MURRAY-DARLING BASIN AUTHORITY

River Murray floodplain salt mobilisation and salinity exceedances at Morgan

Prepared by Australian Water Environments

August 2012

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Cover Image: Near Renmark, South Australia. Photo by Asitha Katupitiya, MDBA.

Prologue

This study was commissioned to understand the processes and thinking of responses to the risk of post flood salt mobilisation from floodplains of the River Murray. This report discussed the Morgan EC exceedences bringing in new knowledge of salt transport from floodplains and backwaters located between Swan Hill and Wellington however, it excludes upstream of Swan Hill floodplains because of perceived low antecedent salt.

The data mining approach presented in this report by which MSM-Bigmod salt load data was reviewed and unpacked provides important assessments of the river reaches from which significant diffuse salt inflows occurred. This report is a first attempt to unravel the significant salt loads from floodplains into the lower River Murray channel. Since this report is based on the regional scale analysis its findings should be carefully interpreted while deriving local scale outcomes.

In its present form this report shouldn’t be seen to describe the Authority or State policy with regard to the basin wide salt mobilisation processes or operation of the river.

Table of contents

List of Tables

List of Figures

List of Figures contained in Appendix

Abbreviations

AEM	Airborne Electromagnetic/Aerial Electromagnetic
AWE	Australian Water Environments
BOM	Bureau of Meteorology
BRS	Bureau of Rural Sciences
BSMS	Basin Salinity Management Strategy
CMA	Catchment Management Authorities
CSIRO	Commonwealth Scientific and Industrial Research Organisation
d	day
DfW	Department for Water (South Australia)
DHI	Company Name
DSE	Department of Sustainability and Environment (Vic)
EC	Electrical Conductivity (Expressed in this report in microsiemens per centimetre) – a measure of water salinity
EM	Electromagnetic
ENSYM	Environmental Systems Modelling Platform
FIM	Refer to RiM-FIM
GIS	Graphic Information System
GL	Giga Litre
ha	Hectare
HYDRUS	Software package for simulating movement of water and solute in variably-saturated media
IAG	Independent Audit Group
kv	Vertical hydraulic conductivity
km	kilometre
L	litre
LiDAR	Light Detection and Ranging – Optical remote sensing technology
mAHD	Metres Australian Height Datum
MDBA	Murray–Darling Basin Authority
MDBC	Murray–Darling Basin Commission
MDBMC	Murray–Darling Basin Ministerial Council
mg	milligram
MIKE-FLOOD	Refer to Glossary
ML	Mega Litre
mm	millimetre
MODFLOW	Refer to Glossary
MODFLOW/MT3D	Solute transport model for MODFLOW
MS (1 etc)	Milestone
MSM	Monthly Simulation Model
MSM_Bigmod	Refer to Glossary
Mt	Mega tonne
MURLEV	Part of the River Murray Flow and Salt Transport (RMFST) computer model
NanoTEM	Refer to Glossary
NEC	Company Name
NSW	New South Wales
P1, P2, P3, P4	Period 1 (July 1970 to June 1979), Period 2 (July 1979 to June 1989), Period 3 (July 1989 to June 1999) Period 4 (July 1999 to June 2009).
p a	per annum
PPK	Company Name
REM	Resource and Environmental Management
RiM-FIM	River Murray Flood Inundation Model
RMFST	River Murray Flow and Salt Transport
RoR	Run of River
SA	South Australia

SIMRAT	Computer model which assesses unconfined aquifer discharge responses
SIS	Salt interception scheme
SKM	Sinclair Knight Merz
SUTRA	Refer to Glossary
t	tonne
TM	Thematic Mapper used on Landsat Satellite
URS	Company Name
WAVES	Water, Atmosphere, Vegetation, Energy and Solutes. Computer model. Refer to Glossary
WINDS	Based on WAVES but is simplified to consider only salinity impacts.
WQSM	Water Quality and Salinity Management (Plan)
Ωm	Ohm metre - measure of resistivity

Glossary

Accounted salt inflows/outflows

A BIGMOD term used for salt inflows to the River Murray from tributaries and drains which are quantified using flow and salinity data. Salt inflows from other unquantified sources are referred to as unaccounted salt inflows., Outflows are those extracted for consumptive use (e.g. irrigation, stock and domestic uses).

AEM

Data collected during airborne electromagnetic (AEM) surveys undergo a process of inversion to yield estimates of spatial changes in ground conductivity. Bulk conductivity is affected by material properties, water salinity, porosity, saturation and temperature.

Anabranches

Branches of river that leave the main stream and rejoin it downstream.

Backwaters

Bodies of water that are held back by a dam or weir.

Bank storage

The water absorbed into the banks of a stream or river channel, when the river stage rises above the water table in the bank formations, then returns to the channel when the stage falls below the water table. See also flood bank storage and inter-flood bank storage.

Bank recharge

The process by which a stream or river recharges the aquifer through its banks when the stream level is higher than the adjacent groundwater.

Benchmark period

1975 to 2000. The Basin Salinity Target established under the BSMS is to maintain the average daily salinity at Morgan, South Australia, at a simulated level of less than 800 EC for at least 95% of the time, modelled with the same climate conditions as those observed over the benchmark period, under the current land and water management regime.

BSMS

Basin Salinity Management Strategy: the 15 year plan for communities and governments in cooperating to control salinity in the Murray–Darling Basin. The strategy establishes targets for the river salinity in each major tributary valley and across the Murray–Darling system. The strategy was agreed by the Murray–Darling Basin Ministerial Council on the 17th September 2001.

CMA

Catchment Management Authorities (CMAs) are responsible for managing natural resources at the catchment scale in the state of Victoria. Victoria has 10 catchment management areas.

Diffuse recharge

The process in which overbank flows recharge the groundwater through the soil surface of the floodplain.

ENSYM

Environmental Systems Modelling Platform (ENSYM) is a computer program that utilises spatial information such as climate data, elevation, vegetation type, soil type and land use to model outputs including surface water/groundwater dynamics and native habitat changes. It was developed by the Department of Sustainability and Environment (DSE) Victoria.

Evaporation
Water converting into a gaseous state (or vapour) from the water surface. Potential evaporation is the amount of evaporation that would occur if sufficient water source was available.

Evapotranspiration
Evaporation plus transpiration.

Flood bank storage
Storage of water and solute in the riverbank and adjacent aquifer caused by increases in river level due to a flood.

Flood inundation
The inundation of land that is normally dry through overbank flow from a body of water such as a river.

Flood recession
The period after a flood peak when river flow continues to decrease.

Floodplain
Land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge. It includes the floodway, which consists of the stream channel and adjacent areas that carry flood flows, and the flood fringe, which are areas covered by the flood, but which do not experience a strong current.

Floodplain Inundation Groundwater Recession
See Groundwater Recession

Freshwater lens
A body of freshwater that sits on top of and within more saline water due to differences in density.

Gaining floodplain
Reaches where the regional groundwater system is discharging into the floodplain alluvium.

Gaining stream
Reaches of river where groundwater is discharging from the floodplain alluvial sediments into the river.

Groundwater recession
The decrease in groundwater flow to the river due to depletion of groundwater in the floodplain following a period of floodplain inundation.

Hydraulic conductivity
The property of soil or rock that describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation.

Inter-flood bank storage
When a losing river condition is established in a gaining floodplain due to high evapotranspiration losses, the water losses through the river-bed and bank are classified in this report as "Inter-Flood bank storage". The losses are stored and subsequently returned to the river after overbank flooding re-establishes a groundwater gradient to the river.

Localised recharge
The process in which the floodwater infiltrates through isolated areas of the floodplain at a higher rate. These isolated areas may be depressions that fill during flooding, old levee banks or dunes with a thin or absent surface clay layer, or old meanders.

Losing floodplain
Reaches where the groundwater flow is from the floodplain sediments to the regional groundwater system.

Losing stream
Reaches of river where the river is losing water to the floodplain alluvial sediments.

MDBA
The Murray–Darling Basin Authority (MDBA) is the regulatory body responsible for managing the Murray–Darling Basin's water resources in the national interest since December 2008.

MDBC
The Murray–Darling Basin Commission (MDBC) was the executive arm of the Murray–Darling Basin Ministerial Council and held this responsibility over the period 1992 to 2008. The functions of the MDBC were subsumed by the Murray–Darling Basin Authority in 2008.

MIKE-FLOOD
A commercial software package which simulates floods involving any combination of rivers, floodplains and urban drainage systems.

MODFLOW
A modular, finite-difference, flow model that uses computer code to solve the groundwater flow equation. The program is used to simulate the flow of groundwater through aquifers.

MSM-Bigmod
MSM-Bigmod are two computer based models that work together. Output from MSM (Monthly Simulation Model) feeds into Bigmod (daily simulation model). The models route flow and salinity in the River Murray and associated storages. Models are used for water accounting, planning and flow and salinity forecasting. MSM-Bigmod can simulate the operation of the River Murray system to investigate what would happen under a given set of conditions.

Murray–Darling Basin
The entire tract of land drained by the Murray and Darling rivers, covering parts of Queensland, New South Wales, Victoria and South Australia, and the whole ACT.

NanoTEM
A geophysical method that measures the resistivity of subsurface materials. This resistivity will be affected by material properties, porosity and saturation of the materials and water salinity.

Pool level
A relatively constant level maintained for a given reach of river which is controlled by locks or weirs.

Recharge
The process of aquifer replenishment, usually from rainfall, irrigation accessions and losses from surface water bodies such as river and lakes.

Root zone drainage
The amount of water which passes below the active root zone.

Run of River
A technique that directly measures river salinity along a stretch of river over a number of consecutive days. Information collected together with flow data is used to calculate salt inflow to the river for each kilometre.

Salt Recession
Salt loads associated with groundwater recession.

Saturated zone
The zone in which the pore spaces in rock or soil are filled with water at a pressure which is greater than atmospheric pressure. The water table is identified as the top of the saturated zone in an unconfined aquifer.

SUTRA
A computer program that simulates fluid movement and the transport of either energy or dissolved substances in a subsurface environment. SUTRA numerically solves equations for fluid-density-dependent saturated or unsaturated groundwater flow by using the finite element method.

Throughflow floodplain
Reaches where the regional groundwater flow lines show that groundwater flows beneath or through the floodplain. In these reaches, the floodplain alluvium is potentially gaining water from the upgradient side, but is losing water to the regional groundwater system on the downgradient side.

Transpiration
The amount of water evaporated (used) by vegetation through leaves for growth. As with evaporation, it is estimated, based on weather data, plant variety and other indicators.

Unaccounted salt inflows
A BIGMOD term used for salt inflows to the River Murray from all groundwater inflows and unaccounted surface water discharges. Many discharges to the river are either un-regulated or not measured, such as discharges from evaporation basins in SA (e.g. Disher Creek Basin and Berri Basin), and outflow from anabranches and lagoons (e.g. Wachtels Lagoon, Gurra Gurra Lakes, Pike River). Accounted salt inflows/outflows are the product of flow and salinity from tributaries and drains, and the extraction for consumptive use (irrigation, stock and domestic uses).

Unsaturated zone
The zone between ground surface and the water table, which includes the root zone, intermediate zone and capillary fringe. Pore spaces in the rock or soil contain water at less than atmospheric pressure. Also known as the vadose zone.

Watertable
The groundwater level in an unconfined aquifer. The porous medium is saturated with water below the water table.

WAVES
A soil-vegetation-atmosphere model that uses Basin-wide datasets and a historical climate dataset to produce estimates of groundwater recharge.

Weir pool
A body of water held behind a weir

Summary

Project context, aims and approach

The environmental health and economic use of the River Murray depends on its salinity. Floodplain processes have proven to be some of the more complicated drivers of River Murray salinity. Aspects of floodplain processes have been studied for decades, but no general synthesis has been developed regarding their salinity impact.

Understanding the salinity impact of flood processes on the River Murray poses a number of interlinked challenges. The region is very large and includes a variety of hydrogeological and hydrological regions which include many small-scale local features. The system is extremely dynamic and in recent decades, management practices have modified the river’s flow rates and other behavior. Numerous processes contribute to the salinity of the Murray but their mechanisms and relative importance are poorly understood. There is also a lack of many kinds of data.

In short, despite ongoing research, we are still at the beginning of understanding salinity processes in the River Murray system. Nevertheless, the management of the River Murray requires the development of an overview, conceptual models, and management strategies.

This project *involves the integration of existing knowledge and the development of a conceptual model to improve the understanding of the flood-recession salt mobilisation in preparation for managing the impacts of high river salinities that are inevitable in the future.*

To meet the project objectives within the allotted budget and timeframe, an approach was developed which makes use of available studies and data, picking out the most critical items. It is not currently feasible to provide answers by only considering processes and upscaling them across the region, so we concentrate on regional-scale data to provide a broad overview.

The study focuses on the Lower River Murray floodplain, from Euston to Murray Bridge, and on salinity exceedances at Morgan. Salinity impacts below Morgan, where river water is extracted for urban water supply, have not been considered in detail as this is outside the scope of this study.

The outputs of the project are:

1. Collation of current findings on biophysical processes in the Lower River Murray floodplain, including surface-groundwater hydrology.
2. Reporting of key geographic areas and features that drive, and are impacted by, floodplain salt mobilisation.
3. A conceptual model that can demonstrably assist in understanding floodplain salt mobilisation and evaluation of mitigation strategies under current and future water management regimes.
4. Reporting of potential river operational strategies e.g., using dilution flows to avoid and mitigate post-flood salt accession to the River Murray.
5. A ‘road map’ for future investigations which will improve planning and prioritisation for the MDBA.

Historic and future salinity exceedances at Morgan

The Basin Salinity Management Strategy sets a modelled salinity target of 800 EC of salinity at Morgan 95% of the time. Understanding the timing of exceedances, and the processes contributing to the exceedances, is a primary aim of this project.

Salinity is salt mass in the river divided by the water volume. Figure ES1 plots river salinity at Morgan against flow rate at Lock 1. Figure ES2 is a close-up, plotting salinity for lower flow conditions and in decadal intervals.

The role of the dilutive capacity of the river is demonstrated in Figures ES1 and ES2, which shows that salinity typically exceeds 800 EC at flows below 5,000 ML/d, although not all low flows result in salinity exceedances.

The salt load entrained in the river at low flows also has a significant impact on the timing of exceedances. Figure ES3 illustrates that the frequency of 800 EC exceedances at Morgan reduced in the 1990s and 2000s compared to the previous two decades, and that there has been only one exceedance in the past decade. This indicates that there is now less salt in the river at flows <5,000 ML/d than there was in the earlier decades. The "salinity holiday" in the 2000s can be attributed to a range of salt load reduction mechanisms, including drought- induced salt storage in the floodplains, improved irrigation efficiencies, implementation of salt iInterception schemes (SISs), and low salinity surface water inputs from Hume Dam.

- Woolpunda and Waikerie SISs, which represent around less than half of the total salt interception capacity, prevent 280 t/day of salt from reaching the River Murray (MDBA 2009b). Figure ES3 demonstrates the impact on salinity if the Woolpunda and Waikerie SISs had not been built, and the 280 t/day were entering the river at all flows in the last decade. The results indicate that these two schemes alone have had a major impact on reducing peak salinity levels at Morgan. Without these two SISs, exceedances above 800 EC increase from 0% to 39% of the record for the last decade. In the last two decades, SIS implementation appears to have contributed significantly to the reduction in peak salinities, as well as reducing average river salinity levels.
- MSM_Bigmod unaccounted salt input estimates were used to estimate the quantum of additional salt stored in the floodplain since 2000. In the Lock 9 to Morgan reaches, where most of the salt reaching the river comes from, the additional salt may be less than 10% of the estimated floodplain salt mass in storage already. While lack of flooding appears to have reduced total salt export in this decade, the modest increase in floodplain total salt mass suggests that the salt load from floodplain salt sources may increase by a similar modest amount. The floodplain salt storage is not thought to be a major contributor to reduced salinity peaks at Morgan, although additional work may be required to quantify this effect.
- The major irrigation districts contributing salt to the river are partially or fully protected by SIS implementation, and irrigation mounds have not declined significantly over the last decade, so the reduction in salt inputs from irrigation are not thought to be a major contributor to the reduction in salinity exceedances.
- Low salinity inputs from Hume Dam and other tributaries during the drought period are also likely to have contributed to keeping salinities at Morgan below the target level.

