Review of Salt Mobilisation from River Murray Floodplains and Wetlands: Processes and Prediction Tools

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Cover Photograph:
Description: Salinised wetland near Berri in South Australia
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EXECUTIVE SUMMARY

In response to the severe environmental degradation of the River Murray system, the Murray-Darling Basin Authority (MDBA) is in the process of implementing major water reform through the creation of the Basin Plan. The purpose of the Basin Plan is to provide an agreed Basin-wide framework for managing water resources in the Basin. The Basin Plan will incorporate an Environmental Watering Plan that informs the management of water held by the Commonwealth Environmental Water Holder and other planned environmental water under the Basin Plan.

It is well known that floodplain and wetland inundation from natural floods leads to mobilisation of salt stored in these environments into the River Murray, particularly in the lower reaches of the river and its tributaries. It is therefore not unreasonable to assume that some of the future environmental watering activities and other environmental management activities such as weir pool lowering and raising may lead to mobilisation of salt into the River Murray system. This potentially poses operational risks for downstream water users who could be exposed to elevated river salinities that limit their use of the water. These environmental activities also pose potential salinity accountability risks to the Salinity Registers operated under the MDBA Basin Salinity Management Strategy 2001-2015.

In this report we review the considerable volume of research and investigation that has taken place over the last 15-20 years on the impacts of natural and artificial flooding on salt loads to the River Murray. We found that while lack of data can often inhibit an estimation of the salt loads generated at any individual site for a particular flood, the driving processes are now well understood. At data-rich sites such as the Chowilla floodplain it has been possible to develop highly sophisticated groundwater and hydrodynamic surface water models that provide robust estimates of salt loads produced by both natural floods and environmental watering activities. At many other sites this level of sophistication may not be possible due to the limitations of low data availability and resources, and so the need for a simplified Rapid Assessment Tool currently exists, as recommended by a recent study by RPS Aquaterra (2011).

The eWater CRC and its partners have been developing a next generation integrated modelling system, known as Source IMS (Welsh et al., 2012). Given that in the near future Source IMS is likely to replace MSM-BIGMOD, IQQM and REALM, the current river systems models used in the Murray-Darling Basin, any development of decision support tools for predicting salt accessions from floodplains/wetlands should be compatible with this new modelling platform. As part of its contribution to the eWater CRC, CSIRO developed functionality in Source IMS that allows modelling of the water fluxes between groundwater and surface water in wetlands/floodplains (Jolly et al., 2010; Rassam, 2011). This functionality was implemented using fairly simple analytical/empirical approaches that allow its use in areas with limited data where detailed groundwater models are not available. A logical extension to this work is to develop capability within Source IMS to predict the salinity accessions from wetlands/floodplains to rivers following overbank flows and environmental watering activities. This will allow salt generation processes by both groundwater and surface water to be modelled.

It is therefore recommended that a Rapid Assessment Tool be developed within Source IMS. This will ensure tight coupling with the river systems model and thus allow rapid testing of large numbers of flow delivery and watering scenarios. Source IMS is the next generation integrated modelling framework and will be the primary tool for future river systems modellers in Australia. Embedding a tool to predict the salinity impacts of environmental watering into Source IMS will have an added benefit of highlighting the importance of this issue to river modellers.
1. INTRODUCTION

1.1. Historical salinity issues in the River Murray

High salinity levels are a long-recognised issue in the lower reaches of the River Murray below Swan Hill (Morton and Cunningham, 1985; Mackay et al., 1988; Williamson et al., 1997; Jolly et al., 2001). High salt concentrations are in part a natural consequence of Australia’s dry climate and highly weathered landscape that leads to large storages of salt in the soils and groundwater. However, clearing of native vegetation and dryland and irrigated agriculture have changed the water balance of catchments, leading to increased mobilisation of salt from saline aquifers into streams and wetlands.

River salinity levels can be highly variable due to fluctuations in river flow, groundwater inflows and groundwater salinity that result from variations in climate and water use. High salinity levels affect the suitability of water for drinking, irrigation, industry and recreation. For example, human drinking water should have a salinity less than 800 µS·cm⁻¹ (electrical conductivity (EC) units). While the impact of salinity on irrigation is complex, due to interactions between crop sensitivity, soils, climate and irrigation practices, damage to some plants can occur at salinity levels as low as 300 EC, and above 800 EC there can be significant impacts on many plants. High salinity levels also affect the health of aquatic and riparian ecosystems. While these ecosystems are adapted to this variability, the increased frequency and duration of high levels of salinity will impact upon their long-term health (Nielsen et al., 2003).

In response, the Murray-Darling Basin Authority (MDBA) (and its predecessor the Murray-Darling Basin Commission (MDBC)) has implemented a number of initiatives to manage the salinity of the river. The Basin Salinity Management Strategy (BSMS) commenced in 2001 with the aim of guiding Basin communities and governments in working together to control salinity and protect important environmental values and assets (MDBMC, 2001). It built upon the 1988 Salinity and Drainage Strategy (MDBMC, 1989) which, through the implementation of salt interception schemes and the effectiveness of state salinity action and land and water management plans, reduced salinity in the lower River Murray. Figure 1 shows a time series of recorded river salinity at Morgan, South Australia along with a modelled salinity time series representing the continuation of 1975 salinity management practices. Observed salinity levels are almost universally below what they would have otherwise been in the absence of the intervention activities.

![Figure 1: The effect of salinity management in the Murray-Darling Basin: comparing recorded mean daily salinity levels at Morgan over a 25 year period (July 1985 to June 2010) with modelled salinity levels without salt interception schemes and dilution flows – the “No further intervention” scenario (from MDBA, 2011a).](image-url)
1.2. Salinity risks to the River Murray from environmental activities

In response to the severe environmental degradation of the River Murray system, the MDBC implemented a major water reform in 2002 with the establishment of the Living Murray initiative. The aim of the initiative was to examine the scope for environmental flows for the River Murray, with an initial focus on maximising environmental benefits at six icon sites (Figure 2). The selection of these sites was part of the First Step Decision for the initiative, which also included recovery of an average of 500 GL·year⁻¹ of water over a five year period and the realignment of the $150 million Environmental Works and Measures program to focus on maximising environmental benefits for the six icon sites (MDBMC, 2004).

