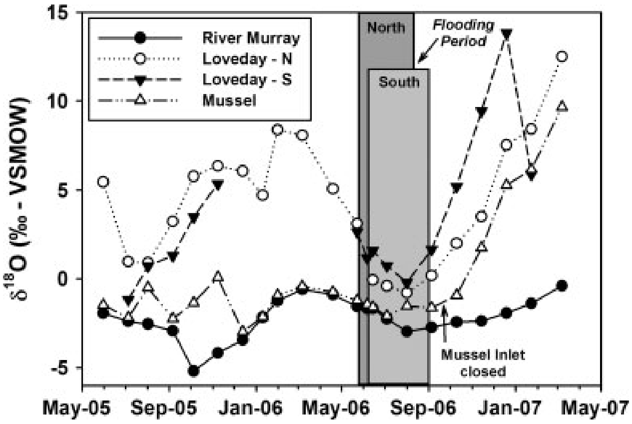

Figure 9. Oxygen-18 concentration in Loveday North (site 2), Loveday South, River Murray and Mussel Lagoon during the monitoring program

is consistent with the main source of water to Mussel and Loveday being the River Murray, subsequently enriched by evaporation (Gonfiantini, 1986). There was also a seasonal pattern in stable isotope concentrations in the River Murray and in the wetlands prior to flooding (Figure 9), with higher values during the summer months. This is also consistent with a greater potential for evaporative enrichment during the warmer summer months. Groundwater samples in the vicinity of Loveday were intermediate in isotopic composition between the River Murray and Loveday surface water (Table II). Upon flooding, isotopic concentrations declined in both basins but increased noticeably once the inlets were closed again. Interestingly, the inlet from the River Murray to Mussel Lagoon was also closed on 1 October 2006 and isotopic concentrations in Mussel Lagoon increased in a similar fashion as in Loveday North and South afterwards. There was a decrease in isotopic concentration in Loveday South following a rain event in January 2007 (when the basin was almost dry), consistent with the relatively isotopically-depleted composition of this rain event ($\delta^{18}O = 1{\cdot}18$‰; Corriveau, 2007).

The trends in isotopic enrichment observed during evaporation at the Loveday sites are similar to the ones observed in similar studies in the Murray—Darling Basin. Simpson and Herczeg (1991) found that the slope for the River Murray δ^2H–$\delta^{18}O$ evaporation line was ~5·8, similar to Loveday waters (~5·1; Figure 10). Overall, the stable isotope concentrations in Loveday North, Loveday South, and in Mussel Lagoon at the end of the drying period were close to values expected from isotopic equilibrium with atmospheric moisture in the region (Allison and Leaney, 1982; Simpson *et al*., 1992; Corriveau, 2007), indicating that evaporation was the main loss of water from all three water bodies during the post-flooding period.

Water balance

During the flooding experiment, approximately 942 and $866{\cdot}10^3$ m^3 of water were added to the North and South basins, respectively (Table III). This is probably a low estimate because it is possible that some water was

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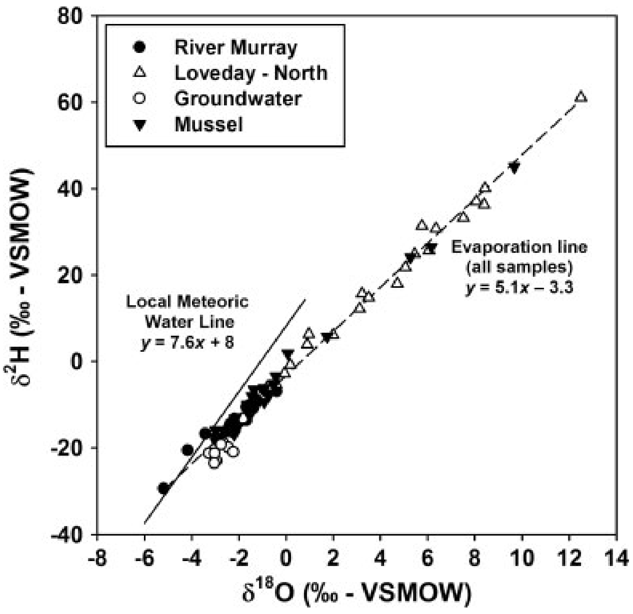