Based on the analysis of salt patterns over the last 30 years, this study concludes that the 2000 to 2009 drought is unlikely to significantly increase the post-flood salt inputs to the river. The post-flood salinity regime and the peak salinity levels will however be affected by flood magnitude and the management of the flood recession.

Salt interception scheme implementation will continue to mitigate salt inflows and reduce salinity peaks at low flows. While the timing and magnitude of the mobilisation of the additional salt stored in the floodplain during the drought cannot be predicted with certainty, it is considered that the impact on river salinity is more likely to be modest than severe.

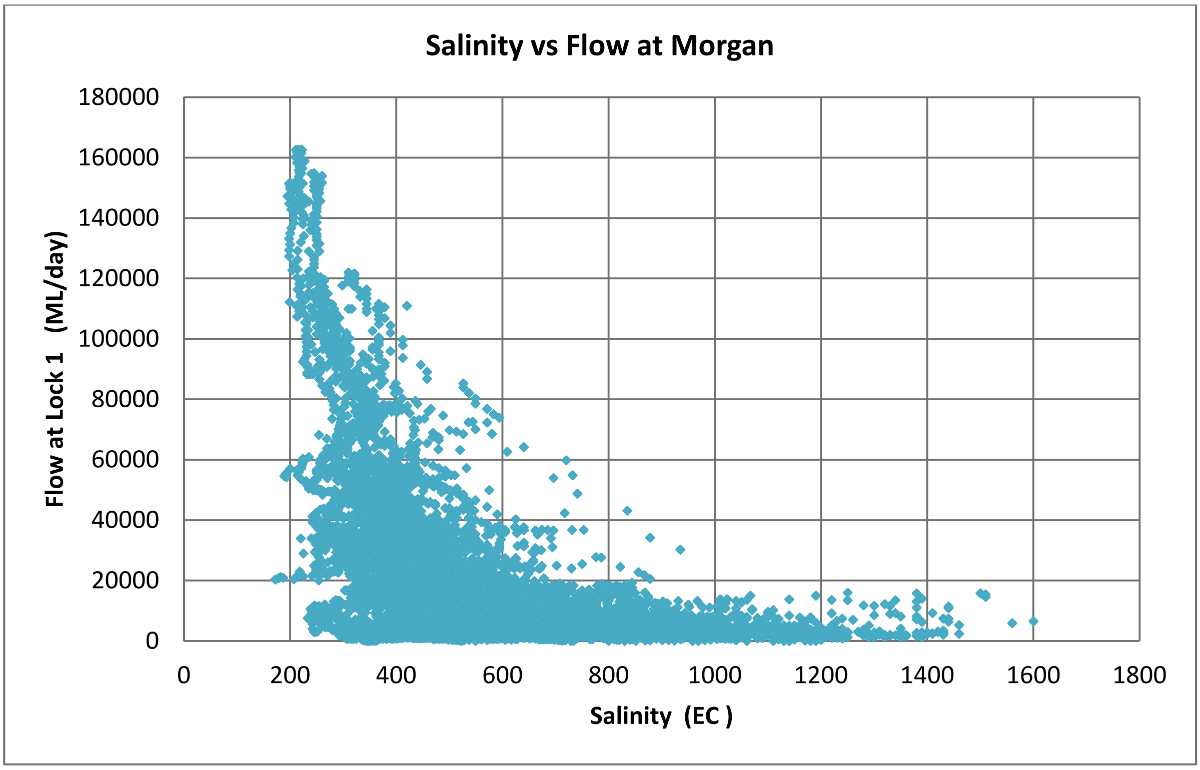


Figure ES1: Flow and salinity

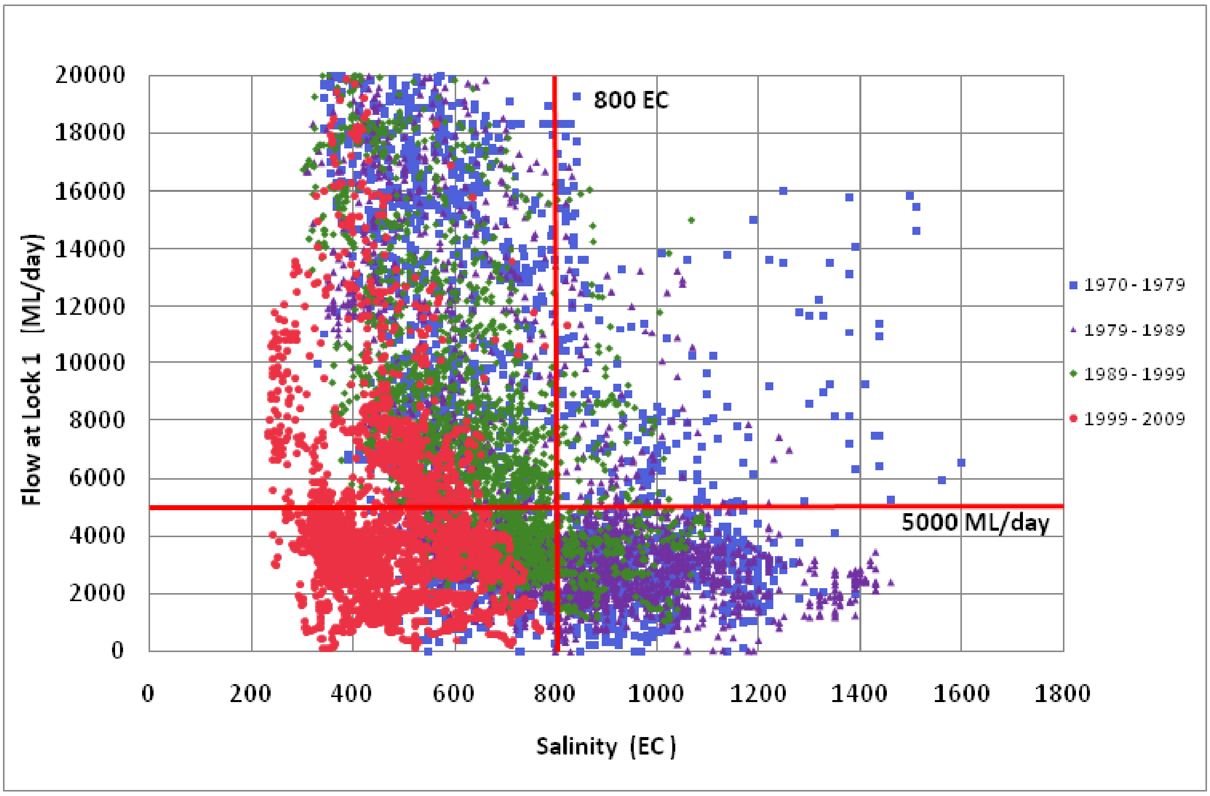


Figure ES2: Flow and salinity by decade

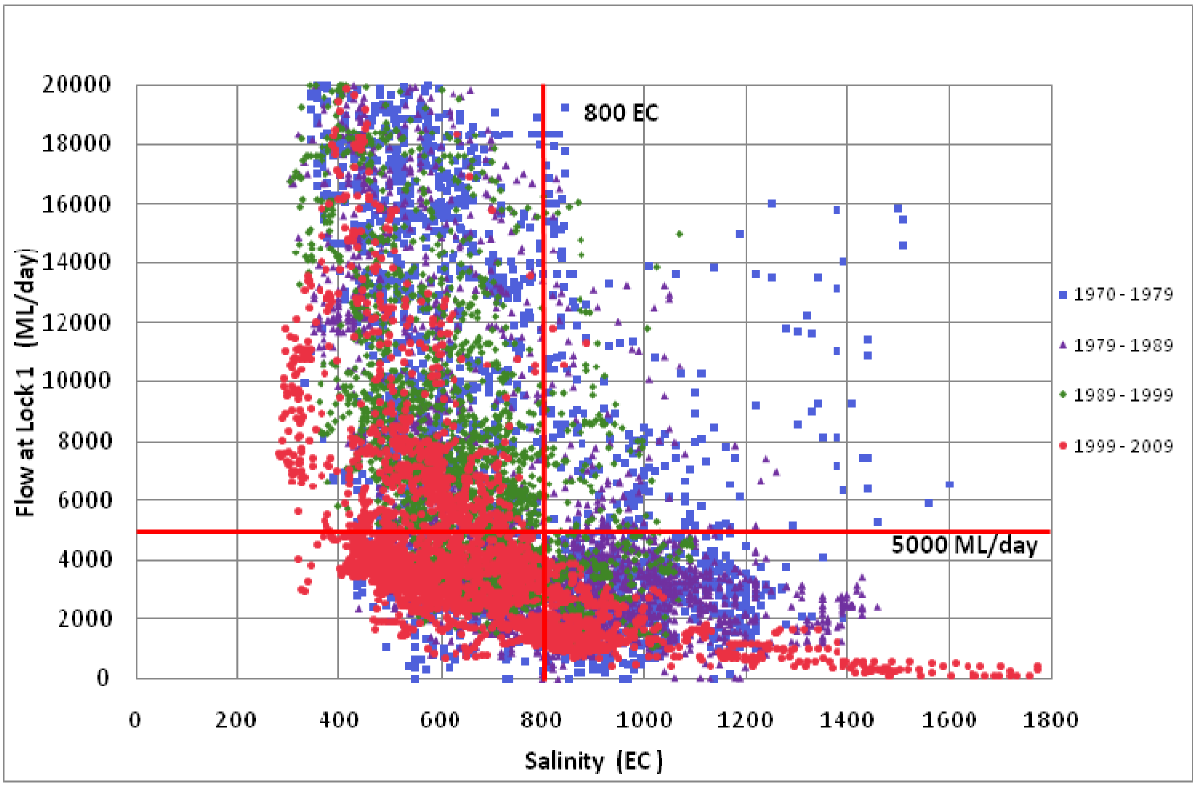


Figure ES3: Flow and salinity by decade without key salt interception schemes

MSM_Bigmod unaccounted salt loads by reach, decade and flow range

The MDBA's MSM_Bigmod model uses measured river flow and salinity data and "accounted" salt inputs and extractions over time, and calculates the "unaccounted" salt loads that need to be added to balance the salt budget in the model. The model accounts for salt inputs and outputs on a reach by reach basis. The accounted salt loads are the product of flow and salinity from tributaries and drains, and the extraction for consumptive use (irrigation, stock and domestic uses). Unaccounted salt inputs include groundwater flow into the river, and surface water inputs from unmonitored anabranches and tributaries.

For the period 1970 to date, the unaccounted salt inputs total 35.4% of total salt inputs (Table ES1) with an additional 61% of the salt coming into the study area from accounted inputs from the upstream River Murray at Euston (49.2%) and from the Darling River (12%). Tributary inputs, irrigation drainage outfalls and major off-stream water bodies (Lake Victoria, Lake Bonney) account for 3.3%.

The unaccounted salt data contain a wealth of information that has not previously been utilised. This study uses the data to quantify salt inputs by reach and through time, and to provide insights into the major processes mobilising and delivering salt to the river at a reach and sub-reach (e.g. Lock to Lock) scale. The MSM_Bigmod unaccounted salt loads are displayed in Figure ES4. The salt loads are displayed by decade (P1 to P4, where P1 is 1971 to 1979, P2 is the 1980s, P3 is the 1990s and P4 is the 2000s), by reach (Euston to Lock 9, Lock 9 to Lock 5, Lock 5 to Morgan, and Morgan to Murray Bridge) and by flow range (<7,000 ML/d, 7,000 ML/d to 40,000 ML/d, and >40,000 ML/d).

The unaccounted salt load analysis illustrates that:

1. The pattern of salt inflow varies by period, by reach and by flow range - there is not one repeated pattern in the entire dataset. This provides an indication of the spatial and temporal variability in salt inputs to the river, which suggests significant spatial, temporal and magnitude variability in the processes and delivery mechanisms delivering salt inflow to the river.
2. The Lock 5 to Morgan reach has the greatest salt inputs, and accounts for 60% of the total unaccounted salt inflow downstream of Euston. Much of this salt is delivered at flows >7,000 ML/d.
3. The Lock 9 to Lock 5 (L9-L5) reach shows the greatest variability between the time periods, and has comparatively more salt entering the river during the inter-flood periods than during the transition and flood periods (compared to the other reaches). This suggests that salt delivery processes differ, or are relatively more active in this reach during the inter-flood periods compared to the other reaches.
4. The Euston to Lock 9 reach deserves analysis, but persistent negative salt inputs suggest a systematic data error(s) which need resolving.
5. Salt inputs in the Morgan to Murray Bridge reach are relatively minor, and are not considered further herein.

The MSM_Bigmod model provides the best available quantification of salt delivery to the River Murray. The MSM_Bigmod unaccounted salt load data is a valuable and underutilised dataset that has significantly informed this study.

In this study, the Lock 9 to Lock 5 data have been interrogated to determine the timing of salt inputs in the inter-flood period, and the Lock 5 to Morgan data have been interrogated to determine the timing of salt delivery in the highest salt input reach. The quantification of salt delivery timing assists in constraining the range of processes delivering the salt.

Table ES1: Accounted and Unaccounted flow and salt quantities

Inflows - Source	Flow		Salt	
	GL (,000)	**%**	**Tonnes** (,000,000)	**%**
Murray at Euston (1)	265	83.4%	35.2	49.3%
Darling River(1)	55.4	17.4%	8.6	12.0%
Lake Victoria (2)	-2.2	-0.7%	1	1.4%
Lake Bonney (2)	-1	-0.3%	0.1	0.1%
Irrigation drains in Victoria (2)	0.55	0.2%	1.3	1.8%
Unaccounted Salt Loads (3)	0	0.0%	25.3	35.4%
Total	317.8		71.5	
Outflows - Destination	Flow		Salt	
	GL (,000)	%	**Tonnes** (,000,000)	%
Murray at Morgan (1)	241.8	76.1%	59.8	83.6%
Evaporation Less Rainfall (4)	25	7.9%	0	0.0%
Extraction and seepage (5)	50.8	15.9%	11.7	16.4%
Total	317.8		71.5	

Notes:

(1) Calculated from raw flow and salinity data

(2) MSM_Bigmod accounted flow and salt load

(3) MSM_Bigmod unaccounted salt load – flow would equate to 1,200 GL if salinity is 20,000 mg/L and is less than 0.3% of total inflow.

(4) Net loss to evaporation (evaporation - rainfall) has been estimated at 33% of total (evaporation plus diversions plus losses) based on MDBC Technical Report (MDBC 2002) Appendix K.

(5) Extraction and seepage has been calculated to balance inflows and outflows, average salinity of extraction and seepage calculates to 384 EC which is considered reasonable.