The next major water reform in the Murray-Darling Basin was the passing of the Water Act 2007 (Cwlth) which increased the powers of the Commonwealth to manage water resources in the Basin, and mandated the creation of a Basin Plan. The purpose of the Basin Plan is to provide an agreed Basin-wide framework for managing water resources in the Basin (MDBA, 2011b). The Basin Plan will incorporate an Environmental Watering Plan that informs the management of water held by the Commonwealth Environmental Water Holder (CEWH) and other planned environmental water under the Basin Plan. The Environmental Watering Plan sets objectives and targets for managing water-dependent ecosystems across the Basin. The hydrological indicator sites for key environmental assets are also shown in Figure 2.

It is well known that floodplain and wetland inundation from natural floods leads to mobilisation of salt stored in these environments into the River Murray and its tributaries, particularly in the lower reaches. These salt accessions to the river can occur for several months after the recession of a flood which, when combined with the reduction in the river’s dilution flows, leads to a downstream increase in river salinity (Figure 3). The short-term salt accessions that occur for the first few days or weeks are believed to originate from processes such as salt wash-off from the surface of floodplain soils and the beds of ephemeral wetlands, flushing of salt stored in the water columns and beds of permanent wetlands, and groundwater mixing processes within bank storage. The long-term salt recessions that can occur for many months after the flood peak are thought to be due to the inundation causing groundwater recharge beneath floodplains and wetlands that leads to a slow displacement of saline groundwater to the river and its anabranches (Jolly, 1996; Overton et al., 2005).

It is therefore not unreasonable to assume that some of the future environmental watering activities and other environmental management activities such as weir pool lowering and raising may lead to mobilisation of salt into the River Murray system. This has the potential to pose operational risks for downstream water users who could be exposed to elevated river salinities that limit their use of the water. These environmental activities also pose potential salinity accountability risks to the Salinity Registers operated under the MDBA Basin Salinity Management Strategy (BSMS) 2001-2015 (i.e. salinity impacts at the Basin target site of Morgan in South Australia). Concerns about this issue were raised in the 2007–08 MDBA Independent Audit Group – Salinity (IAG) report (MDBA, 2009) and have led to the recent study on River Murray floodplain salt mobilisation (MDBA, 2012) that is discussed in detail below.

A further complicating factor is that increases in river flow for environmental purposes could also potentially dilute salinity levels in the river which may offset the impacts of salt mobilisation from wetlands and floodplains. Overall, the salinity impacts of environmental activities remain a complex and open issue with a lack of technical understanding of the key processes. Consequently, there currently exists a paucity of modelling tools able to analyse policy options.
Figure 2. The Murray-Darling Basin, including Basin Plan regions, hydrologic indicator sites for key environmental assets, and Living Murray icon sites (from Crossman et al., 2011).
1.3. Purpose of this report

The aims of this report are to:

(i) succinctly summarise the current knowledge of the processes believed to influence river salinity impacts from environmental activities (Chapter 2); and

(ii) recommend a way forward for the development of appropriate decision support tools to assist in the development and analysis of policy options to manage any adverse river salinity impacts of these activities (Chapter 3).

To keep the review concise we have not included every publication on this topic but rather have focused on the studies that we believe have described the key driving processes and/or developed modelling and risk assessment tools. We describe the studies in approximately chronological order to illustrate the history of the knowledge that has been developed.
2. PREVIOUS STUDIES

There have been a number of efforts to assess the river salinity risks posed by natural flooding, weir pool lowering, and environmental watering activities. These are summarised below. Figure 4 shows the location of the places of interest described in this section.

2.1. Chowilla floodplain

A series of CSIRO studies in the 1990s focussed on natural flooding of the Chowilla floodplain (sites LM4/A16 in Figure 2). As shown in Figure 3, very large salt loads emanate from this floodplain following major floods, and the salt recessions can continue for more than 18 months after the flood peak.

Prior to the CSIRO studies, it was believed that the source of the salt was primarily from the floodplain soils. Jolly et al. (1993) indeed found that there were very large storages of salt in the floodplain soils. However, subsequent field (Jolly et al., 1994; Akeroyd et al., 1998) and modelling (Narayan et al., 1993; Jolly et al., 1998) studies found that there was very little ‘diffuse’ vertical recharge of floodwater due to the highly dispersive nature of the sodic Coonambidgal Clay surface soils which rendered them relatively impermeable once flooded. As a result there was only minimal evidence of leaching of salt from these soils. While there may be some early-time ‘wash off’ of salt from the surface of soils in the first days or weeks after the flood peak, it was concluded that the soils were not the major source of salt that entered the floodplain creeks and River Murray following a flood.

However, the field and modelling studies did show that there was good hydraulic connection between the floodplain aquifer (Monoman Sands) and the anabranch creeks and the river. There was clearly exchange of water in bank storage during floods, and given that the floodwaters and groundwaters had vastly different salinities, it was concluded that there was density-driven mixing of the two waters within bank storage (see Jolly et al., 1998; Massmann et al., 2006). As a result there could be water flowing from the aquifer back into the floodplain streams and the river after the flood recession that had enhanced salinities, although this process could only explain the first six months of the salt recession.