Figure 10. Deuterium and oxygen-18 concentrations in the River Murray, Loveday North, groundwater and Mussel Lagoon during the study period. Local meteoric water line from Simpson and Herczeg (1991)

Table III. Water balance estimates for the Loveday North and South basins

Period	*P*	*E*	*D*	*V*	ΔV	*I*
			North Basin			
Pre-flooding	204	1091	102	208	112	897
Flooding	40	156	26	1061	853	943
Post-flooding	96	1534	52	250	−811	575
			South Basin			
Flooding	65	304	—	645	645	866
Post-flooding	36	1135	—	0	−645	454

All values in 10^3 m^3. V is the volume at the end of the period and ΔV is the change in volume during the period. I is a combination of inflow from the River Murray, storm runoff, groundwater discharge, and groundwater recharge.

also lost from the basins as groundwater recharge to the Coonambigdal Clay aquitard during filling. Evaporative losses were large during the post-flooding period (1557 and $1135 \cdot 10^3$ m^3 for the North and South basins, respectively) while precipitation and drainage inputs were relatively small (Table III). Evaporative losses were greater in the South Basin relative to its volume, owing to its larger increase in surface area relative to the North Basin after flooding. I was relatively large in both basins in the post-flooding period (575 and $454 \cdot 10^3$ m^3 for the North and South basins, respectively). While two temporary surface water releases were the likely source for most of the post-flooding I in the North Basin, the source of I in the South Basin during the same period is less clear.

DISCUSSION

The flooding experiment provided an opportunity to evaluate potential mechanisms to explain the rapid re-salinisation of disposal basins following flooding events. The proposed mechanisms included: (i) evapoconcentration; (ii) dissolution of evaporites; (iii) mixing of floodwater with saline vadose water and shallow groundwater; and (iv) ongoing saline groundwater discharge. While the knowledge of the water balance for the Loveday Basin flooding experiment is incomplete, it is clear that evapoconcentration was the principal resalinisation mechanism. However, there is circumstantial evidence that drainage of shallow groundwater or vadose water from the Coonambidgal Clay contributed to the basin's water and salt balances during the post-flooding period. The evidence for both processes is reviewed below.

Evaporation alone during the post-flooding period would have been sufficient to remove all the water stored in either basin at the end of the flooding period. Maximum depth of the basins at the end of flooding was ~1·2 m in the North and ~1·0 m in the South Basin. In contrast, total pan evaporation between September 2006 and early March 2007 was ~1·6 m. Likewise, the strong enrichment of the stable isotopes of water during the drying phase demonstrated that evaporation was the dominant hydrological process post-flooding. Direct rainfall and drainage discharge to the basins were minimal during the post-flooding period (Table III). Thus, additional inputs (I in Table III) of water occurred in the post-flooding period as otherwise the basins would have receded more rapidly. Possible sources of water in the North Basin included the two temporal openings of the gates post-flooding and groundwater discharge. The origin of the additional water input to the South Basin post-flooding is less obvious because the inlet remained closed and the basin appeared to be losing relative to the regional groundwater system. Storm runoff could not have been the sole contributor for I in the South Basin because much of the additional inputs occurred outside of large rainfall events. The only remaining possibility is drainage of shallow groundwater or vadose water from the surrounding Coonambidgal Clay as the water body receded.

While the water table was not measured in the Coonambidgal Clay during the experiment, the rapidly declining surface water levels in the South Basin post-flooding could have generated a gradient towards them. Similarly, along the River Murray, bank discharge from the Coonambidgal Clay can occur following flood events when surface water levels recede rapidly (Lamontagne *et al.*, 2005). While the Coonambidgal Clay is usually considered fairly impervious and with low vertical recharge rates (Jolly *et al.*, 1994), lateral movement of water and solutes in the upper meter of this geological unit could be relatively larger. This process would be helped by the tendency for significant dessication features to form when sediments from disposal basins are drying (examples in Loveday Basin are given in Lamontagne *et al.*, 2006).