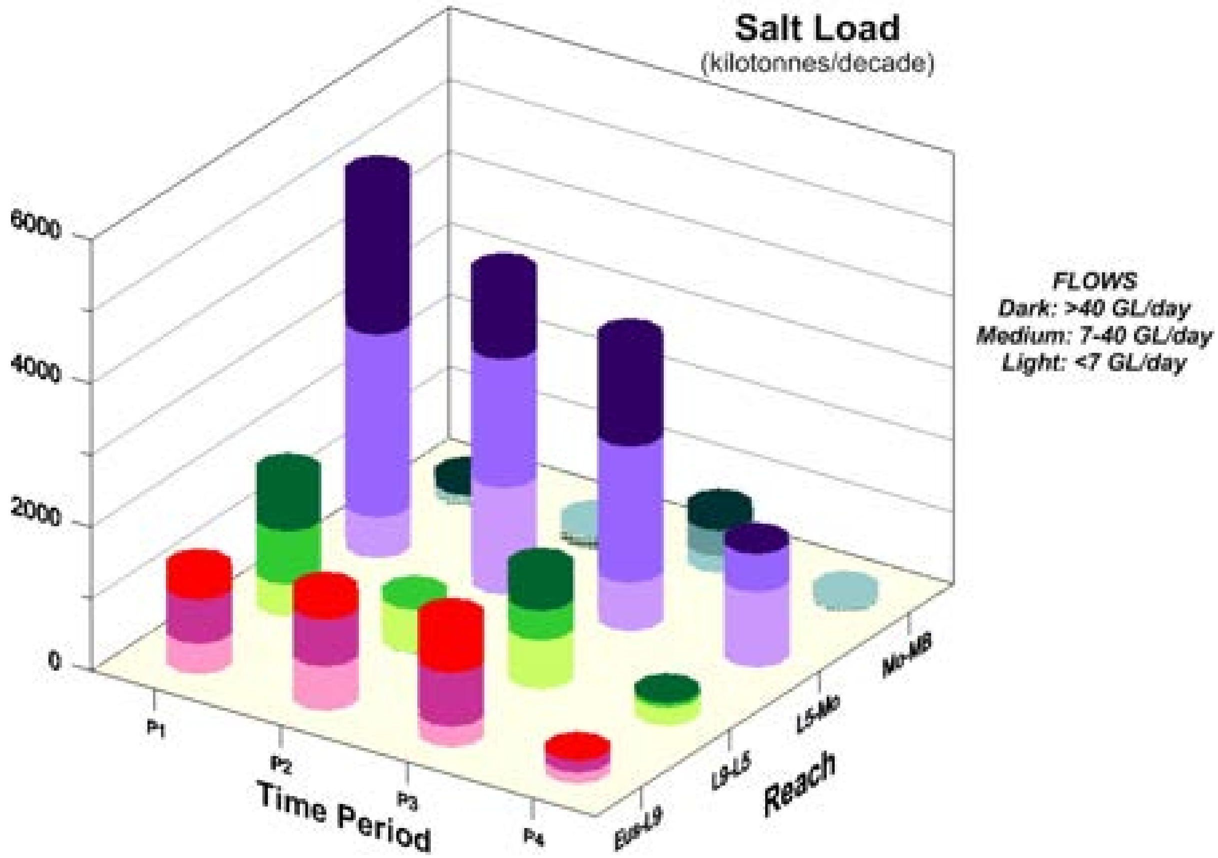


Figure ES4: BIGMOD unaccounted salt inputs by reach and decade

MSM_Bigmod analysis - Lock 9 to Lock 5 inter-flood period data

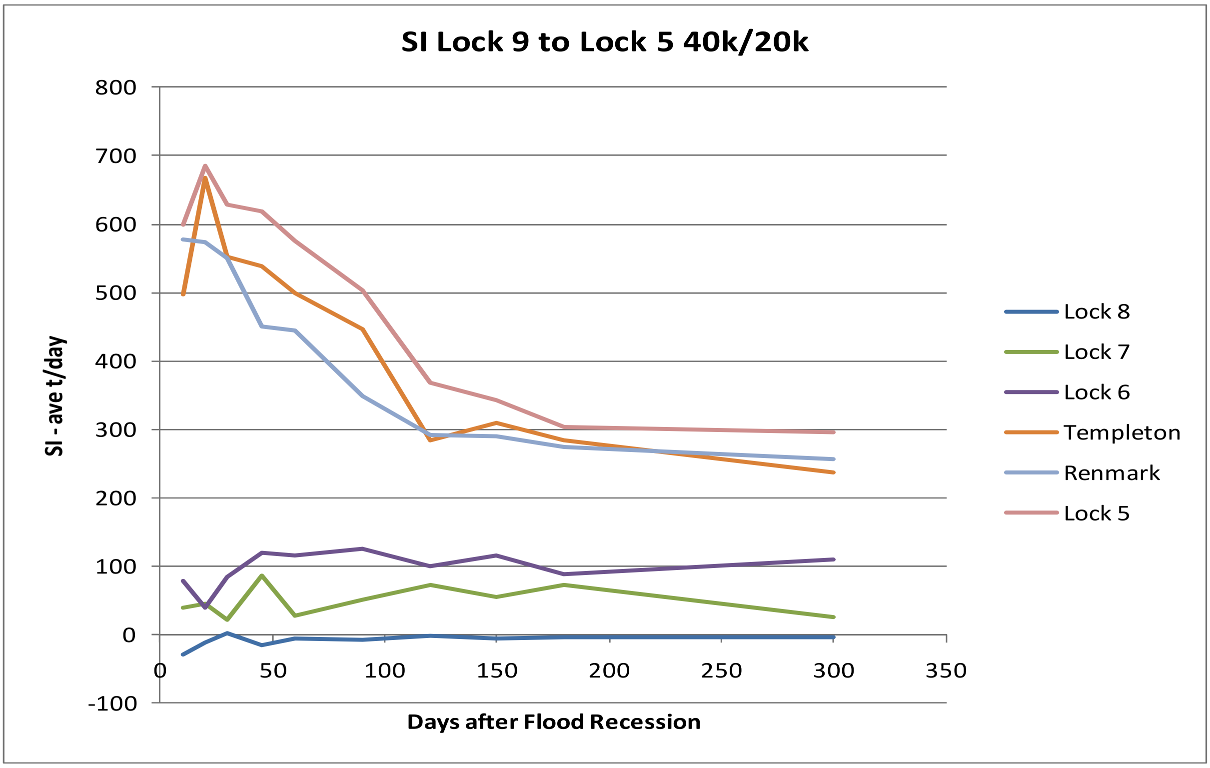
The cumulative unaccounted salt loads to the River Murray for sub-reaches between Lock 9 and Lock 5 were considered for each flood. The average unaccounted salt inputs per day are plotted against days since flood (i.e. days since flow dropped below 20,000 ML/d) for all floods since 1970 in Figure ES5. There is a uniform increase of around 100 t/d between Lock 9 and Lock 6 in the first 300 days of the inter-flood period, suggesting that salt inputs from unaccounted groundwater and surface water inputs are not strongly affected by processes initiated during floods. However in the Lock 6 to Renmark reach some 500 t/d is added to the river in the first 50 days after river flows fall below 40,000 ML/d, and these salt inputs decline asymptotically toward a baseline of 200 t/d after 300 days. This reach demonstrates a strong response to time since flood, indicating flood-related processes are activated in this reach. The remaining sub-reaches show only small additional increases in salt load following floods, although total unaccounted inputs are approximately 300 t/d from the Lock 9 to Lock 5 reach at 300 days.

The Lock 6 to Lock 5 reach includes inputs from the Chowilla Creek anabranch, which circumvents Lock 6. Post-flood salt loads from the Chowilla area have been studied since the 1990's, and significant work was undertaken in the Chowilla area on groundwater and vegetation management. Jolly *et al*. (1994) postulated that the post-flood salt recession in the Chowilla reach was due to the infiltration of floodwaters through isolated areas of the floodplain at a higher rate than the remainder of the floodplain. The post-flood groundwater induced salt load model has been thought or assumed to be a significant driver of inter-flood salt loads in the lower Murray.

Additional analysis of the MSM_Bigmod data suggests that the post-flood salt loads following floods of >75,000 ML/d are significantly higher than for smaller floods (Figure ES6 – flow data included in legend as

GL*1000/d), and that this may be due to floodwaters retained in Coombool Swamp which does not fill until flows exceed the threshold value.

Analysis of the patterns of salt export from all post-flood periods at Chowilla indicates that the salt load in the inter-flood period is dependent on the size of the flood, not on the duration of the preceding inter-flood period. This indicates that salt accumulation in the floodplain does not significantly affect salt export rates, further supporting the view that inter-flood salt accumulation has only minor impacts on salinity exceedances at Morgan.



Note: Salt inflow cumulative from Lock 9 to the graphed station (e.g. Lock 6 is the sum of all salt between Lock 9 and 6)

Figure ES5: Cumulative MSM_BIGMOD Unaccounted salt inputs post-flood for Lock 9 to Lock 5 sub-reaches

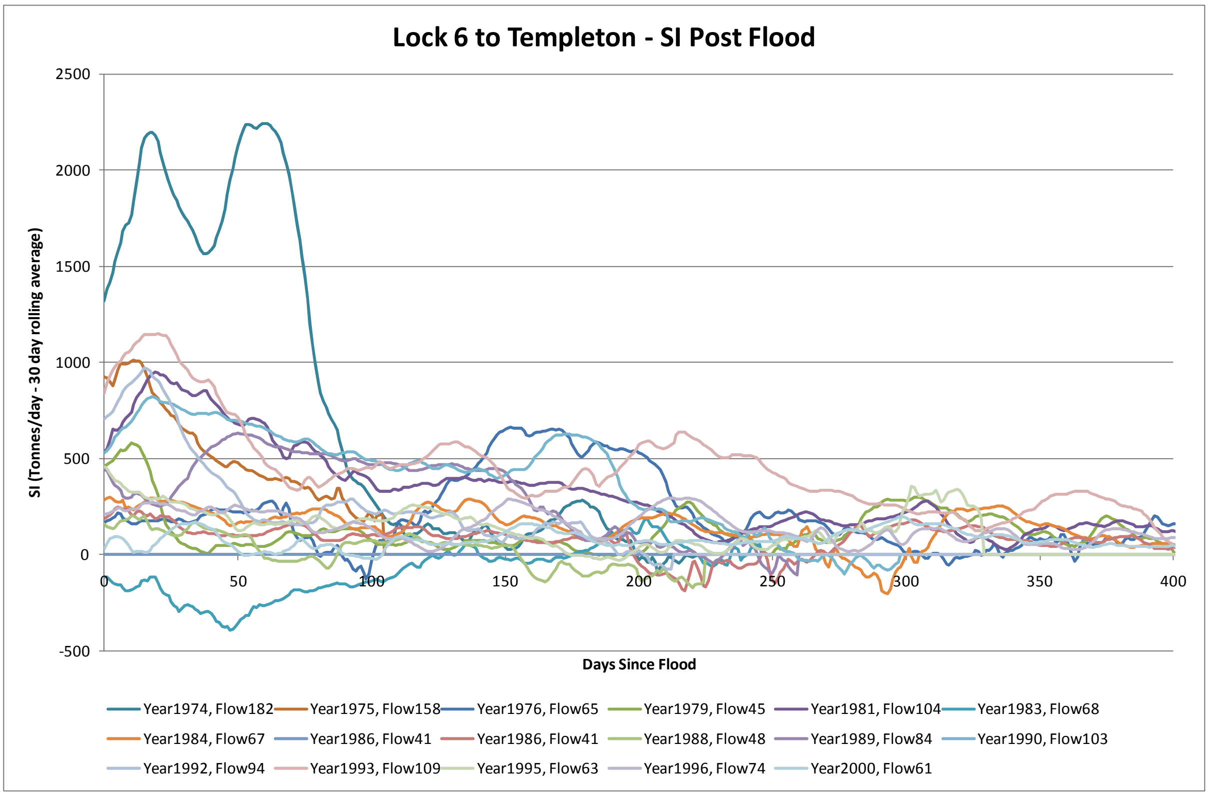


Figure ES6: Lock 6 to Templeton salt inflow post flood – 30 day rolling average

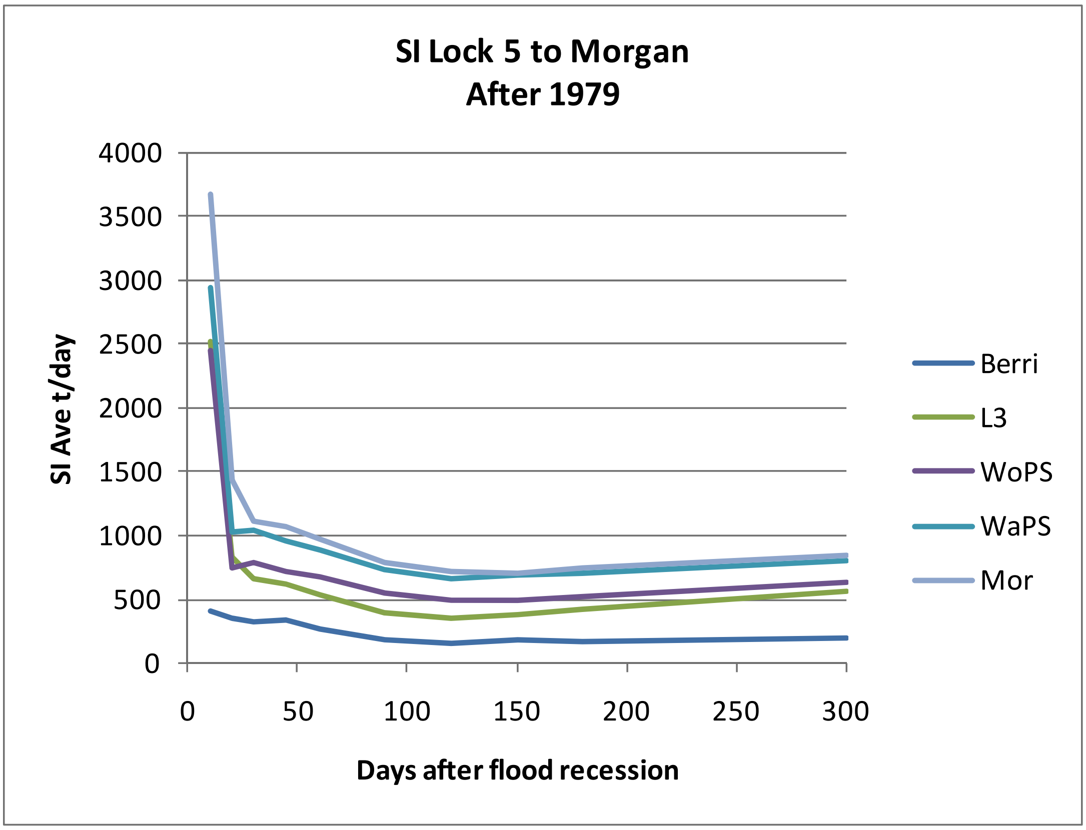
MSM_Bigmod analysis - Lock 5 to Morgan inter-flood and flood period data

MSM_Bigmod unaccounted salt inputs are plotted against time since flood for the Lock 5 to Morgan reach in Figures ES7 (average for all floods) and Figure ES8 (individual floods). The pattern is very different at early time from that observed in the Lock 9 to Lock 5 reach, when it is dominated by a short duration very high salt inflow in the first 20 days. After that the salt inflows are similar in pattern to those observed in the Lock 6 to Templeton reach, but around double the magnitude until 150 days. The increase beyond 150 days is possibly due to interactions between off-stream water bodies and seasonal flow and evapotranspiration patterns.

The major early time salt input suggests that an additional major process is active in this reach in addition to the groundwater inputs resulting from floodplain inundation. It is proposed that the salt load is derived from the draining of backwaters and anabranches, although additional work is required to verify this interpretation because this process has not been identified as a major salt delivery mechanism in previous work and hence no systematic data collection or analysis of this process has occurred. Unaccounted salt loads following the initial peak decline sharply but contribute approximately 750 t/d of salt to the river after 300 days.

Very little is known about the salinity interactions between the backwaters and the river. One possibility supported by the MSM_Bigmod data is that the backwaters act as salt reservoirs as has been observed at Ramco Lagoon (AWE 2000), accumulating salt during summer and discharging it to the river during winter.

Additional work is required to discriminate the sources of salt during the inter-flood periods. The relative importance of flood inundation groundwater recession salt loads, backwater salt loads and groundwater hydraulic responses to small changes in pool level are unquantified.