The process that controlled the salt recession beyond the first six months was inferred from observations that the relatively impermeable Coonambidgal Clay is thin or absent in some areas within the floodplain leaving the underlying Monoman Sands aquifer exposed. The hydraulic conductivity of the Monoman Sands is quite high (10 m·day⁻¹ or more) and so significant ‘localised’ vertical recharge may occur when these areas are inundated during a flood (evidence for this is the significant localised flood-induced freshening of groundwater at sites such as the “Garden of Eden” near Hancock Creek). If the recharge is high enough, then a localised groundwater mound may form beneath these areas. Dissipation of a mound over the subsequent months causes displacement of in situ groundwater stored in the region between the mound and the nearest stream. If the displaced groundwater is saline (as is the case over most of the Chowilla floodplain) then this will result in increased stream salinity. Jolly et al. (1994) estimated that a mound located 2.5 km from a stream would take about 18 months to begin displacing groundwater into the stream. Figure 5 summarises the major mechanisms that lead to the accession of saline groundwater to floodplain streams and the river following major floods.
Figure 4. Map of the lower River Murray showing key locations referred to in the text.
In the early 2000s, the South Australian government and the MDBC began to address the poor environmental health of the Chowilla floodplain. Several different environmental flow and groundwater management options were considered and CSIRO carried out a number of studies to assist in assessing the viability of the proposals. When options concerned with improving the flooding regime were considered, the potential for significant downstream salinity impacts was recognised; therefore CSIRO revisited the hypothesis that the dominant process of salt mobilisation was via 'localised' recharge during floods. Because of the complexity of the recharge processes, particularly identifying exactly where and when 'localised' recharge occurs, it is difficult to predict a priori the salt loads that will result from a particular flooding scenario.

Overton and Jolly (2004) and Overton et al. (2005) analysed the historical flow and salt load records for Chowilla Creek between 1974 and 2001 (Figure 3) to examine the major drivers of the high salt loads and long recession times following overbank floods. Two possible processes that could explain the observed salt loads were proposed:

- Higher flood levels inundate larger areas, which therefore ‘wash off’ more salt from the surface and leach the sub-soil by ‘diffuse’ recharge. In this hypothesis, post-flood salt loads would be greater after long periods of drought, as additional salt would be mobilised from salt stores that had accumulated in the soil profile and on the surface during the long dry periods.

- Higher flood levels raise groundwater levels by ‘localised’ recharge in more areas and create greater salt loads and longer recessions following the flood peak. In this hypothesis, post-flood salt loads would vary with the size of the flood, but not with the time since the last flood.

Overton and Jolly (2004) found a linear relationship between the size of a flood and the mass of salt released for the 12 month period following a flood (Figure 6). As the size of the flood determines the area of inundation, it was not surprising that Overton et al. (2005) also found a linear relationship between the area of inundation and the mass of salt released in the 12 months after a flood (Figure 7).
Figure 6. Relationship between salt load and peak river flow at Chowilla for 18 floods (from Overton and Jolly, 2004).

Figure 7. Relationship between salt load (tonnes day\(^{-1}\)) and area of inundation for Chowilla for 18 floods (from Overton et al., 2005).

Overton et al. (2005) also found that there was no relationship between the salt load following the flood and the time since the last flood (Figure 8). In this analysis, they minimised the effect of flood size by using 11 of the 18 floods with similar flood sizes. Each flood inundated between 1000 and 5000 hectares of floodplain. This suggests that salt leaching from ‘diffuse’ recharge and ‘wash-off’ was not the major contributor to post-flood salt loads. Instead, Overton et al. (2005) concluded that this was further evidence that localised recharge was the dominant process in long-term salt load release.
Overton et al. (2005) categorised each flood into four types, based on both the conditions preceding the flood as well as conditions in the 12 months after the flood peak (Figure 9). The amount of salt mobilised after a flood was not predicted by the conditions preceding the flood, i.e. salt loads for floods following a drought period (red symbols) were not greater than salt loads for floods following a recent flood (yellow symbols). Instead, Figure 9 shows that the conditions following a flood affect the amount of salt mobilised for a given maximum flow, with floods followed by very low flows (green symbols) displacing greater salt loads than floods followed by very high flows (blue symbols). This means that when a flood is followed by high flows for the following 12 months, there are lower than average salt loads to the river. It is likely that the ‘missing’ salt will be delayed, not entering the river until river levels return to low flow conditions. They note that this is not a dilution effect, as the graph shows total salt loads and not salt concentrations. They conclude that salt loads following floods are driven by groundwater levels and not ‘diffuse’ recharge or ‘wash off’. As a result of this and earlier CSIRO research the South Australian government used this conceptual understanding to make predictions of the downstream salinity impacts of environmental flow options at Chowilla (e.g. Howe et al., 2007).
2.2. Are the findings at Chowilla applicable elsewhere?

One of the key questions in the management of river salinity in the lower River Murray is whether the salt mobilisation processes observed at Chowilla are applicable elsewhere in the region. In theory they should be, given that floodplain soils, vegetation and climate are similar along the river in the region. Conversely, regional and floodplain hydrogeology does vary along the river (Evans and Kellett, 1989), which may influence flood recharge processes. Overall, this question is difficult to answer definitively as the very long period (17 years) between major floods in 1993 and 2010 has hampered the widespread implementation of field studies at other sites. Two recent studies undertaken in the lower River Murray area shed some light on this important question.

Lamontagne et al. (2005) studied groundwater–surface water interactions in the riparian area of a floodplain at Hattah–Kulkyne near Mildura in 1999-2001, a period that included two small floods. A combination of piezometric surface monitoring and environmental tracers were used to study two sites: the first on a sandy point bar on a bend of the river, and the other in an area with steep clay-lined banks. The environmental tracers suggested that the origin of groundwater under the floodplain was principally bank recharge in the riparian zone and a combination of diffuse rainfall recharge and localised floodwater recharge elsewhere in the floodplain. Although the River Murray was losing water to groundwater during periods of low flows, bank discharge occurred during some flood recession periods. The way in which the water table responded to changes in river level was a function of the type of stream bank present, with point bars providing a better connection to the alluvial aquifer than the more common clay-lined banks. The groundwater chloride response to a small flood indicated that significant ‘diffuse’ vertical recharge did not necessarily occur following the inundation of the riparian zone.