Changes in salt storage—pre-flooding

The trends in the amount of salt stored in surface water also provide some evidence that an exchange of

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Table IV. Salt storage in the first meter of the subsurface over exposed areas of Loveday North Basin prior to flooding

	EC (dS m^{-1})	Depth interval (m)	Salt storage (kg m^{-2})
Efflorescences[a]	3·2–4·9	0–0·005	1[c]
Soil[a]	0·54–71	0–0·5	34[c]
Groundwater[b]	~70	0·5–1·0	7[d]
Total		0·0–1·0	42

The water table was 0·5 m below the surface on average at the sites where pits were sampled (see Lamontagne *et al*. (2006) for details). The large accumulation of salt in the soil is due to water table evaporation.
[a] From 1 : 5 soil–water extracts.
[b] Measured in the pits used for soil characterisation.
[c] From Pits COB1 and COB2 in Lamontagne *et al*. (2006) and assuming a bulk density of 0·7 kg m^3 between 0 and 0·2 m depth and 1·6 kg m^{-3} between 0·2 and 0·5 m depth.
[d] Assuming a porosity of 0·3 in the Coonambidgal Clay.

water and solutes occurred between the basins and the surrounding Coonambidgal Clay over the course of the study. However, before looking at the trends in surface water, salt storage in the Coonambidgal Clay prior to flooding is examined using data collected by Lamontagne *et al*. (2006) for the North Basin.

A large amount of salt is stored in the Coonambidgal Clay in the Loveday Basin area. In only the top meter of the Coonambidgal Clay profile in the North Basin (comprising a 0·5 m vadose zone and a 0·5 m saturated zone), 1 kg m^{-2} of salt is stored in surface efflorescenses, 34 kg m^{-2} as saline porewater in the vadose zone, and 7 kg m^{-2} in groundwater (Table IV). This large accumulation of salt in the vadose zone is common in areas with shallow water tables in Lower Murray floodplains because of relatively high rates of groundwater discharge by water table evaporation (Jolly, 1996; Slavich *et al*., 1999).

The increase in salt storage in the basins during the study could easily be accounted for by exchange of solutes with the Coonambidgal Clay. In the North Basin, salt storage between May and August 2005 (during the pre-flooding period) increased from ~6, 000 to ~9, 000 t (Figure 11). This corresponded to a time when the North Basin filled slightly (by ~189·10^3 m^2) presumably because of lower evaporative losses during the austral winter (Figure 3). Using the average values from Table IV, salt storage for only the top 1 m of the subsurface under the areas flooded between May and August 2005 would be ~8, 000 t. Thus, exchange of solutes with the Coonambidgal Clay during filling could easily account for the increase in salt storage in surface water. Because one of the filling mechanisms was probably decreased water table evaporation rates during winter, the salt gain may have been fostered by rising saline water tables in the Coonambidgal Clay along the margins of the wetland.

Drain discharge and regional groundwater discharge are unlikely to account for the observed changes in surface water salt storage between May and August 2005 in the North Basin. Salt input from drain discharge and the River Murray inlet (which was closed) was <100 t