Note: Salt inflow cumulative from Lock 5 to the graphed station (e.g. Lock 3 is the sum of all salt between Lock 5 and Lock 3)

Figure ES7: Flood recession salt Inflow – Sub reaches Lock 5 to Morgan 1979 to 2009

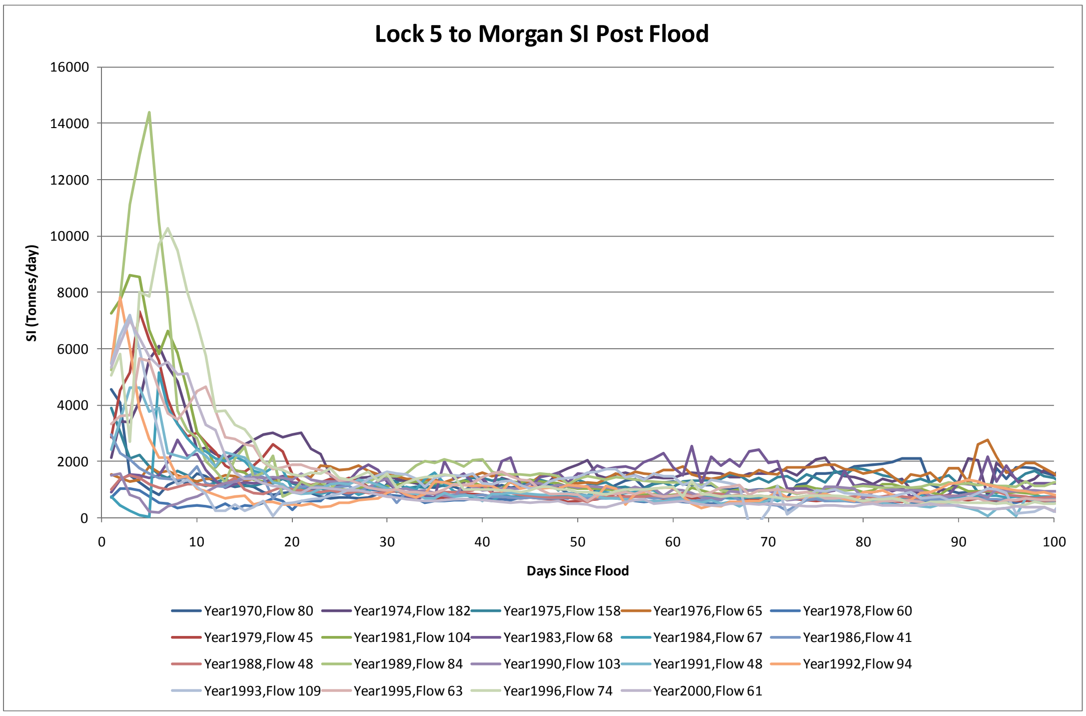


Figure ES8: MSM_BIGMOD Unaccounted salt inputs post-flood for Lock 5 to Morgan sub-reaches

Floodplain Salt Conceptual Model

Despite the significant amount of work undertaken on the River Murray floodplains in relation to salt and vegetation management over the last three decades, a conceptual model encompassing the range of processes and salt delivery pathways had not been developed. Floodplain processes are sometimes incompletely conceptualised, and are usually poorly quantified.

The Floodplain Salt Conceptual Model (Figure ES9) developed in this study is likely to assist with improving the current understanding of the sources of salt, the storage locations in the floodplain landscape, the mobilisation processes, the transport pathways to the river, and the river salinity impacts. The aim of the Model is also to provide a framework for future investigation, quantification and documentation.

The Floodplain Salt Conceptual Model seeks to aid systematic conceptualisation and quantification by considering salt in relation to regional, floodplain and river elements. Figure ES9 is an overview, and each box in the figure represents a range of separate elements that are discussed fully in the report.

- **Regional** elements include sources of salt to the floodplain landscape and measures which reduce the salt inputs.
- Some regional salt passes through the floodplain direct to the river from regional sources. Other regional salt inputs pass into a number of salt stores within the floodplain landscape, for later mobilisation.
- **Floodplain** elements address the storage and mobilisation of salt within the floodplain and the surface waters.
- The river elements consider salt inputs, river flow rates, and river salinity.

The likely timing of activation of key floodplain salt processes and delivery mechanisms is illustrated in Figure ES10.

A key predictor of floodplain salt risk is the Floodplain and River Classification Matrix (Figure ES11). The risk of salt inputs to the river from regional groundwater systems increases from the bottom right (i.e. losing stream in a losing floodplain poses virtually no risk) to the top left (gaining stream in a gaining floodplain poses the highest risk) of Figure ES11. Salt interception schemes are all implemented in floodplains from the top left corner and the remaining high risk areas also fall within this area.

Development of a floodplain salt predictive model is premature at this stage, because significant major data sources have not been evaluated. Analysis of the in-stream salinity data and further analysis of the MSM_Bigmod unaccounted and accounted salt load data, will provide significant advances in conceptualisation and quantification of key processes. The development of a predictive model will need to be carefully planned, as modelling the complexity of salt delivery processes and pathways along the length of the river may prove difficult.

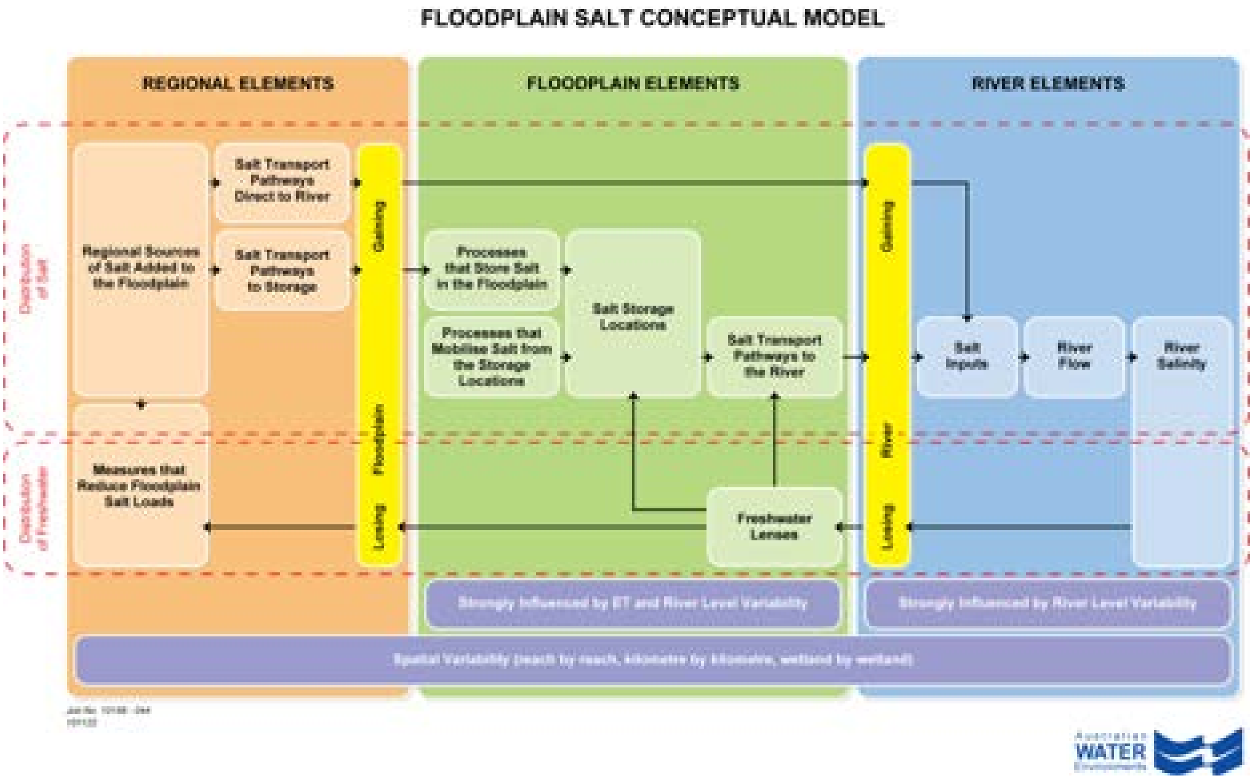


Figure ES9: Floodplain salt conceptual model

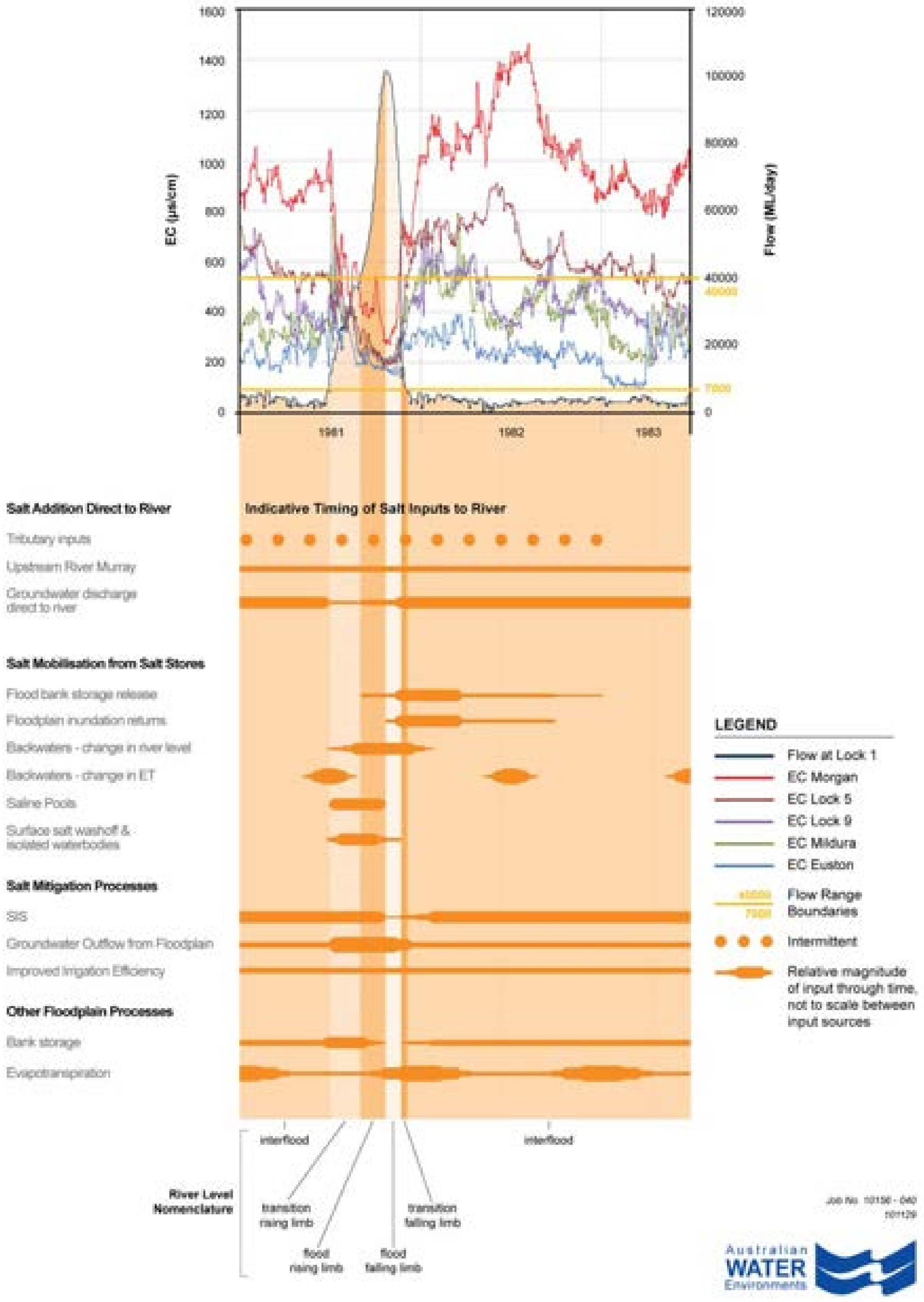


Figure ES10: Indicative timing of salt inputs to the River Murray through a flood cycle

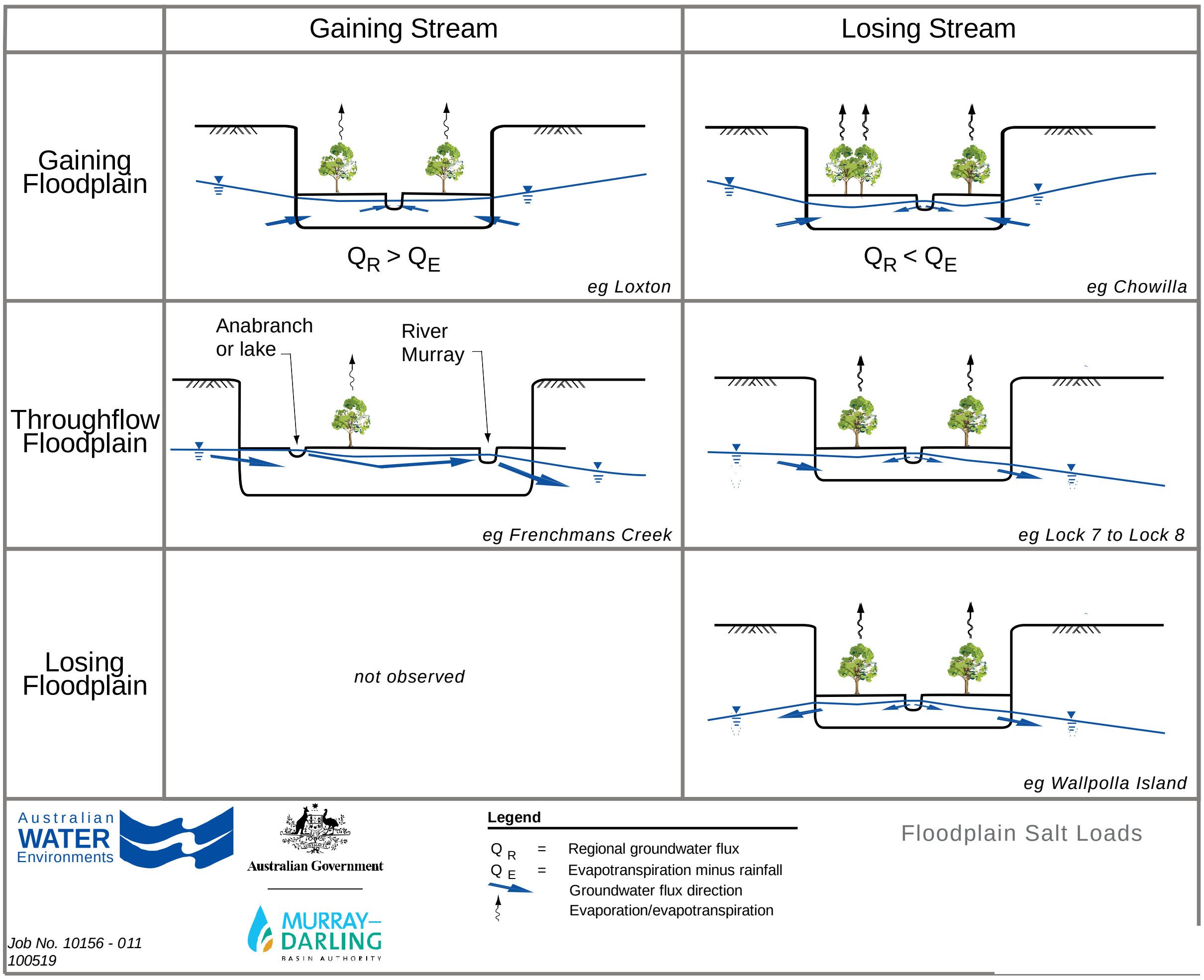


Figure ES11: Floodplain and river classification matrix

Knowledge and data gaps

Numerous data gaps and knowledge gaps occur. The key knowledge gaps include:

1. How the broadscale salinity impacts estimated in this report from MSM_Bigmod data relate to the small-scale features and transient effects which impact water quality for critical human needs, irrigation and environmental assets. Floodplain processes will vary reach by reach, kilometre by kilometre and wetland by wetland.

2. The timing, rate and processes controlling groundwater discharge to backwaters and other surface water bodies on the floodplain are poorly understood and quantified, however salt release from these connected water bodies is thought to be a major mechanism in the Lower Murray Floodplain salt balance.

3. The processes controlling release of water and salt from the backwaters and anabranches, particularly in the Lock 5 to Morgan reach, need additional attention. Data are required to quantify the sources and rates of salt mobilisation at the sub-reach and at individual water body scale.

4. The role of the unsaturated zone and the saturated zone in storing salt during a drought and salt mobilisation from the unsaturated zone. The unsaturated zone is often cited as the salt storage location during inter-flood periods, however salt storage and release mechanisms in the floodplain unsaturated zone appear to be incompletely conceptualised and sparsely quantified.

5. Recharge rates through the Coonambidgal Clays, and distribution of rates across the floodplain during inundation and also in inter-flood periods, are almost completely unquantified.