The SA Department of Water, Land and Biodiversity Conservation carried out an artificial flooding experiment on the Bookpurnong floodplain near Lock 4 in 2005-2007 (White et al., 2009). Soil salinity was measured at several sites in the flooded area before and after two inundation events. While leaching at the top of some of the profiles was observed, complete
flushing (as would be expected if there were significant ‘diffuse’ vertical recharge from inundation) was not observed. Groundwater levels in the inundated area rose during inundation but a coincident river level rise meant that it was difficult to distinguish between the groundwater response to inundation (i.e. ‘diffuse’ vertical recharge) and that due to the river level rise (i.e. lateral bank storage exchange). Earlier experiments of artificial flooding in a wetland at Chowilla (Holland et al., 2009a), and weir pool raising downstream of Chowilla (Jolly, 2001; Berens et al., 2007) showed the potential significance of bank storage. In the case of the Bookpurnong floodplain experiment, attempts were made to detect the increase in river salinity due to inundation. No clear observation could be made during the first inundation event due to high river flows. A localised 20 $\mu$S·cm$^{-1}$ (8%) increase in river salinity was detected following the second inundation, indicating that artificial inundation of a floodplain could mobilise salt to the river (White et al., 2009).

The overall conclusion that can be drawn from these field studies is that the findings are consistent with those of the extensive research at Chowilla, as described in Section 2.1.

### 2.3. Salt accumulation in wetlands

Another important difference between Chowilla and many other lower River Murray floodplains is that the wetlands are mostly ephemeral, whereas wetland complexes elsewhere are predominantly permanent wetlands connected to the river. The salt accumulation and mobilisation processes in permanent wetlands are likely to differ from those in ephemeral wetlands. This work was informed by an international literature review by Jolly et al. (2008) of the key processes affecting groundwater-surface water interactions in arid/semi-arid wetlands.

As was highlighted by Holland et al. (2005) the transport of saline groundwater from local and regional aquifers to the river can be greatly influenced by the incised lagoons and wetlands that are present in the adjacent floodplain. Banks et al. (2009) studied the interactions between a saline lagoon and the semi-confined Monoman Sands aquifer on the Bookpurnong floodplain over a one year period using hydrogeological techniques and environmental tracers. Piezometric surface monitoring showed that the lagoon acted as a flow-through system intercepting local and regional groundwater flow. A chloride mass balance calculation determined that approximately 70% of the lagoon winter volume was lost by evaporation. A stable isotope mass balance calculation estimated leakage from the lagoon to the underlying aquifer. Around 0–38% of the total groundwater inflow into the lagoon was lost to leakage compared to 62–100% of groundwater inflow lost to evaporation. Overall, it was concluded that floodplain wetlands of the type examined in this study behave as groundwater flow-through systems, in which groundwater discharge is intercepted and concentrated before eventually being recharged to the floodplain aquifer.

Crosbie et al. (2009) investigated the surface water – groundwater interactions of three wetlands of the lower River Murray during a wetting and drying cycle aimed at mimicking the natural surface water flow regime. This study, which used a combination of hydrometric, natural tracer and geophysical techniques, found that when inundated, two of the wetlands (Banrock Station Wetland near Lock 3 and Lake Littra at Chowilla) were groundwater recharge features, while the other (Hart Lagoon near Waikerie) was a groundwater throughflow system. Following drying of these wetlands, a reversal of the hydraulic gradients occurred, resulting in all three wetlands becoming groundwater discharge features (Figure 10). The transformation of these wetlands into groundwater discharge features after the removal of surface water suggests that there is an increased risk of salinisation when wetting and drying cycles are re-introduced to permanent wetlands. Whilst the study clearly established the salt accumulation processes in the wetland it did not extend to the salt mobilisation processes following natural or artificial floods.
Saline drainage water from irrigation areas along the lower River Murray has often been disposed of in evaporation basins, several of which are former ephemeral floodplain wetlands. This has caused them to become extremely ecologically degraded due to high soil and water salinity. An experimental flooding of one of the wetlands used for drainage disposal (Loveday Disposal Basin near Barmera) was carried out in 2006 to evaluate the environmental benefits of periodic flooding with freshwater. Lamontagne et al. (2009) evaluated the water and salt balances of the permanent North Basin and ephemeral South Basin during the experiment using hydrometric techniques as well as observations of changes in total dissolved solid (TDS) concentrations and the stable isotopes of water at four sites. Filling of the basins with freshwater decreased the surface water salinity (as total dissolved solids) from approximately 60 to 9 g L⁻¹. Once flooding was completed, the water level in both basins receded rapidly and then within five months they had re-salinised to pre-treatment levels (Figure 11). 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 found to be a source of salt to the basins. The salt mass stored in the South Basin surface water increased during flooding and early after flooding, suggesting there was a significant salt input from the flooded soils.
The overall conclusion that can be drawn from these studies is that the wetlands of the lower River Murray are typically groundwater discharge areas when empty and store significant masses of salt in their beds and the underlying soils. Furthermore, when river water enters these wetlands (e.g., via a permanent connection to the river, or from natural overbank floods or by artificial flooding) the salt is mobilised into the surface column where it can be evapor-concentrated. Moreover, in flow-through wetlands this can lead to recharge of more saline water to the floodplain aquifer. If there is good surface water connection to the river then flooding of a wetland can potentially pose a significant risk to river salinity if the saline surface water is partially or fully flushed out of the wetland. Additionally, if there is significant recharge to the underlying floodplain aquifer when the wetland is flooded, it can also pose a risk to river salinity via the ‘localised’ vertical recharge groundwater process described in Section 2.1.

2.4. Weir pool lowering

During the early 2000s the lowering of weir pools (i.e., the reaches between the major river regulation structure such as the locks and the barrages) in the lower River Murray was considered as a means of reinstating elements of the natural river water level fluctuations, in order to improve wetland and river ecosystem health. Due to the large volumes of saline groundwater and surface water stored within the floodplains and wetlands there was concern that weir pool lowering could lead to adverse river salinity outcomes.