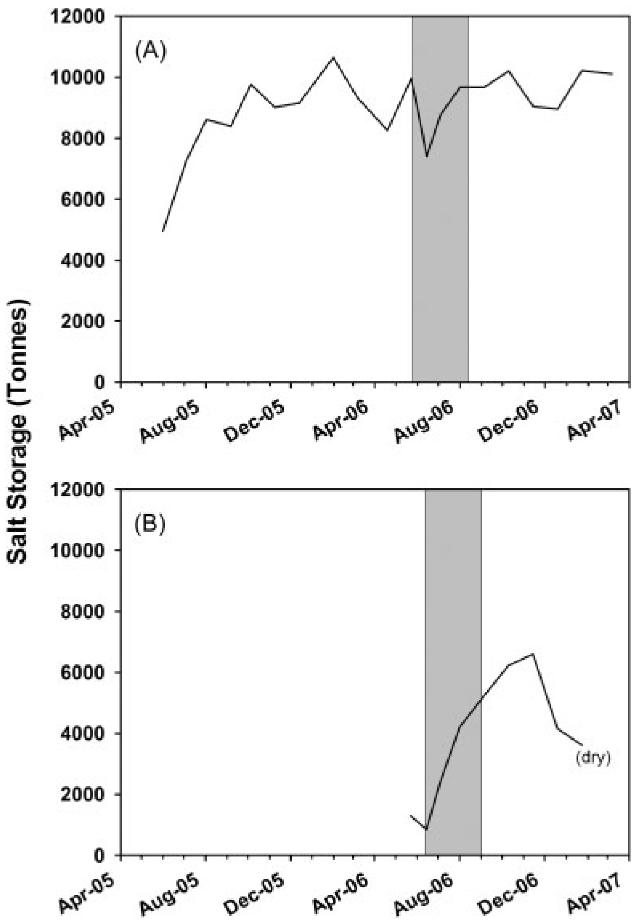

Figure 11. Salt storage in the water column of the North and South basins during the wetting-drying experiment

during this period. While not known accurately, regional groundwater discharge to the floodplain area of the two Loveday Basins was estimated at ~320·10^3 m^3 by GHD (2004). Assuming an average TDS of 25 g l^{-1} in regional groundwater, an even discharge rate over the year, and that all the groundwater discharge occurred to the North Basin, this would represent a salt input of ~1, 900 t between May and August 2005, or 2/3 of the observed salt load. However, the contribution of groundwater discharge to the surface water salt load was probably significantly smaller because a large fraction of regional groundwater discharge occurs as water table evaporation in this system (that is, not as discharge to the surface water bodies). In addition, a fraction of the estimated groundwater discharge would occur to the South Basin. While the contribution from other sources cannot be estimated accurately, mixing with shallow Coonambidgal Clay vadose water and groundwater could easily account for the increase in salt storage in the North Basin between May and August 2005.

Change in salt storage—flooding and post-flooding

There were more important changes in salt storage in the South than in the North Basin during and after flooding (Figure 11). In the North Basin, salt storage appeared to have decreased slightly early during the

Table V. Estimated salt balance for the Loveday basins (in tonnes)

Period	Precipitation	Drain	Change in Storage	Other inputs	Maximum river input[a]
North Basin					
Pre-flooding	2	303	4277	3972	197
Flooding	0·4	76	−162	−238	207
Post-flooding	1	155	349	193	128
South Basin					
Flooding	0·6	—	4225	4224	191
Early post	0·1	—	466	466	—
Late post	0·2	—	−5915	−5915	—

[a] When assuming that $I = S$ and TDS in River Murray water = $0{\cdot}22$ g l^{-1}.

flooding period but increased back to pre-flooding levels later. In the South Basin, salt storage increased during the flooding period, continued to increase early during the post-flooding period (Table V), and then declined to nil as the water body dried out. The period when salt storage decreased in the North Basin coincided with the occurrence of density stratification. As care was taken to collect integrated samples of the water column during that period, this probably represented a decrease in storage as opposed to sampling variability. One possible mechanism for the 'loss' of salt from the North Basin early during the flooding period may have been induced groundwater recharge by the added freshwater head on top of the saline water table (Massmann *et al.*, 2006).