6. Recharge rates to groundwater in irrigated regions adjacent to the floodplain and within the floodplain.

7. Emplacement mechanisms and rates, size, shape, persistence and stability of freshwater lenses and the degree of protection they afford the river to groundwater recession salt inputs.

8. Floodplain evapotranspiration rates, which are known to vary according to soil type, vegetation type, groundwater salinity and climate, but for which there is no agreed method of estimating on the regional scale.

Operational procedures for mitigating salinity exceedances

Three indicative operational procedures which might reduce River Murray salinity have been conceptualised, but need additional work. The procedures were evaluated in terms of their impact on salinity exceedances at Morgan: local environmental impacts, management and operational constraints, water sharing arrangements, engineering feasibility and other issues will need to be evaluated.

Dilution flows: For a given salt inflow, an increase in flow will provide additional dilution of the salt and will lower river salinity. However there are many complicating factors when trying to assess the impact of additional flows which make it difficult to accurately predict the EC impact of additional flows with currently available data and tools. However the history of EC exceedances at Morgan has been analysed using some simplifying assumptions. The results suggest that dilution volumes required to maintain Morgan salinity to below 800 EC would have been in excess of 200 GL/year during the 1980s. However if the same 1980’s river flow pattern were to recur in the future, but with the benefit of the construction of SISs, implementation of other salinity mitigation measures and changed River Management rules, the volume of water required to keep salinity below 800 EC at Morgan would reduce to around 40 GL/year.

The addition of dilution flows does however have some complications because when an additional flow is introduced it effectively causes an increase in flow for the entire reach and, as has been found in the study, an increase in flows may also increase salt inflows. It may be that some water could be provided by rescheduling the monthly flows under South Australia’s annual entitlement (*Water Act* (Cwlth 2007), Schedule 1, Clause 90), or keeping current additional dilution flows for the times when most needed. Water sharing and storage arrangements between the States are bound by Agreements and these options may require negotiation of the operating rules between the States. The operational and management issues of how the additional water is provided and which allocation the water comes from would need to be discussed/negotiated between the river management bodies

Manipulation of Lock 3 Weir: There are very large salt inflows to the river in the tail end of and immediately following a flood in the Lock 5 to Morgan reach. The peak loads occur in the initial 10 to 15 days after the flow drops below 20,000 ML/day. We hypothesise that a significant contributor to the high salt loads is the draining of the very large permanent backwaters (including Lake Bonney) upstream of Lock 3. Lowering local river levels during a flood recession could allow the salt in the backwaters to discharge into significant river flows. The strategy would have dual benefits of discharging high salt loads when there is still enough flow to dilute it, and more salt would be discharged from the backwaters leaving a fresher water body for the post-flood period. Further investigation would be required to determine the most appropriate threshold flows and levels, the impact on river operations, and the impact on the environment and other users. It is considered that the Lock 3 weir pool manipulation would be the best location to pursue further investigation and a possible trial.

Pulsing of flows: Analysis of MSM_Bigmod salt inflow data has illustrated that in specific reaches (eg Lock 5 to Morgan), an increase in flow and its associated increase in water levels causes an increase in salt load to the river. During these occurrences, whilst the salt inflow does increase, the additional flow is sufficient to result in a lower salinity. It may be possible, at times of lower salinity, to introduce more flow variability to facilitate the export of additional salt and thus maintain lower salinity levels in wetland water bodies. This is likely to be most effective in the Lock 5 to Lock 3 reach where there are a large number of wetlands “activated” by an increase in flow and level. The processes that are causing the increase in salt load at higher flows are not fully documented, and more analysis into the cause would be required before developing an operational strategy. A proposal to introduce pulsed flows would also need to be investigated in more detail to determine operational ability to provide periods of higher flow, operational impacts and possible benefits.

Salt interception schemes: The SISs are major investments that have a significant effect on River Murray salinity. Historically, the design of SIS has focussed in intercepting the direct discharge of groundwater to the river. The operation of SIS during floods varies, with some being turned off during high flow events (e.g. Mildura, Mallee Cliffs), others being decommissioned due to borefields being on the floodplain (e.g. parts of Waikerie and Bookpurnong) and others operating unchanged (e.g. Woolpunda). With the new understanding of floodplain salt processes and mobilisation pathways gained during this project, it is likely that the operation of some SIS assets may be able to be modified to enhance benefits to the river or the floodplain environment. For example, this may be through the targeted building of freshwater lenses at critical locations which may in-turn reduce peak salt loads and enhance environmental benefits.

It is suggested that a set of aims be established and in light of the greater understanding of floodplain process, that operation of the SISs be reviewed.

Recommendations for further work

A detailed set of recommendations is provided in the main body of the report. These can be summarised as:

1. The Conceptual Model developed by this project can be adopted for communicating and developing programs for improving the understanding of all aspects of salt in the Lower River Murray floodplains. Future programs should amend the conceptual model and add additional detail as understanding improves.
2. This study has not exhausted the value that can be mined from the MSM_Bigmod accounted and unaccounted salt load datasets and significant potential remains for gleaning additional insights from the data. Additional work includes analysis of the other reaches to identify the major patterns of salt delivery and hence indicate the major salt delivery processes, and more detailed analysis of all reaches to extract additional information.
3. Further analysis of available datasets from outside MDBA sources should be conducted, for example, South Australian in-stream salinity data, backwater data, AEM, and flow and salinity data from tributaries above and below Morgan should be considered in order to better clarify MSM_Bigmod unaccounted salt loads.
4. Floodplain processes should be investigated by developing predictive models taking into consideration (i) groundwater-backwater-river interaction, (ii) floodplain inundation and salt transport between Lock 5 and Lock 3 and (iii) floodplain inundation and salt transport in Sunraysia, (iv) salt storage and release between the ground surface, unsaturated zone and saturated zone, (v) the relationship between floodplain vertical hydraulic conductivity and leakage rates through the Coonambidgal Formation, and (vi) freshwater lenses.
5. Further monitoring programmes should be designed and implemented to capture and characterise salinity dynamics of floodplains’ antecedent salts (e.g. using AEM surveys), backwaters, Coombool Swamp and behaviour of the river under high flows.
6. Operational procedures should be further investigated and refined to gauge their efficacy, feasibility and local impacts.

Part 1 - Background

1 Introduction

1.1 Requirement for the study

The environmental health and economic use of the River Murray depends on its salinity. Its waters, wetlands and anabranches require low salinity levels to maintain their ecosystems, while irrigators and other industrial users likewise depend on a supply of fresh water. The River Murray also provides water to many towns and to the city of Adelaide, which relies on the River Murray during drought years. Higher salinity levels in the River Murray lead to ecosystem degradation, less profitable agriculture, and risks to urban water security.

To manage salinity in the River Murray, the Murray–Darling Basin Commission (MDBC) (now the Murray–Darling Basin Authority (MDBA)) established the Salinity & Drainage Strategy in 1989 and the Basin Salinity Management Strategy (BSMS) for 2001 to 2015 (MDBMC 1987, 2001). The Basin Salinity Target established under the BSMS is to maintain the average daily salinity at Morgan, South Australia, at a simulated level of less than 800 EC for at least 95% of the time, modelled with the same climate conditions as those observed over the benchmark period, i.e. 1975–2000, under the current land and water management regime (MDBA, 2009a). The MDBA is currently developing a Basin Plan which will incorporate a Water Quality and Salinity Management Plan (MDBA 2010).

The BSMS relies upon a comprehensive understanding of the salt mobilising processes, salt accessions into the various reaches of the river, salt transport down the river and consequential impacts on water users. While our understanding of the River Murray system has improved over time, as data have been gathered on its hydrology and hydrogeology and its processes have been researched, some aspects have proved more intractable than others. Floodplain processes have proven to be some of the more complicated drivers of River Murray salinity.

Some aspects of the River Murray's floodplain processes have been studied for decades. Some known processes have not been adequately conceptualised, and data for enumerating processes is generally lacking. No general synthesis has been developed regarding floodplain salt processes and their salinity impact in the river.

The MDBA Independent Audit Group - Salinity (IAG), in the 2007-08 report (MDBA 2009a), identified as the highest priority recommendation:

> ***Flood recession salt risks: That the MDBA Office urgently facilitate development of a conceptual model of flood recession salt mobilisation in the floodplains and operational response management plans in preparation for the next high flow event.***

The estimation of the salinity impact of flood recessions requires a sound understanding of how floodplain features interact dynamically and spatially. The river, its tributaries and anabranches exchange water and salt with the groundwater system; evapotranspiration depends on topography, watertable levels, climate, vegetation and soils; human interventions include the river locks, accessions of river water, and groundwater pumping. Rainfall, evaporation, river levels, flood extents and management approaches change over time. River channels, wetlands, topography, vegetation, and hydrogeological properties vary spatially.

To summarise and synthesise information from previous studies and available datasets, and to develop a conceptual model of floodplain salinity impacts, is a substantial task. Any initial attempt will inevitably be partial and provisional owing to the complexity of the processes, the varying level of understanding of the processes, and the varying geographical and geological regions of the River Murray floodplain.

The MDBA has engaged Australian Water Environments (AWE) to undertake this task.

1.2 Policy context

The BSMS is a long-term strategy for the management of salinity across the whole of the Murray–Darling Basin. It adopts the approach of setting in-stream salinity targets over a dynamic benchmark sequence for climate: this is the “benchmark period”, currently 1975 to 2000 (MDBA 2010). However, the BSMS also considers the implications of real-time salinity events and the consequences of salt accumulation on the floodplain affecting the health of the river corridor.

The BSMS Independent Audit Group for Salinity (IAG) considers flood recession salt loads to be the most significant risk to salinity management in the Murray–Darling Basin (MDBA 2009). The IAG recommends a synthesis of existing data and the development of a conceptual model to help quantify this risk. The IAG considers that the BSMS target of 800 EC of salinity at Morgan 95% of the time cannot be met without flood recession management.

The River Murray system must serve multiple, and often competing, demands for water. These demands include water conservation and supply, including for critical human water needs, environmental protection and enhancement, protection of cultural heritage, protection of water quality, recreation, hydro-power generation, and flood mitigation. In recent years, environmental management is increasingly considered in relation to River Murray system operations, through management of water entitlements for The Living Murray Initiative and other environmental purposes.

River Murray Operations consider the high variability of: weather conditions and associated factors, such as precipitation and rates of evaporation; river inflows, and therefore water availability; the use of water allocations and private carryover water allocations by water entitlement holders, and the use of water by others; the discharge of groundwater to surface water and from surface water to groundwater; and water quality.

The River Murray Operations Group has established general objectives in the following areas:

> Structures, water orders, water security, water trade, environmental watering, other environmental outcomes, water quality, floods, Aboriginal cultural heritage, navigation and recreation.

Flood recession and the risk to River Murray salinity form part of the responsibility of the MDBA Basin Plan. The Commonwealth *Water Act 2007* requires the development of a Basin Plan which includes:

- identification of risks to the condition or continued availability of Basin water resources and strategies to manage those risks
- a Water Quality and Salinity Management Plan (WQSM Plan).

The risk assessment considers risks to River water quality and its impact on aquatic ecosystems, irrigated agriculture, drinking water and recreation. The Water Quality and Salinity Management Plan (WQSM Plan) must, under the Act,

- identify the key causes of water quality degradation in the Murray–Darling Basin
- include water quality and salinity objectives and targets for the Basin water resources.

The WQSM Plan “will recognise the contribution of groundwater to in-stream salinity levels”. *The Guide to the Proposed Basin Plan* notes that “Mobilisation of salt from saline aquifers to the rivers is a major quality concern, particularly in the lower River Murray” (MDBA 2010b).

To address the aims of the Basin Plan, the MDBA must develop an understanding of the biophysical processes responsible for post flood salt movement from the floodplains to the River Murray. This involves the development of an understanding of the post flood salinity risks and an evaluation of avoidance and mitigation strategies.

The official public consultation period for the WQSM Plan has commenced. It is anticipated that the plan will be presented to the Commonwealth Water Minister for consideration in 2011 and will be reviewed and revised as knowledge about the Basin expands.

In the future, river operational strategies are likely to change as a result of environmental flow management and changed water sharing rules under the proposed Basin Plan. These changes are likely to modify salt export patterns. The WQSM Plan will need to address all of these issues as a matter of priority. The results of this study may inform development of the WQSM Plan.

1.3 Scientific context

The Murray–Darling Basin includes more than 1 million km² of south-eastern Australia and includes a variety of climates, 23 River valleys, extensive floodplains and 30,000 wetlands, including 16 listed under the Ramsar Convention (MDBA 2010b).

The hydrogeological configuration of the Murray–Darling Basin has made the lower reaches of the River Murray prone to high salinities. The Basin is a series of interlinked sedimentary aquifers with no outlet to the sea except through the River Murray mouth. The aquifers are recharged by rainfall, flood waters, irrigation and surface water features such as the River Murray, wetlands and lakes. Water leaves the aquifers via evapotranspiration at the surface, through discharge to springs and the river system and, in some regions, from pumping for human use and SISs. Over time, the loss of water to evapotranspiration has lead to a concentration of salt within the lower-rainfall regions of the Basin. This salt is stored within the aquifer waters and soil, or is mobilised into surface waters. The saline groundwater of the lower Murray discharges into the river. The recorded River salinity at Morgan since 1970 shows that salinity varies significantly over time, from ~200 EC to ~1600 EC (Figure 4.1 and Appendix Figures A9 and A10).

The salinity of the River Murray is a world-class and unique problem. The Colorado River, where significant resources are being expended to address in-river salinity problems, perhaps provides the closest analogy from a scientific and policy context. However, the salt loads are mostly generated from the tail water of irrigation on the saline Mancos Shale. Only a handful of point source salt loads have been identified and management activities focus on irrigation management. One salt interception scheme has been constructed to intercept over 200,000 tons of salt per annum from saline groundwater that originates where a tributary of the Colorado River (the Dolores River) crosses a salt dome (Bureau of Reclamation 2009).

Understanding the salinity impact of flood recessions on the River Murray poses a number of interlinked challenges.

Firstly, the region is very large. The river reach most prone to salinity is the lower River Murray, which extends 1,125 kilometres from Robinvale/Euston to the River mouth. Its floodplains include Chowilla (a Ramsar site) and wide floodplains spanning much of the irrigation regions of Sunraysia in New South Wales and Victoria, as well as the South Australian Riverland.

Secondly, the hydrogeology varies substantially along the reaches. Different aquifers are important in different reaches. Aquifer tests and sieve analyses of aquifer materials have shown that aquifer properties may be highly variable within floodplain sediments and adjacent aquifers (e.g. AWE 2009, 2010c). In some regions, the watertable is strongly affected by root zone drainage from irrigation areas, drainage systems and drainage bores.

The surface water systems are also complex. For example, the Chowilla floodplain includes numerous anabranches and backwaters, including critical anabranches such as Chowilla Creek.

The system is also extremely dynamic. Under natural conditions, river flows are highly variable and floods are common, due to the variability of Australia's climate. Some processes vary on a daily basis, others seasonally, and others vary over multi-year timeframes or geological time scales.

In recent decades, management practices have modified the river's flow rates and other behaviour. Irrigation extractions, the management of dams and wetlands, the 'millennium' drought and climate change may all have had an impact. The combined pumping volume from SISs is around 10 ML/d and hence the prevention of this flux of saline groundwater to the river has a negligible effect on River flows, which are only occasionally less than 5,000 ML/d at Morgan.

Numerous processes contribute to the salinity of the River Murray. Their mechanisms and relative importance are the subjects of ongoing research. Many or most of the floodplain processes are poorly understood. While numerous studies have been conducted of specific sites, comparatively little work has focused on developing a single unifying Conceptual Model to describe the system as a whole. Hydrological studies of surface water systems have tended to neglect or minimise hydrogeological aspects, and hydrogeological studies often over-simplify surface water aspects. The interaction between surface water and groundwater systems is a "hot topic" in research.

Data is also a constraining factor. Key parts of the floodplain water budget, such as evapotranspiration and recharge rates, remain difficult to widely measure and estimate. There are extensive historical records of some features, such as River Murray water levels, but very little data on other aspects, such as floodplain potentiometric head. Critical properties such as riverbed hydraulic conductivity are rarely measured.