Figure 11. Total Dissolved Solids concentrations in Loveday Disposal Basin (A) North (sites 2 and 3) and (B) South (site 4) (from Lamontagne et al., 2009).
The study of Barnett et al. (2003) described the key processes and driving factors which could result in salinity impacts in the river and reviewed previous weir pool lowering trials and periods of naturally low river levels. They found that weir pool lowering is likely to induce increased salt loads towards the river from both groundwater and backwaters (i.e. wetlands and anabranches). The major factors found to control the movement of salt towards the river from weir pool lowering were: (i) the salinity of the groundwater adjacent to the river; (ii) water table gradients adjacent to the river; (iii) aquifer hydraulic conductivity adjacent to the river; (iv) rate of weir pool lowering; (v) connection of the backwaters with the water table; and (vi) the sill level of the backwater connections.

Barnett et al. (2003) also developed prediction tools to estimate the magnitude of the salt load increases using a combination of different techniques, including calibrated MODFLOW (McDonald and Harbaugh, 1988) groundwater models, GIS models, spreadsheets using Darcy’s Law and backwater salinity measurements. They applied these prediction tools to all of the weir pools in the South Australian portion of the River Murray and found that the highest predicted impacts would be in the reach between the barrages and Lock 1, and also the reaches between Lock 2 and Lock 5. However they cautioned that there were very large uncertainties (±50%) associated with the estimated groundwater contributions. They also cautioned that the complex relationship between river flow and salinity, and the uncertainties in estimating both, meant that the salinity impact from weir pool lowering may be difficult to distinguish from natural fluctuations in river level and salinity and so the actual impact may be difficult to quantify.

2.5. Chowilla MODFLOW model

Concerns over the salinisation of the anabranch creeks and soils of the Chowilla floodplain and the associated impacts on River Murray salinity and floodplain vegetation health led to a proposal for a salt interception scheme (SIS) on the Chowilla floodplain. A MODFLOW model of the Chowilla floodplain was developed by Yan et al. (2005) to assist in assessing the effectiveness of a range of SIS options.

The focus of subsequent investigations at Chowilla then moved to environmental flow options. It was considered that artificial flooding that mimicked the natural conditions could be an important management option for improving the health of Chowilla floodplain vegetation during periods of below average flow in the River Murray. It was concluded that long-term improvements in flooding regime could be achieved by the construction of a flow regulator on Chowilla Creek (the main anabranch of the Chowilla floodplain) and that this would have significant benefits for the floodplain vegetation (Overton and Doody, 2008). One of the issues concerning the use of the regulator was that its operation would result in mobilisation of salt from the floodplains and backwaters of the Chowilla system (Overton et al., 2005).

The Chowilla MODFLOW model was then used by Howe et al. (2007) to simulate the aquifer hydraulic response to natural flooding and to predict impacts of the proposed flow regulator. Thirty year (1977-2007) scenarios were run which allowed estimation of the salt load accession to the anabranch creeks (which ultimately enter the River Murray via Chowilla Creek) resulting from: (i) natural flooding; (ii) flooding induced by the proposed flow regulator; (iii) operation of a proposed groundwater management scheme; and (iv) operation of both (ii) and (iii). The model predicted that operation of the proposed regulator nine times over the thirty year period would result in a 25% increase in the average salt load from that which would occur under natural flooding. It was also predicted that operation of the proposed groundwater management scheme alone would result in a 39% reduction in the average salt load from that which would occur under natural flooding. When the proposed regulator and groundwater management scheme were operated in unison over the 30 year period the model predicted a 21% reduction in the average salt load from that which would occur under natural flooding.

The Chowilla MODFLOW model is currently being revised in response to an independent review (Salient Solutions, 2008) and more recent data collected since the original model development by Yan et al. (2005).
2.6. Chowilla Salt and Water Balance Model

As described in Section 2.5, one of the issues concerning the use of the Chowilla Creek flow regulator is that its operation may result in mobilisation of salt from the floodplains and backwaters of the Chowilla system. The aim of the SKM (2010) study was to develop a salt and water balance model that would allow in-stream impacts of the flow regulator to be estimated at a timescale of days within the River Murray. The model was constructed and run using outputs from the Chowilla MODFLOW model (described in this report in Section 2.5), and from a hydrodynamic surface water model of the Chowilla floodplain. The primary improvement of this model upon the previous Chowilla MODFLOW model was the ability to simulate the surface water pathways for salt mobilisation to the River Murray (i.e. (i) floodplain salt wash-off during flood inundation, and (ii) backwater connection, inundation during flooding, discharge on flood recession and subsequent disconnection). The model was validated using historical flooding events and three regulator scenarios (each with a different operating height for the regulator wall) were run in order to predict the incremental salinity (as EC) increase in the River Murray downstream of the Chowilla Creek confluence. The predictions estimated that the higher the level the water was held behind the regulator wall, the greater the incremental EC increase in the River Murray, and the higher the proportion of the salt load that came from surface wash-off rather than groundwater inflows. However, the contribution to the incremental EC increase in the River from surface wash-off (6.2% - 13.2%) was estimated to be much smaller than that from groundwater inflows (93.8% - 86.7%). These results concur with the conclusions of the CSIRO research described in Section 2.1.

2.7. Lindsay-Mulcra-Wallpolla floodplain system

The Lindsay-Mulcra-Wallpolla floodplain is an anabranch system immediately upstream of Chowilla and is part of the Living Murray Riverland-Chowilla Icon Site. Like Chowilla, the ecosystem health of Lindsay-Mulcra-Wallpolla (LMW) system is threatened by floodplain salinisation and lack of flooding. There also exists the same concern that flow management options to improve the health of this ecosystem may result in the mobilisation of salt into the River Murray. Such concerns led the Mallee Catchment Management Authority to commission a study (REM, 2007) to examine this issue in the light of the considerable knowledge developed from the research and investigations at Chowilla. The study analysed the relationships between historic changes to groundwater levels, surface water flows and salt loads.