The initial state of the basins (partially filled as opposed to nearly empty) and their morphometry may explain why more salt was remobilized in the South Basin following flooding. Because the surface area of the South Basin increased by 1250% (rather than by 72% in the North Basin), flooding in the South Basin provided a greater opportunity to gain salt from the Coonambidgal Clay. However, the South Basin continued to accumulate salt well into the post-flooding phase (Table V and Figure 11), even as it was shrinking in surface area. As there was no surface water input, regional groundwater discharge, evaporite mineral dissolution (see below), or large precipitation event during that period, the only possible salt source would be saline groundwater or vadose water from the Coonambidgal Clay. It is not possible to prove this latter mechanism because the water table in the Coonambidgal Clay was not monitored during the experiment. However, it is difficult to identify another potential large source of salt to the system. Using the salt storage estimates for the North Basin (Table IV), the salt gain to the South Basin during the flooding and early post-flooding phases (~4500 t) could easily be accounted for by exchange with the Coonambidgal Clay (the total salt storage in the top meter under flooded areas of the South Basin would be ~67, 000 t). Thus, only a small lateral exchange of water between the Coonambidgal Clay and surface water would be required to increase salt storage in South Basin.

Table VI. Solubility indices for various mineral phases that could be present in Loveday Disposal Basin

Formula	Mineral	High EC	Low EC
		31/05/2005	1/11/2006
EC (dS m^{-1})		73·2	14·7
$CaSO_4$	(anhydrite)	−0·18	−0·87
$CaCO_3$	(aragonite)	1·14	0·83
$CaCO_3$	(calcite)	1·29	0·98
$MgSi_2O_5$	(chrysotile)	4·16	1·44
$CaMg(CO_3)_2$	(dolomite)	3·14	2·12
$CaSO_4{\cdot}2H_2O$	(gypsum)	0·05	−0·62
NaCl	(halite)	−2·21	−3·74
$Mg_2Si_3O_7{\cdot}5OH{\cdot}3H_2O$	(sepiolite)	0·98	−1·03
$Mg_3Si_4O_{10}(OH)_2$	(talc)	5·45	2·39

Solubility indexes indicate the tendency for minerals to dissolve (when negative) or precipitate (when positive). Minerals actively controlling solute concentrations tend to have a SI ~0. Indexes estimated using the computer program PHREEQC (USGS).

Evaporite mineral dissolution

Evaporite mineral dissolution probably occurred at Loveday during flooding but was unlikely to have significantly changed salt storage in surface water. Prior to flooding, Loveday surface water was supersaturated with respect to carbonate minerals and gypsum (Table IV). This is consistent with mineralogical investigations of Loveday sediments which have found a wide range of carbonate minerals as well as gypsum stored in the top 30 cm of the sediment profile (Lamontagne *et al.*, 2006). Salinity was reduced enough during flooding to potentially reverse the solubility indices for gypsum and other accessory minerals (Table VI). This indicates that Ca^{2+} and ${SO_4}^{2-}$ in particular may have been transported into the water column from the sediment mineral pool. This is consistent with the observed small changes in the ratio of Ca^{2+} to Mg^{2+} in the water column following flooding (Lamontagne *et al.*, 2008). However, NaCl (the main pool of salt in the water column) remained undersaturated at all times. As NaCl represents ~75% of the salt mass in Loveday, no major gain or loss in salt mass occurred in the water column due to mineral precipitation or dissolution processes during the flooding experiment.

Conclusion

The flooding experiment at Loveday Disposal Basin indicated that flooding alone brings limited and short-lived environmental benefits to these wetlands from a salinity point of view. Because of the large salt store within the basins, flooding alone cannot lower salinity to levels where a healthy freshwater aquatic community would be expected to re-establish even in the short-term (Hart *et al.*, 1991; Nielsen *et al.*, 2003). The contrasting behaviour of the Loveday North and South basins to the same flooding experiment demonstrated that small differences in wetland morphometry can have a large impact on their hydrology in semi-arid floodplains. Loveday North is slightly more incised in the floodplain than the South Basin and remains a permanent water body because of a better connection with the regional groundwater system. The North Basin was also less prone to evaporative losses because it did not increase in surface area to the same extent as the South Basin for a similar volume of water added. A key finding of this study is the possibility that significant lateral exchange of water and solutes can occur between wetlands and the Coonambidgal Clay, a widespread surface aquitard in the Lower Murray floodplains. Because of the large mass of salt stored in shallow soils in the vicinity of disposal basins, even a small lateral exchange of water could result in a significant exchange of solutes in this environment.

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