In summary, it is still early days in our understanding of salinity processes in the River Murray system despite the ongoing research efforts. The size of the region, the number of different hydrogeological and hydrological regions, the medium and small-scale heterogeneity, the number of processes, our present poor understanding of many of those processes, and a lack of data makes an overview of floodplain salinity challenging.

Nevertheless, the management of the River Murray requires the development of a conceptual model, predictive models and management strategies. Preparing a Floodplain Salt Conceptual Model is one aim of this report.

1.4 Scope of work

The current study aims to address issues raised by the Basin Salinity Management Strategy's Independent Audit Group for Salinity. The results of the Study will inform the River Murray Operations review and the upcoming MDBA Basin Plan (MDBA 2010b).

The Request for Tenders for this project stated that the project:

> *…essentially involves the integration of existing knowledge and the development of a conceptual model to improve the understanding of the flood-recession salt mobilisation in preparation for managing the impacts of high river salinities that are inevitable in the future.*

The Request for Tenders specifies project objectives, outputs and outcomes as follows.

The project objectives are to:

1. Provide contemporary assessment of processes of floodplain salt accumulation and transportation of salt load to the River Murray.
2. Describe how these processes can be influenced and/or controlled by other actions.
3. Develop a conceptual model that outlines floodplain salt accumulation and transportation processes.
4. Undertake an assessment of possible operational management strategies to mitigate the salt mobilisation risks.
5. Ensure that floodplain salt mobilisation risks are articulated to the stakeholders (partner Government agencies, CMAs, environmental water holders etc.).

6. Provide relevant technical and operational advice to support recommendations to address floodplain salt mobilisation risks, to feed into the River Murray Operations review and the Basin Plan. This should include, but not be restricted to, salinity issues to be addressed by the Water Quality and Salinity Management Plan.

The anticipated outputs of the project are:

6. Collation of current findings on biophysical processes, including surface-groundwater hydrology and new information available through AEM surveys of floodplain salt mobilisation on river salinity.
7. Report key geographic areas and features that drive and are impacted by floodplain salt mobilisation.
8. A conceptual model that can demonstrably assist in understanding floodplain salt mobilisation and evaluation of mitigation strategies under current and future water management regimes;
9. Report all potential river operational strategies e.g., using dilution flows to avoid and mitigate post-flood salt accession to the River Murray.
10. Report test scenarios for the application of the conceptual model specifying salinity mitigation options and recommending potential future staging of investigations.

The anticipated outcomes are:

1. A clearer understanding of post-flood salt accession processes amongst decision-makers and other interested parties.
2. Enhancement of predictability of existing salinity models and hence basin salinity management strategies.
3. A ‘road map’ for future investigations which will improve planning and prioritisation for the MDBA.
4. An appropriate recognition of the level of importance of post-flood salinity risks within the Basin Plan.

The study area (Appendix Figure A1) was constrained to the River Murray downstream of Euston, and the analysis period to 1970 to present, which includes the benchmark period and the subsequent decade of drought. Analysis of salinity impacts is constrained to the impacts at Morgan – this study does not analyse the salinity trends for stations (e.g. other major water offtakes) downstream of Morgan, or develop management suggestions for salinity impacts at locations at upstream locations (e.g. local salinity spikes caused by natural processes or management actions).

Appendix Figure A1 also illustrates the major and minor flow and salinity stations within the study reach.

1.5 Our approach

To meet the project objectives within the allotted budget and timeframe, an approach was developed which makes use of available studies and data, picking out the most critical items.

There are two potential approaches to estimating the impact of floodplain processes on river salinity:

- This report adopts an approach where regional-scale empirical data are analysed for correlations with what is known about floodplain processes. Understandings are developed about how processes impact river salinity under different conditions, based on the empirical data and the correlations between the datasets and processes affecting in-river salinity.
- An alternative approach is to upscale the numerous processes of the conceptual model across the Lower Murray. However, previous studies experienced difficulty in delivering precise and unequivocal solutions, even in quite spatially and conceptually constrained areas, so we do not consider this approach to be feasible for this initial project, given the complex interactions between

the processes, the paucity of regional-scale data for many of the processes, parameter heterogeneity and the remaining uncertainty about how the processes work.

The adopted approach is well suited to the provision of regional-scale recommendations for management of the river salinity and its floodplain salt sources and delivery processes, but not to detailed management of sites.

The key aim of the authors is to convey both known and inferred understandings of the system, the system behaviour, and its impact on in-river salinity. In some instances, the findings, conclusions and recommendations are supported by a sufficiently robust body of work to provide confidence in the outcomes; in other instances, the findings, conclusions and recommendations are based on a "balance of probability" or a "most likely" basis: these latter are appropriately qualified as such in the text.

Therefore some conclusions are tentative and will require further investigation; however, given the need for river managers to manage risk from this point forward, we provide our best interpretations of the data within the current budget and timeframe constraints. Additional work is warranted in most areas to improve the understandings and the predictions of system behaviour. These recommendations are discussed.

1.6 Report structure

We start with a review of key papers on River Murray floodplain processes (Chapter 2). Numerous studies have been conducted, each typically concentrating on a small number of processes within a single geographical area.

We then consider the available data (Chapter 3 and 4). As the scope of the project covers floodplain processes for the whole of the lower River Murray, we concentrate on datasets which span the Murray's main channel, floodplains and anabranches. This includes river levels, flow rates, in-stream salt load estimates, AEM data, NanoTEM data and BIGMOD's "unaccounted salt inflow". Some of these datasets, such as river level, consist of relatively simple observations. Others rely on complex models to turn observations into an interpreted format, such as the AEM and NanoTEM inversion methodologies, and BIGMOD's calculations of surface transport of water and salt.

We consider how these datasets vary reach by reach and over time. Comparing the timing and magnitude of salt inputs with flow ranges tells us which salt delivery processes are likely to be active in that flow range. Geographic data also assist with the discrimination between processes, such as whether it is an anabranch or a backwater input.

Chapters 5 and 6 are devoted to the analysis of the MSM_Bigmod datasets, particularly the "unaccounted salt loads". The data have not been examined for this purpose previously, and its analysis has lead to surprising and useful outcomes.

In Chapters 7, 8, 9 and 10 we develop a Floodplain Salt Conceptual Model based on current knowledge and interpretations of floodplain salinity processes. It summarises key findings of the available literature and is informed by the data analysis. However, because this is the first project to our knowledge that formulates a Conceptual Model for salt in the floodplain of the River Murray, it must be stressed that the Conceptual Model is provisional. It is anticipated that later projects will draw on past reports in greater detail, and that the provisional conceptual model presented herein will be tested and refined for specific processes and geographical regions.

Chapter 11 consolidates the analysis of BIGMOD and the review of processes to develop an understanding of the timing of the salt inputs to the River Murray.

Management options are proposed in Chapter 12, while Chapter 13 summarises the current understanding of some key aspects of floodplain salt, river salinity and salinity and salt management. Chapter 14 gives our conclusions, and our recommendations are provided in Chapter 15.

2 Previous work

In this chapter we summarise much of the previous work on floodplain processes which impact upon salinity in the lower River Murray. We discuss development of a Floodplain Salt Conceptual Model in Section 2.1. We define terminology regarding gaining and losing rivers and gaining and losing floodplain in Section 0, consider studies of surface water processes in Section 2.3, groundwater processes in Section 2.4, and the unsaturated zone in Section 2.5. We stress that the surface water, groundwater and unsaturated zone processes are highly interdependent.

The work presented in this chapter informs the Conceptual Model described in Chapters 7 to 11.

2.1 Floodplain Salt Conceptual Model

The implications of the riverine corridor floodplain on salt mobilisation processes have been an issue of concern since at least the River Murray irrigation and salinity investigations project, when the implications of floodplain drainage disposal basins were a matter of primary concern. The Chowilla salinity control investigations in the later 1980s generated more intensive interest in floodplain processes, including the issue of salt accumulation and post-flood discharge. Those early investigations were summarised in the Chowilla SIS environmental impact study (NEC 1988), followed up by the Chowilla Resource Management Plan (MDBC 1995). Subsequently there have been many other local studies which have addressed the issues. With the advent of proposals for The Living Murray works and measures, the MDBC initiated further conceptual investigations (REM 2005) to consider the consequences of nominal works and measures throughout the floodplain.

These studies did not consider floodplain processes as a whole. However, the spectrum of floodplain processes were considered as part of a framework for assessing salinity impacts for The Living Murray Works and Measures program (AWE & URS 2007). That work developed the concept of gaining and losing floodplains, analogous to gaining and losing rivers, and categorised the river from Barmah Forest to the Murray Mouth. This report also documented potential and proposed environmental watering strategies, the salt mobilisation processes set in train by each watering activity, the key hydrological and hydrogeological parameters controlling the rate of salt mobilisation for each watering strategy, the uncertainty in key parameters and the importance of the parameter in quantifying salt loads. Floodplain vertical hydraulic conductivity was identified as a key unknown parameter with large (orders of magnitude) potential range and little measured data. The report identified that understanding floodplain processes was potentially very important for vegetation health although poorly understood. Resource and Environmental Management (2009) considered the impact of floodplain processes on salinity between Lock 10 and the South Australian border. The primary drivers of the floodplain processes are given as: river losses, evapotranspiration and the interaction between the Parilla Sands and Channel Sands. It is argued that because the river level is above the adjacent groundwater level in that reach, floodplain salts there do not exit via the River Murray under current conditions (REM 2009).

2.2 Floodplain and river classification nomenclature

In the context of addressing the issue of salt mobilisation, it is useful to think of the various reaches of the river and floodplain as either 'gaining' or 'losing' streams, noting that this has the potential to change over time.

Gaining and losing streams are common terms, and are defined as:

- In **gaining stream reaches**, the regional groundwater is discharging through the floodplain alluvial sediments into the river reach.
- In **losing stream reaches,** the river reach is losing water to the floodplain alluvial sediments.

The floodplain classification discussed below is based on AWE and URS (2007), where gaining and through-flow floodplains were first defined. Losing floodplains have been added for this report. Gaining, through-flow and losing floodplains are defined as follows:

- **Gaining floodplain** reaches of the river are reaches where the regional groundwater system is discharging into the floodplain alluvium.
- **Through-flow floodplain** reaches are defined as reaches where the regional groundwater flow lines show that groundwater flows beneath or through the floodplain. In these reaches, the floodplain alluvium is potentially gaining water from the upgradient side, but losing water to the regional groundwater system on the down-gradient side.
- **Losing floodplain** reaches are those reaches where groundwater flow is away from the floodplain sediments on both sides.

Figure 2.1 categorises floodplain/river systems according to the river and floodplain characteristics. It also identifies example River Murray reaches for each floodplain/river reach type.

Jolly (2004) proposes a classification nomenclature for flood recharge:

- **Bank recharge** in which the stream recharges the aquifer through its banks when the stream level is higher than the adjacent groundwater.
- **Diffuse recharge** in which overbank flows recharge the groundwater through the soil surface of the floodplain.
- **Localised recharge** in which the floodwater infiltrates through isolated areas of the floodplain at a higher rate. These isolated areas may be depressions that fill during flooding (e.g. Werta Wert wetland at Chowilla), old levee banks or dunes with a thin or absent surface Coonambidgal Clay layer, or old meanders (Jolly 1994).

2.3 Surface water processes

In this section we consider studies of:

(i) flow and salinity in the River Murray

(ii) flood inundation extent

(iii) salt delivery from floodplain surface water bodies (e.g. anabranches, backwaters and the river itself).

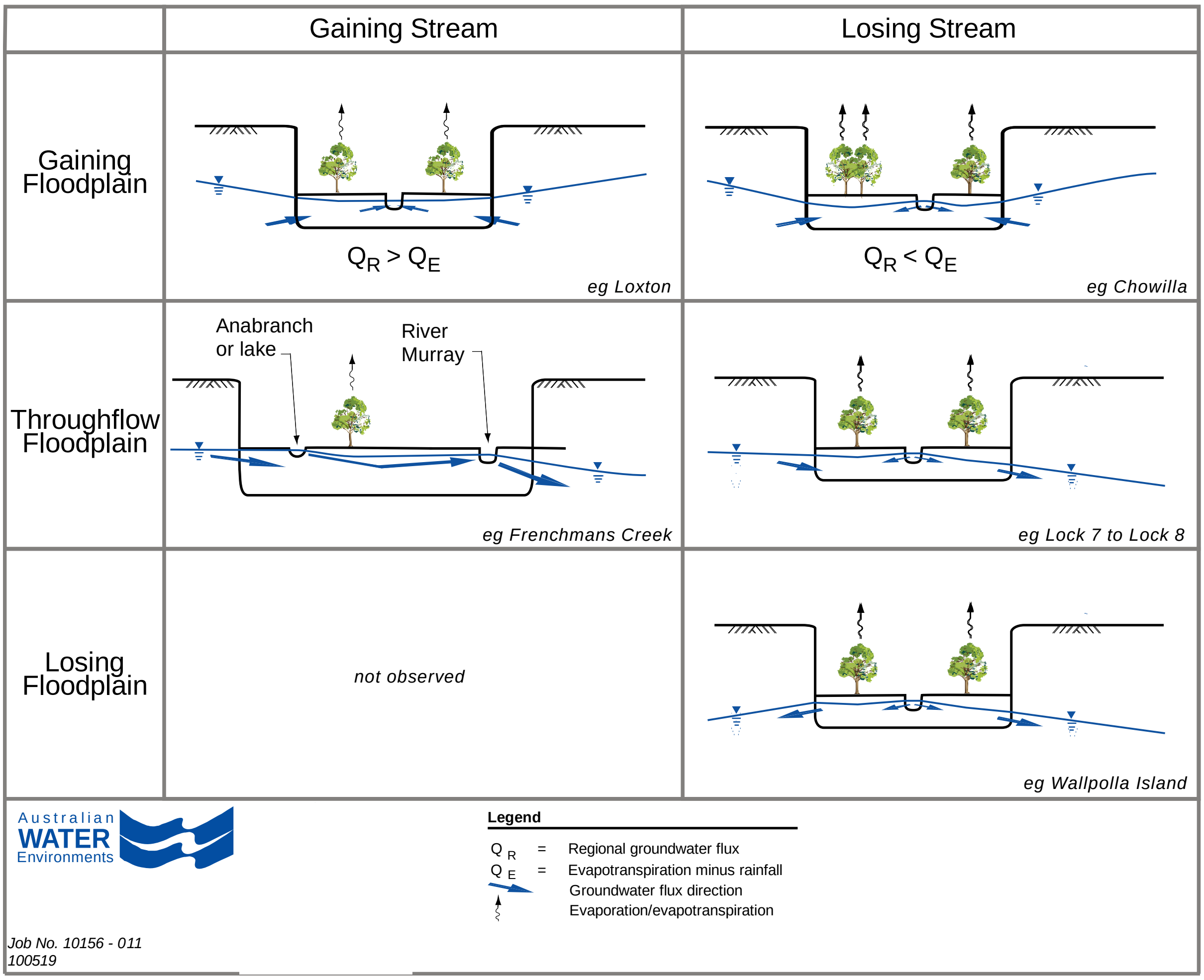


Figure 2.1: Floodplain and River Classification Matrix – the relationship between regional groundwater inflow, floodplain losses and gaining/losing stream conditions.

2.3.1 River flow and salinity

In-stream salinity is the attribute of water quality that most affects water users; it is a consequence of the prevailing salt load and stream flow. Salinity is measured in many locations along the River Murray. While salinity measurements can be made with reasonable accuracy, flow is more difficult and is measured at far fewer locations and with lower frequency. Salt load, in particular the incremental salt load at a particular location, is imputed through observations of flow and salinity, but must necessarily take travel time into account. In a slow-moving river such as the Murray, this is particularly important. It is not uncommon to observe salt slugs moving slowly down the river system gradually being attenuated. However, taken over the long run, a general increase in both salinity and salt loads is typically observed. The overall salt load within the river system is sensitive to the flow regime. While salt load export from the basin averages 2 Mt/p.a. (over 25 year benchmark sequence), it can reach 5Mt/p.a. in a flood year and zero at other times. BIGMOD uses a parameter called dead storage volume, which is the volume of water held in the river at zero flow. It is used to differentiate between the travel time for flow changes and the travel time for salt.