In terms of temporal patterns in salt mobilisation processes, the REM (2007) study found differences between Chowilla and the LMW system. At Chowilla, peak salt loads were found to lag behind peak flows and were followed by a very long salt recession, whereas in the LMW system peak salt loads appear to rise and fall sharply with peak flows (Figure 12). This observation inferred that rapid export of salt occurs from the LMW system during a flood. They concluded that this result indicated that the conceptual model used to explain peak salt loads at Chowilla may not hold for the LMW system. The study found only a few differences in the hydrogeological setting between Chowilla and Lindsay-Mulcra-Wallpolla. The latter site features a deeper water table, a larger area of low salinity groundwater, and the occurrence of low-permeability Blanchetown Clay on the floodplain beneath Wallpolla Island. Therefore it was concluded that differences in the timing of salt loads and flow were due to fundamental differences in the salt export processes. It was suggested that the peak salt load from the LMW system could be due to the flushing of salt from floodplain soils and backwaters that are stranded between floods. However, it is important to note that REM (2007) concluded that there were insufficient data to determine the relationship between salt load and flow for the whole of the LMW system and so these conclusions may only relate to the Lindsay River.
In terms of the magnitude of the salt loads mobilised, the REM (2007) study found that the temporal pattern of salt loads in the upper Lindsay River indicated that the base salt load in the early to mid 1990s (when more frequent flooding occurred) was one to two orders of magnitude higher than the base salt load measured during the mid 2000s. They concluded that the main reason for this was that groundwater levels had fallen on the floodplain due to lack of flood flows and so the rate of discharge of saline groundwater had also fallen. They further concluded that the implementation of flow strategies to replicate high flow periods would increase the base salt load from around 1 T·d⁻¹ to 10 – 100 T·d⁻¹ in the upper Lindsay River system.

This study highlighted the potential for differences between sites in the timing and magnitudes of salt load mobilised to the River Murray following flooding, depending on whether the exportation of salt is dominated by floodplain groundwater processes or by the flushing of surface features such as backwaters. This study also highlighted the fact that

Figure 12. Salt loads from Chowilla and Lindsay Island (from REM, 2007).
data paucity makes it hard to provide a reliable estimate of the salt loads generated from a given site.

2.8. MDBA Flood recession salt mobilisation project

The 2007-08 IAG report (MDBA, 2009) recommended that the MDBA urgently facilitate development of a conceptual model of flood recession salt mobilisation as well as operational response management plans in order to prepare for the next flood.

The MDBA subsequently commissioned a study (MDBA, 2012) focussing on salinity impacts at Morgan, the Basin salinity target site for the BSMS. The study comprised: (i) a literature review of previous studies of River Murray floodplain processes; (ii) an examination of the key regional data sets and key floodplain characteristics for each of the five major reaches and 28 sub-reaches of the lower River Murray floodplain between Euston and Murray Bridge; (iii) an analysis of in-stream salinity and flow data, both measured and predicted [by the MSM-BIGMOD model (Close, 1996; MDBC, 2002)]; (iv) development of a floodplain salt conceptual model; and (v) a preliminary investigation of operational procedures for mitigating salinity exceedances at Morgan.

The MDBA (2012) literature review provided a general overview of floodplain and wetland salinisation processes, but omitted the wetland salinisation studies of Banks et al. (2009), Crosbie et al. (2009), Holland et al. (2009a) and Lamontagne et al. (2009), and regional-scale floodplain salinisation modelling of Overton et al. (2003), Holland et al. (2005) and Holland et al. (2009b). The report presented a generalised floodplain salt conceptual model (Figure 13) highlighting the potential salt storage locations and mobilisation processes. The review presented a summary of the indicative timing of salt inputs to the river before and after the 1981 flood, distinguishing between bank storage, floodplain inundation, backwaters, saline pools and surface wash off (Figure 14).

![Figure 13. Floodplain Salt Conceptual Model (from MDBA, 2012).](image-url)
Figure 14. Indicative timing of salt inputs to the River Murray through a flood cycle (from MDBA, 2012).
The MDBA (2012) study carried out an analysis of the unaccounted salt inflow data from a MSM-BIGMOD history match run for the period July 1970 to June 2009. MSM-BIGMOD estimates unaccounted salt inflows in order to achieve the best fit to the observed river salinity data. Therefore this fitting parameter should include all groundwater inflows and unaccounted surface water inflows. The unaccounted salt inflows for the 39 year period were divided into three flow ranges (i.e. <7 GL·day⁻¹, 7-40 GL·day⁻¹, and >40 GL·day⁻¹), four decadal time periods (i.e. 01/07/1970 to 30/06/1979, 01/07/1979 to 30/06/1989, 01/07/1989 to 30/06/1999, and 01/07/1999 to 30/06/2009) and four river reaches (Euston to Lock 9, Lock 9 to Lock 5, Lock 5 to Morgan, and Morgan to Murray Bridge). These were presented in a three-dimensional bar diagram (Figure 15), from which it was concluded that the reach between Lock 5 and Morgan features the highest salt inflows. The reach between Lock 9 and Lock 5 features the greatest variability between time periods. The study then analysed the unaccounted salt inflow data for both of these reaches in greater detail.

From analyses of MSM-BIGMOD model outputs and interpretation of measured in-stream salinity and flow data, it was concluded that the 2000-2009 drought would not significantly increase the post-flood salt inputs to the river. Post-flood salinity regime and peak salinity levels would be affected by the flood magnitude and the management of the flood recession, particularly for the reach between Lock 9 and Lock 5, which concurs in agreement with earlier findings described in Section 2.1. It was also concluded from the unaccounted salt inflows analysis that the high salt loads and the predominance of short-duration early-time salt inflows after floods in the Lock 5 to Morgan reach were due to the draining of backwaters and anabranches, which are common in this reach. This was an important finding as it highlighted the role of permanent wetlands as an additional source of salt. Permanent wetlands may be the dominant source of salt to the river in reaches containing large areas of permanent wetlands.