Background papers to the Salinity and Drainage Strategy (Close 1987) illustrate the extent to which salinity levels rise downstream of Swan Hill and how these are influenced by the transient behaviour within the river.

The MDBA uses MSM_Bigmod (MDBC 2002) to model river flow and salinity. MSM is a monthly simulation model used for modelling flows, operating rules for storages, irrigation demands, water resource assessment and water accounting. BIGMOD is a daily model routing flow and salinity from Hume Dam and Menindee Lakes to the barrages at the Murray Mouth. MSM and BIGMOD are now run sequentially to ensure that the simulated flow data from the two models are synchronised.

BIGMOD has an array of input files including: flow, salinity, volumes and travel time for the main river, tributaries and storages. The model routes flow and salinity to best match the recorded data. Where there is a difference between recorded and computed salt concentration in the river, the model minimises the difference by introducing an '*unaccounted salt inflow*' (SI); a negative value indicates a salt outflow. Unaccounted salt inflow is inferred to be a mix of groundwater inflows and surface water flows that are not specifically accounted for in the model. Significant unaccounted salt outflows indicate errors in the data or model, but small negative values may indicate a salt outflow via diversions to consumptive use or to temporary storage in backwaters and wetlands.

Figure 2.2 compares BIGMOD results with observed flows and salinities at Morgan. The data were provided by Andrew Close of MDBA. In the MDBA Technical Report on the setting up of the MSM-Bigmod modelling suite (MDBC 2002) it is concluded for the calibration period that:

> *The match between observed and simulated salinity at Morgan is very good. Comparisons between observed and simulated salinity are very good at intermediate sites as well as at Morgan and this provides some assurance that the calculated salt load inflows are reasonable*.

The MDBC report also identifies that "salt loads estimated using the methodology are inclusive of error associated with flow and salinity measurements" and that the match for timing is mainly a reflection of the salinity routing algorithms while the match between concentrations is to a great extent influenced by the use of model calculated salt loads input to the various river reaches.

The report provides results of statistical comparison between recorded and simulated values, which for daily flows at Euston and Lock 1 had coefficient of determination (R^2) values of 0.98 and 0.97 respectively. For salinity at Euston and Morgan, R^2 values were 0.70 and 0.88 respectively. The results are reasonable, given the overall uncertainties regarding salinity processes in the lower River Murray. A new model of the River Murray is under development by eWater CRC and is scheduled to replace MSM-Bigmod in the next few years (Welsh & Black 2010).

Other hydrodynamic models simulate specific and shorter reaches of the River Murray system. Overton *et al*. (2006) mention the River Murray Flow and Salt Transport computer model but do not provide a full description of the model or reference. Water Technology "has developed hydrodynamic models of many Murray floodplains, including Lindsay, Wallpolla and Mulcra Islands, Chowilla, Katarapko, Pike River, Gunbower and Barmah, and also many of the major tributaries to the Murray" (Ben Tate, Water Technology, pers.comm.; e.g. Water Technology 2006). A MIKE-FLOOD model has been developed for Chowilla (DHI 2006). A spreadsheet-based model has been developed and calibrated for Lake Bonney and its surrounds in South Australia by Parsons Brinckerhoff; its groundwater component was calculated by AWE using a separate MODFLOW model (Parsons Brinkerhoff & AWE 2006).

Katupitaya and Cuthbert (2008) consider salinity management measures such as dilution flow through the operation of Lake Victoria and Menindee Lakes, salt interception rules and salt disposal. Two case studies of salinity spikes are documented, one in considerable detail. They conclude that:

> *Once a salt slug or spike has been observed within the Murray system, models are capable of accurately predicting the progression of the slug or spike through the river system and the likely benefit of dilution flows. However, prediction of the amount of salt mobilised to the river (from groundwater and tributaries) as a consequence of a climatic event is significantly more difficult.*

Three reasons are given for the difficulty in predicting groundwater accessions: the need to know antecedent conditions immediately prior to the event (i.e. the initial conditions); insufficient detail in groundwater models of groundwater salinity and discharge locations; and the need to simulate dynamic short-term behaviour.

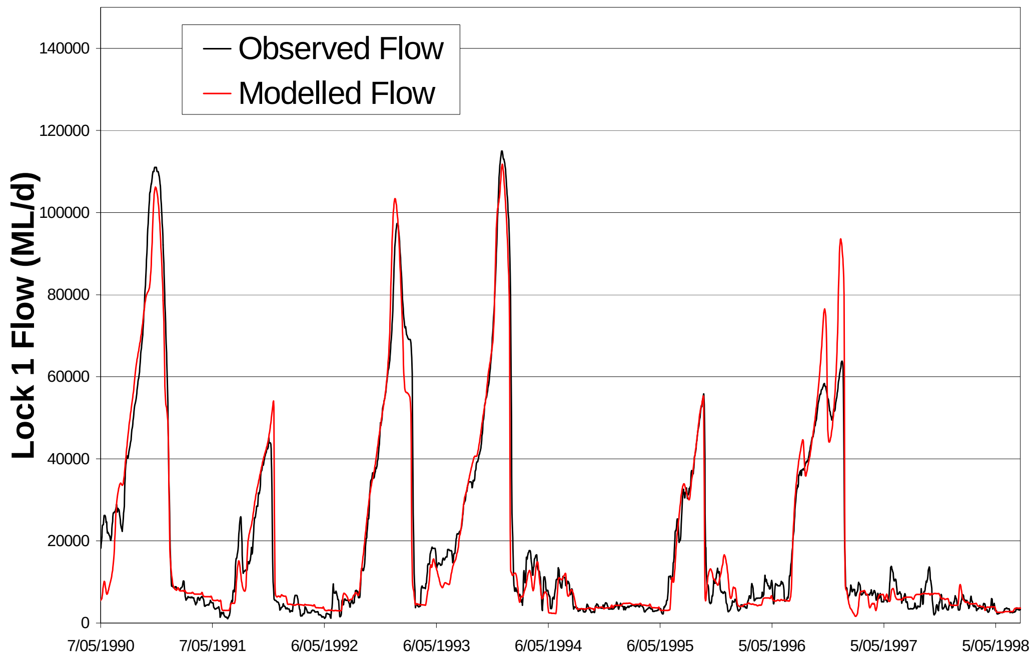
BIGMOD uses many fixed EC stations along the river to route salinity. There are many more EC recording stations that provide additional information for specific purposes. For example BIGMOD uses some 25 EC stations in SA, whereas the Department for Water (DfW) maintain 70-80 salinity measuring sites along the river. Many of these sites use pontoon mounted toroidal coils for the continuous monitoring of salinity. Instruments require regular (approximately six weekly) maintenance at which time data are also downloaded. The EC stations have been placed to enable the spatial delineation of salinity impacts in reaches of specific interest, e. g. EC stations at the upstream and downstream end of SISs are used to monitor SIS performance, EC stations upstream and downstream of an anabranch inflow location are used to monitor salt load from the anabranch (e.g. Chowilla Creek and Pike River).

The pattern of salinity variation between the upstream and downstream EC station, together with flow and travel time data, can be analysed to provide an assessment of salt inflow to the specific reach (AWE 2000b). The information can be used to assess how salt inflow has varied over time. The continuous EC recorders also provide detailed information on salinity spikes and how they attenuate as the water body travels downstream. Detailed analysis of the salinity records allows assessment of operational events, both natural and management initiated.

Run of River salinity surveys, which have been undertaken by DfW since 1985, provide data which can be analysed to assess salt inflows to the river on a kilometre by kilometre basis. Porter (2001) describes Run of River measurements and their analysis. The Run of River surveys are conducted during times of steady low river flows, and measure salinity at each kilometre along a river reach on (nominally) five consecutive days. The difference in electrical conductivity (EC) of a body of water, on consecutive days, is assumed to be due to saline inflow. The EC difference between the daily measurements is analysed, using travel time and river flow, to provide an assessment of the salt inflow, in tonnes per day. Surveys have been carried out mainly in South Australia, concentrating on reaches of known saline inflows where surveys are conducted annually. AWE has recently developed a new methodology for analysis of Run of River survey data and is currently reviewing the historical data in SA.

Run of Rivers provide an annual snap-shot of salt inflows at low flow, but give little insight into how saline inflows vary through the year or with a change in flow regime. The strength of the surveys is that they provide spatial detail of saline inflows and provide a quantification of the salt inflow. The results have provided and continue to provide vital information regarding the design and performance of salt interception schemes (SIS). The change in saline inflow pre and post scheme can be used to demonstrate the salt inflow reduction achieved by schemes and identify the location of remaining salt inflows.

Close-spaced EC methods (Barry Porter, SA Dept for Water, 2010, pers. comm.) use weighted salinity and temperature probes to evaluate salinity stratification in the flowing river, and to measure the salinity of disturbed river bed sediments. The results can be used to pinpoint the locations of saline groundwater input to the river and have been noted to correlate well with the NanoTEM riverbed resistivity measurements and the inferred locations of groundwater inflow to the River.



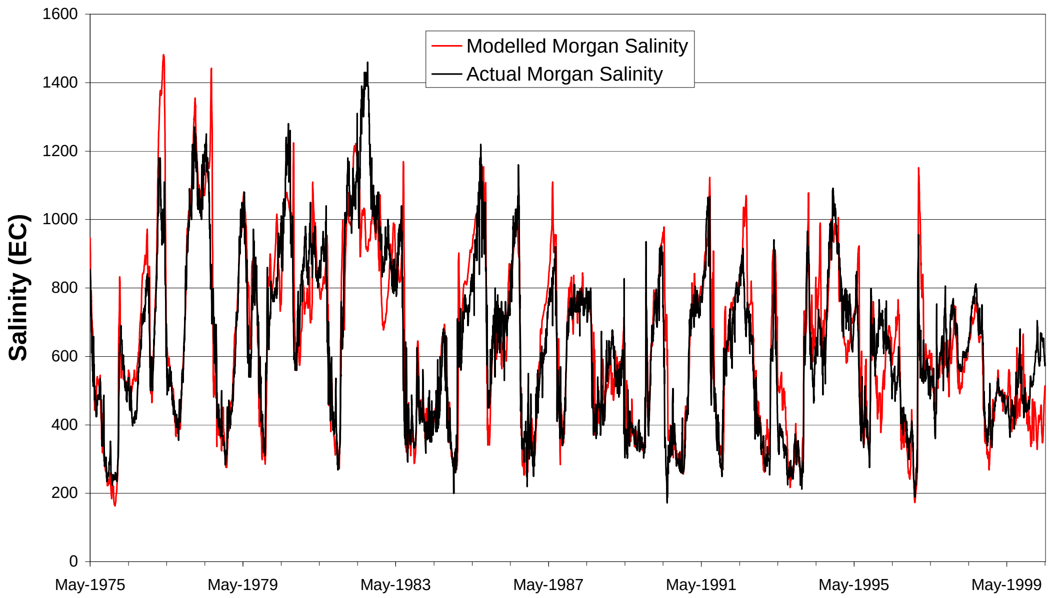


Figure 2.2: Comparison of BIGMOD modelled and observed flows and salinities at Morgan

2.3.2 Flood extent

The importance of the extent and duration of floods for both the health of the floodplain and also the potential for mobilising salt back to the river has been recognised since the earlier Chowilla investigations (Jolly *et.al*. 1994; MDBC 1995). A 1995 study used satellite imagery to determine the extent of flooding since the 1970s and correlated to the observed river flows and levels (Sykora *et al*.1995).

The scale of salt mobilisation to the river from floodplains and wetlands has been noted as roughly proportionate to the spatial extent of floods (Overton 2004). This observation was first noted during the Chowilla investigations (MDBC 1995), where Roger Ebsary and David Cresswell generated a concept of salt load curves related to the peak of the previous flood.

CSIRO has developed a Geographical Information System based model which predicts the flooding extent of the River Murray for different river flows and weir levels (Overton *et al*. 2006). The River Murray Floodplain Inundation Model (RiM-FIM) is based on 78 Landsat Thematic Mapper satellite images of floodplain inundation areas and MURLEV, part of the River Murray Flow and Salt Transport (RMFST) computer model, which was used to estimate backwater curves. (Note: We have not compared the RMFST to our conceptual model but recommend that this be done in future.)

RiM-FIM has some limitations and may need further testing. Its predictions are for a given flow on the first day of the flood, and do not consider the effect of antecedent conditions or the effect of flood duration. Overton *et al*. (2006) recommend that: "Further research on the wetting and drying behaviour of the floodplain and its wetlands needs to be incorporated into the model to be able to predict time sequences for management scenarios".

The RiM-FIM results also need to be compared to "outputs from existing hydrodynamic models of some sections of the River Murray to test its applicability to floodplain scale modelling of flood inundation."

RiM-FIM has been used to create "commence-to-flow figures" (i.e. showing the areas flooded for different threshold River flows). Its results have been incorporated into groundwater models of Chowilla (Howe *et al*. 2007).

2.3.3 Salt delivery from floodplain surface waters

Surface water bodies are classified as:

- the River Murray
- anabranch – two connections to the river at minimum flow, whereby water flows through the system at minimum flow
- backwater – only one connection to the river at minimum flow, whereby water does not flow through the system at minimum flow
- billabong – disconnected surface water bodies at minimum river flow, i.e.no connection to river.

There are anabranches, backwaters and disconnected surface water bodies throughout the lower Murray floodplains. All three types of wetlands can be the destination for mobile salt in the floodplain. Salt introduced to anabranches is usually mobilised immediately into the river, whereas salt introduced to backwaters and billabongs may become saline between flood events.

The extent to which these features are salt interceptors is worthy of consideration within the context of this study. The permanently flowing anabranch systems such as Chowilla and Pike River are known to collect salt from the groundwater system and deliver it continuously to the river itself. The Bookmark Creek, which would normally circumvent Lock 6, is operated as a salt interception scheme with excess salt being pumped to the Disher Creek floodplain evaporation basin. Further upstream, close to Lake Victoria, the Brilka Creek has been blocked off for low flows and collects salt between Lock 8 and Lock 7 (between Frenchman Creek and the mainstream river).

To some extent, the closed backwaters provide some protection to the mainstream channel by storing salt until the next flood arrives. The Yarra Lagoon in the Lock 3 – Lock 2 reach is a prime example.

Backwaters may become disconnected from the main river channels during periods of low flow. Evaporation may lead to high salinities in these backwaters, as illustrated by close-spaced EC surveys of the Pike River (AWE 2010d). It is anticipated that this salt is mobilised during periods of higher river flow.

Following the 1956 flood and subsequently during the early 1960s, salinity levels within the lower Murray reached 1500 EC in 1957 and greater than 1200 EC regularly during the 1960s at Waikerie. The relationship with post-flood salt accessions was acknowledged by the construction of regulating structures on backwaters designed to hold back salt and release it during periods of high flow. Examples include Barr Creek in the Kerang area of the Riverine Plains and Brilka Creek in the floodplain below Lake Victoria upstream of Lock 7. The Bookmark Creek (Renmark Reservoir) was blocked off in 1967 and subsequently diverted through Disher Creek basin to the Noora basin in 1984.

Similar backwater management works were investigated and proposed for the Lindsay River near Lock 7 and Chowilla floodplains near Lock 6, but have not been constructed due to concerns raised about the local impacts of salt retention in the creeks and anabranches. The Chowilla salinity control proposals generated very considerable concern within the community and lead to a substantial increase in field studies and research during the late 1980s and early 1990s. The agency work on behalf of the MDBC, led by the Engineering and Water Supply Department in South Australia resulted in the draft environment impact statement (NEC 1988), which documented the hydrological studies (in particular the work by Collingham 1990a, 1990b). Subsequently, the intensive effort by the CSIRO led to intensive interest in the local floodplain processes resulting in further analysis of the interrelationship between the hydrology of floods and the health of the vegetation (these publications are discussed further in Sections 2.4.1 to 2.4.6).