Figure 15. MSM-BIGMOD unaccounted salt inflows by flow range (<7 GL·day⁻¹; 7-40 GL·day⁻¹; >40 GL·day⁻¹), decadal time period (P1: 01/07/1970 to 30/06/1979; P2: 01/07/1979 to 30/06/1989; P3: 01/07/1989 to 30/06/1999; P4: 01/07/1999 to 30/06/2009) and river reach (Euston to Lock 9; Lock 9 to Lock 5; Lock 5 to Morgan; Morgan to Murray Bridge) (from MDBA, 2012).
2.9. Salinity impacts of Commonwealth environmental watering activities

The Commonwealth Water Act 2007 established the Commonwealth Environmental Water Holder (CEWH) to manage the Commonwealth’s environmental water holdings and to protect or restore environmental assets in the Murray-Darling Basin and any other areas where environmental water is held. Concerns over potential salinity impacts from current and possible future Commonwealth watering activities led to a study by RPS Aquaterra (2011) that was conducted in four stages: (i) an initial risk assessment of the salinity impacts of the 2008-09 and 2009-10 environmental watering programs under a range of different watering scenarios; (ii) quantification of the potential salt mobilisation impacts of the 2008-09 and 2009-10 environmental watering programs; (iii) investigation and quantification of potential salt mobilisation under projected future environmental watering programs; and (iv) compilation and comparison of analytical and modelling techniques applied in assessing salinity impacts at Morgan, in accordance with the BSMS requirements.

In the first stage of the study, a framework was developed to assess the potential risk of an increase in river salinity at Morgan due to each of the 2008-09 and 2009-10 watering sites (37 in total) that were under the auspices of CEWH. Using the assumption that each of the sites was watered annually over the BSMS benchmark period (1975-2000), the study categorised each into low, moderate and high risk. It then assigned a risk confidence level for each site.

In the second stage, 18 sites that had a moderate or high risk rating with sufficient site data were quantitatively assessed for their salt load and EC impacts at Morgan using tools such as MODFLOW, MSM-BIGMOD and a proprietary analytical groundwater model (Hotspots2: Heritage Computing, 2010). A total of nine watering scenarios were assessed: (i-iii) inundation every year for 20 days, 50 days and 100 days duration; (iv-vi) inundation every 3 years for 20 days, 50 days and 100 days duration; and (vii-ix) inundation every 5 years for 20 days, 50 days and 100 days duration. The greatest impact for all sites arose from inundation for 100 days every year (total impact over 18 sites was an increase of 5.4 EC at Morgan. The lowest impact arose from 20 days of inundation every 5 years (total impact over 18 sites was an increase of 0.4 EC. The site with the greatest overall salinity impact was found to be the Chowilla floodplain. It was noted that where a river system is strongly losing with respect to groundwater, impacts of environmental watering activities are likely to be minimal. The risk of adverse impacts increases as systems become slightly gaining to strongly gaining. The potential salinity dilution benefits of delivery of the environmental water (and the return flow from watering) were also assessed in this stage. It was found that a continued annual watering of one of the Lower Lakes (Lake Albert) of 124 GL·year⁻¹ may result in a reduction of 3-9 EC, which is a similar order of magnitude to the total salinity impacts for the 18 sites analysed.

The third stage of the study involved development and use of a risk framework for river salinity at Morgan in order to assess the effect of projected future environmental watering programs on salt loads and river EC levels. The risk framework was applied to 11 reaches of the southern Murray-Darling Basin, of which three (Murrumbidgee to Darling, Loddon, and Darling to Lock 1) were found to be at moderate to high risk of adverse impacts. To assess the potential range of salt load impacts, quantitative assessments for each of these reaches were undertaken by modelling a range of groundwater flux and salinity scenarios. Model results suggested that environmental watering in the reach between the Darling and Lock 1 resulted in the greatest impact on river salinity at Morgan, with increases of 12-62 EC with a best estimate of 21 EC. Watering in the reach between the Murrumbidgee and Darling Rivers resulted in increases of 4-20 EC with a best estimate of 7 EC. Watering in the Loddon reaches resulted in increases of 1-14 EC with a best estimate of 5 EC. In contrast, it was found that an annual total future watering volume of 1600 GL·year⁻¹ over all of the reaches considered in the study could result in a dilution benefit of approximately 78 EC. This was calculated by scaling the findings of a MSM-BIGMOD model run of the use of 500 GL·year⁻¹ at the six Living Murray Icon sites, which found a total decrease of 24.4 EC at Morgan (i.e. 1600/500 * -24.4 = -78).
The final stage was concerned with a review of all available methodologies for quantifying the salinity impacts of environmental watering. This included comparing assumptions and associated confidence intervals, data requirements, availability, timeframes and costs. It was concluded that no single tool simulates all of the relevant processes; therefore a range of tools and supporting methods will be required for assessments. It was also concluded that high-risk sites will require sophisticated purpose-built models; conversely, low-risk sites may only require simple methods. Recommendations from this stage of the study (encapsulated in Figure 16) included: (i) that floodplain salinity risk maps should identify the level of salinity risk at each potential water site in the MDB; (ii) that risk maps be further developed to produce a Rapid Assessment Tool in order to estimate the long-term local salinity impact at a site; and (iii) that purpose-built numerical models be developed for high-risk sites where environmental watering would be an accountable action under the BSMS.

While the RPS Aquaterra (2011) study was comprehensive, several shortcomings are evident. Firstly, it focused only on the watering sites currently within the jurisdiction of CEWH. It is possible that these may change over time and that there may be watering activities supplementary to those carried out under the auspices of CEWH. The study also highlighted a number of existing tools that can be used to quantify the salinity impacts of environmental watering. These range from simple mass balance and flow net analyses through to simple analytical groundwater models (e.g. Hotspots2) and highly complex coupled groundwater (e.g. MODFLOW) and hydrodynamic (e.g. MIKE-FLOOD) numerical modelling techniques. A limitation of these techniques is the poor coupling between these models and the existing river systems models (i.e. MSM-BIGMOD) which provides the flow delivery predictions that are used in the assessments as well as the salinity, salt load and flow impacts at the Basin target site.
Figure 16. Proposed future framework to assess salinity impacts due to environmental watering (from RPS Aquaterra, 2011).
2.10. New generation river systems models

Traditionally, surface water planning in the Murray-Darling Basin has been carried out with the assistance of river systems models such as IQQM (Simons et al., 1996) in the Queensland and New South Wales/Australian Capital Territory tributaries, REALM (Perera et al., 2005) in the Victorian tributaries and MSM-BiGMOD (Close, 1996; MDB, 2002) in the Murray and the lower Darling Rivers.

None of the above models have the capability to simulate salt generation from floodplains and wetlands (although MSM-BiGMOD has some salt inflow capability, as described in Section 2.8). Moreover, the lack of uniformity of these models has hampered integrated basin-wide modelling required for the development of the Basin Plan. As a result of these shortcomings the eWater CRC and its partners have been developing a next generation integrated modelling framework, known as Source IMS (Welsh et al., 2012). The MDBA and each of the Basin States/Territory jurisdictions have been involved in the development and testing of Source IMS to ensure that its river modelling capabilities encapsulates all of the functionalities of the existing models river systems models. This has ensured that in the near to medium future it will become the replacement river modelling tool for each of the IQQM, REALM and MSM-BiGMOD models used in the Basin.

Source IMS also has many new functionalities, including the ability to model the water fluxes between groundwater and surface water in floodplains using the Groundwater-Surface Water Link Model (Jolly et al., 2010; Rassam, 2011; Figure 17). This functionality was implemented using fairly simple analytical/empirical approaches that enable use in areas with limited data where detailed groundwater models are not available.

![Figure 17. Schematic of the Groundwater-Surface Water Link Module in Source IMS showing: (A) 1-dimensional river link model, (B) processes for unsaturated connection, (C) processes for saturated connection, and (D) conceptual cross-sectional schematic for the analytical solutions (from Rassam, 2011).](image-url)
Source IMS also has the functionality to model the diversion of water into and out of wetlands as shown in Figure 18. This training example models Lake Bonney in South Australia receiving water from the River Murray via a Wetlands Hydraulic Connector (Lake Bonney Connector). Wetlands in Source IMS are modelled as Storages and so complete water balances for the wetland can be simulated.

![Figure 18. A training example Source IMS schematic of a section of the lower River Murray with a wetland (Lake Bonney) connected to the river.](image)

Whilst neither the Groundwater-Surface Water Link Module nor the Wetlands Hydraulic Connector currently models salt movement from floodplains/wetlands to a river, there is already quite a bit of functionality already in place that could be built upon to develop this capability. So a logical extension to the eWater CRC work is to develop capability within Source IMS to predict salinity accessions from wetlands/floodplains to rivers following overbank flows and environmental watering activities. This will involve developing functionality to model the salt balances of wetland Storages and to return salt and water leakage from these wetlands to the river via groundwater pathways with appropriate delays, and the exchange of salt and water stored in the wetland water column via the surface water connection(s) to the river. The development of such functionality will allow salt accession processes via both groundwater and surface water pathways to be modelled and could form the basis of the Rapid Assessment Tool recommended by the RPS Aquaterra (2011) study. As the functionality could be implemented as a generic capability within Source IMS it will be flexible and therefore have widespread applicability. Moreover, the MDBA and all of the Basin States/Territory jurisdictions in the Murray-Darling Basin are co-owners of Source IMS and so this will lead to a non-proprietary Rapid Assessment Tool that they will all be able to use in a consistent manner.
3. CONCLUSIONS AND RECOMMENDATION

There has been considerable research and investigation over the last 15-20 years into the impacts of natural and artificial flooding on salt loads to the lower River Murray. While a lack of data can often inhibit an estimation of the salt loads generated at any individual site for a particular flood, our understanding of the driving processes is now well established. At data-rich sites such as the Chowilla floodplain it has been possible to develop highly-sophisticated groundwater and hydrodynamic surface water models that provide robust estimates of the salt loads mobilised by natural and environmental flooding. However, at many other sites this level of sophistication may not be possible due to the limitations of low data availability and available resources.

RPS Aquaterra (2011) proposed that a Rapid Assessment Tool could be developed to quickly estimate the river salinity impacts from environmental watering due to groundwater salt mobilisation processes in a similar format to the SIMRAT (URS, 2005) tool used to determine salinity impacts from irrigation developments (i.e. based on simple aquifer parameters and analytical solutions). They suggested that a Rapid Assessment Tool could be used by managers as a first step toward estimating salinity impacts from environmental watering in the absence of detailed site specific assessments. We agree with their proposal for the development of a Rapid Assessment Tool and suggest that it is done in a manner that would ensure good coupling between a Rapid Assessment Tool and future river systems models. Given that in the near-medium future Source IMS is likely to replace the current river systems models used in the Murray-Darling Basin (i.e. MSM-BIGMOD, IQQM and REALM), any development of decision support tools for predicting salt accessions from floodplains/wetlands should be compatible with this new modelling platform. A logical extension to the eWater CRC work on groundwater-surface water interactions and wetlands is to develop further capability within Source IMS to predict salinity accessions from wetlands/floodplains to rivers following overbank flows and environmental watering activities. This will allow salt accession processes via both groundwater and surface water pathways to be modelled.

It is therefore recommended that a Rapid Assessment Tool be developed within Source IMS. This will ensure tight coupling with the river systems model and thus allow rapid testing of large numbers of flow delivery and watering scenarios. Source IMS is the next generation integrated modelling framework and will be the primary tool for future river systems modellers in Australia. Embedding a tool to predict the salinity impacts of environmental watering into Source IMS will have an added benefit of highlighting the importance of this issue to river modellers.
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