Australian Water Environments (2000) identified that groundwater inflows to the Ramco Lagoon at Waikerie were combining with annual evapotranspiration variations to deliver salt loads in winter to the river. Groundwater inflows were estimated to be approximately uniform during the year based on piezometry, with upward heads causing saline groundwater discharge to Ramco Lagoon. However, the evapotranspiration rates in summer exceeded the groundwater input fluxes as evidenced by the occurrence of river water in the inlet/outlet channel, and consequently the salt load in the Lagoon increased during summer. In winter, as evapotranspiration rates dropped to less than the inflow rates, the lagoon inlet/outlet became saline as the saline lagoon water discharged into the river. The quantum of discharge was sufficient to warrant an extension of the existing interception borefield to prevent the saline discharge to the lagoon. The processes are conceptualised in Figure 2.3. The depicted salinity of the Lagoon is for the start of each season.

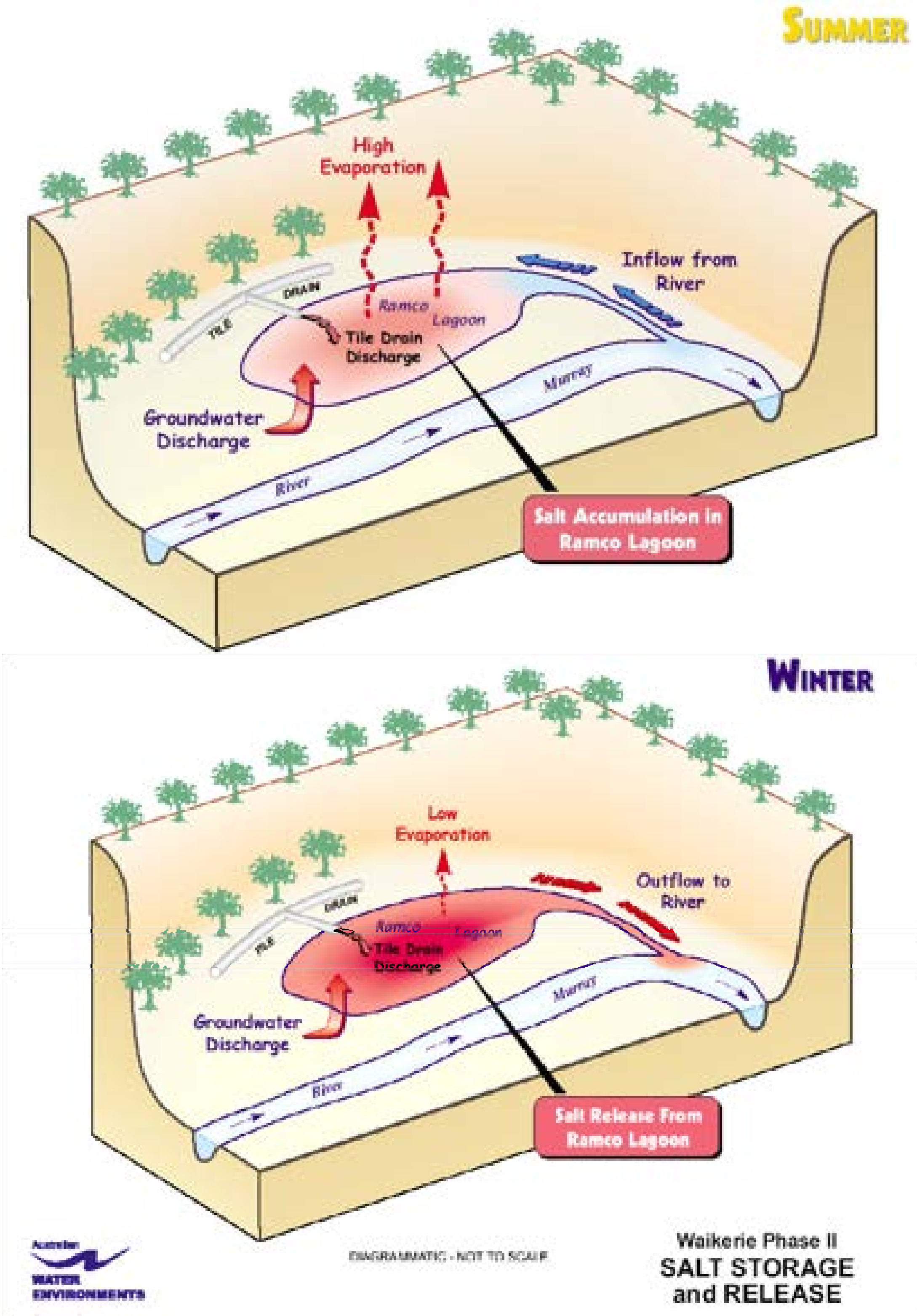


Figure 2.3: Wetland inflow/outflow seasonal variation

Within gaining rivers and anabranches, depressions in the riverbed elevation may contain saline groundwater - the causes are discussed in Section 2.4.6. These saline pools are mobilised by floods or high river flows. Saline pools in the Edward–Wakool system are mobilised when flow is first re-introduced after no-flow conditions to the Edwards–Wakool system and dumped into the River Murray at low flows (Green 2001). Saline pools occurred in the River Murray at Woolpunda before the SIS was implemented, and are thought to have been flushed by turbulent flows during floods (Telfer 1989). Saline pools in the Lindsay River were observed to gradually develop following cessation of a flood when flows were less than 62 ML/d and were flushed by flows of up to 30,000 ML/d (Dudding 1992).

Yan *et al*. (2005) present a MODFLOW model of the Chowilla region before and after construction of a weir lock. The model was developed to inform an impact assessment model of moderate complexity, capable of simulating the regional aquifer system to inform hydrogeological understanding, borefield concept design, and quantification of salt loads from the Chowilla area. The model does not include flooding or the Coonambidgal formation. The model shows that before locking the anabranches were not connected to the river, so:

- the groundwater levels would have been lower
- evaporation was sufficient to remove the groundwater flux to the creeks
- groundwater levels were lower across the floodplain and evapotranspiration was therefore lower
- the salt input:output ratio of anabranches was balanced.

Post locking, higher water levels caused:

- 75 t/d more salt to be stored in the floodplain aquifer
- increased water tables and increased evapotranspiration in some parts of the floodplain but not in others
- the increased salt storage results in large salt loads in the post-flood period.

The model calibrates with 1 mm/day evapotranspiration from groundwater from eucalypt forest.

The River Murray Irrigation and Salinity Investigations Project investigated the salinity implications of floodplain drainage disposal basins (Cole 1985).

2.4 Groundwater processes

Groundwater processes affecting the River Murray's salinity include:

(i) evapotranspiration

(ii) root zone drainage and aquifer recharge

(iii) flux between groundwater and the River Murray under pool conditions

(iv) bank storage and freshwater lens development and variability

(v) regional hydrogeological conditions and the salinity of both regional and floodplain groundwater

(vi) the impact of flooding and floodplain inundation on groundwater recharge and groundwater recessions

(vii) density effects.

2.4.1 Evapotranspiration

Water may be removed from the floodplain via evaporation or via transpiration by plants from the root zone. The term evapotranspiration is used for the combination of these two processes. The water removed may come from surface waters, the unsaturated zone and from groundwater and it is typically difficult to distinguish the proportion from each. The Bureau of Meteorology Climatic Atlas of Australia: Evapotranspiration (2001) notes that "evapotranspiration is a large component of the water balance; almost 90 % of the precipitation that falls on the Australian continent is returned through evapotranspiration to the atmosphere. However, despite its importance, evapotranspiration is almost impossible to measure or observe directly at a meaningful scale in space or time."

Recent studies confirm evapotranspiration's importance in the lower Murray while demonstrating that the measurement of evapotranspiration on larger scales may be possible.

Modelling studies of floodplains at Murtho (AWE 2010c) and Sunraysia (Aquaterra 2010; SKM 2010) show that evapotranspiration from groundwater appears to dominate the water budget for saturated floodplain sediments, and that evapotranspiration can directly contribute to the development of losing reaches of the river by inducing flow from the river to the floodplain.

In the Wetland Baseline Surveys (AWE 2005, 2007, 2008) of approximately 32 South Australian wetlands, surveys of groundwater levels showed that around three quarters of the floodplain water levels were below river level in 2005, 2006 and 2007. We observe that floodplain groundwater heads can be below river level by more than a metre due to evapotranspiration e.g. at Murtho (AWE 2010c) and Pike (AWE 2010d).

Recent advances in remote sensing have started to provide large-scale measurements of evapotranspiration at scales not previously possible (Evans *et al.* 2010). Sinclair Knight Merz (2010) reviewed methods for estimating evapotranspiration in the Mallee Region of the Lower Murray, including both field methods and remote sensing techniques. They concluded that while ground-based methods provide a good estimate over time, they are very limited spatially, so remote-sensing techniques are the more cost-effective option at a catchment scale.

In field studies of the River Murray floodplains, evapotranspiration has most often been studied in terms of its relationship with vegetation health. For example, Thorburn *et al*. (1994) demonstrate that red gums use saline groundwater and soil water even when proximal to freshwater in creeks. Taylor *et al*. (1996) provide an analysis of 80 sites which showed that tree health was significantly greater where groundwater salinity was less than 40,000 EC, flooding occurred more than once every ten years, and depth to groundwater was greater than 4 m. An association was shown between GIS-predicted and field-verified groundwater salinity but not groundwater depth. Jolly and Walker (1996) consider whether the field water use of black box trees is affected by short-term flooding. Results from three sites, two of which were flooded for 32 days in December 1992, showed transpiration rates of 0.05 to 0.2 mm/d (winter to summer) to 0.2 to 0.4 mm/d. The differences are attributed to vegetation density. Indications are that floodwaters infiltrated only 1 m into the profile. Jolly (2004) summarises previous studies estimating evapotranspiration rates, which range from 0.03 mm/d to 2.00 mm/d depending on vegetation type, watertable depth and groundwater salinity.

Models based on the Richards equation and other equations have been developed to estimate evapotranspiration and root zone drainage. WAVES (Zhang & Dawes 1998; Slavich *et al*. 1999a) calculates balance equations for energy, water, carbon and a conservative solute. Overton and Jolly (2004) summarise previous work for the purpose of vegetation health management. They describe WAVES and WINDS (Slavich *et.al* 1999b), which is based on WAVES but is simplified to consider only salinity impacts.

The Department of Sustainability and Environment in Victoria has developed a one-dimensional model currently known as ENSYM (Ha *et al*. 2010). ENSYM uses climate data, elevation, vegetation type, soil type and land use to model outputs including surface water, groundwater dynamics and native habitat changes. ENSYM calculates a water balance, including deep drainage volumes, based on soil parameters, climate data, vegetation parameters and agricultural management information.

Doble *et al*. (2005) describes a GIS model which produces estimates of evapotranspiration/recharge for use with MODFLOW. The GIS model includes spatial datasets for vegetation, soil type, groundwater salinity, and elevation, as well as time series information on flood duration and frequency. Flux to and from the surface to groundwater is estimated. It was developed to aid the design of groundwater models in the Mallee regions of the River Murray.

The rates of evapotranspiration from the floodplain groundwater have been estimated in calibrated regional groundwater models. Calculations on the Yan *et al*. (2005) model of Chowilla indicates that the actual evapotranspiration rate from the floodplain groundwater needs to be only around 5 mm/p.a. to account for the regional groundwater inputs to the floodplain (i.e. this is the average annual volume of water removed by MODFLOW's evapotranspiration module divided by the area of the Chowilla floodplain in the calibrated model). AWE, at Murtho and Pike, calculate rates of the same magnitude. Greg Hoxley (SKM, pers. comm., 2005) suggests that a range of 5 to 20 mm/p.a. of actual evapotranspiration from groundwater is a reasonable estimate for the Victorian Mallee floodplains, based on models of those systems. Even at these low rates, the evapotranspiration components in the models are still usually the largest components of the water balance.

We could find no systematic study comparing the evapotranspiration estimates from the various field and modelled estimates for River Murray floodplains.

2.4.2 Root zone drainage and recharge

Root zone drainage is the water which percolates down from the root zone into the unsaturated zone and eventually to the watertable, at which point it is termed groundwater recharge. Alternatively, the root zone drainage may reach a perched water table and possibly be captured in subsurface drainage systems. Groundwater levels within a watertable aquifer, including those within a floodplain, are sensitive to recharge.

Recharge occurring due to the inundation of floodplains during floods is discussed separately.

Field measurements

It is impractical to measure root zone drainage directly, however a range of surrogate tools have been adopted, at least for root zone drainage from the Mallee irrigation areas (Newman 2009).

Field estimates of recharge rates in the floodplain and Mallee regions of the River Murray initially concentrated on recharge under native vegetation and under cleared (but not irrigated) land. Cook *et al*. (2004) give a value of 0.1 mm/p.a. recharge for native vegetation and an average 2.7 mm/p.a. for cleared land. The field values varied by soil type and were extrapolated using soil maps for the South Australian Mallee, yielding an average drainage rate of 12 mm/p.a. (Cook *et al*. 2004). This higher average value may reflect a bias in the soil maps used to develop the drainage maps, because soil maps are often based on samples which do not extend the full depth of the root zone. Cook *et al*. (2004) recommend that 4 mm/p.a. be adopted for cleared land in the north-eastern Mallee. An unpublished study by Maschmedt supports this - when 2 m soil profiles were used to estimate clay content, the mean rate was 4.9 mm/p.a. (Fred Leaney, CSIRO, pers. comm.).

Recharge rates have been more difficult to determine for the irrigated areas adjacent to, or situated on, the floodplains of the River Murray. Most of the relevant work remains unpublished. CSIRO has sampled sites at Bookpurnong and AWE has sampled sites at Murtho. The MDBA is currently funding a review of recharge rate estimates.

Estimates derived for and from groundwater models

Groundwater modelling in the lower Murray–Darling Basin has developed a set of heuristics for estimating recharge rates for irrigation areas. In very broad terms, the following ranges for recharge rates are often accepted for different land uses:

- less than 100 mm/p.a. for irrigated areas of high irrigation efficiency with a surface drainage system
- 100 mm/p.a. under irrigated areas of high irrigation efficiency, which is simply calculated as 10% of the 1000 mm/p.a. application rate
- up to 1000 mm/p.a. under inefficient irrigation areas in past decades, based on the 2000 mm/p.a. application rate multiplied by a 50% (in)efficiency factor.

Groundwater modellers have also used a "time lag" for recharge to represent the time taken for water to percolate from the root zone to the water table. This is influenced by initial soil moisture and the presence of clays in the unsaturated zone, including substantial layers such as Blanchetown Clay. Jolly *et al*. (1989) and

Cook *et al*. (1989) developed equations for the time delay in non-irrigated lands assuming uniform properties within the unsaturated zone. Cook *et al*. (2004) develops an equation for a two-layer soil profile (e.g. sand and clay) and typically, for each metre of Blanchetown Clay, the time lag increases by 2 to 5 years. The equations by Cook *et.al* (2004) were used within the geographical model SIMRAT (Fuller *et al*. 2005) to provide a spatial distribution of recharge time-lags which could be used by groundwater modellers and others.

However, groundwater modellers found that SIMRAT time-lag estimates were difficult to reconcile with observed and modelled heads. In practice, groundwater modellers have used recharge rates and time-lags in irrigated areas as calibration parameters. This may be due to two limitations of the Cook/SIMRAT equations (which may also apply to other methods of estimating recharge from surface observations such as agronomic water balance, see Newman 2009).

Firstly, the equations were developed for the case in which irrigation starts on a previously non-irrigated site. It is assumed that the unsaturated zone starts out at a low residual saturation level. Hydrodynamic conductivity increases as saturation increases, so flow in the unsaturated zone depends on whether there has been any previous wetting-up. The equations cannot be used to calculate the time-lag for a *change* in irrigation drainage to reach the watertable.

Also, the equations assume vertical flow only, which may not be appropriate under irrigation areas where there is a thick clay layer in the unsaturated zone. AWE (2010a) simulates flow in both the unsaturated and saturated zone, and demonstrates that perched aquifers can form above clay layers. These layers spread the footprint of the recharge area, so the assumption of vertical-only flow does not apply. The SIMRAT equations then underestimate time-lags and rates at early times (years to decades).

Estimates derived from root zone drainage models

As mentioned in Section 2.4.1, a number of models have been developed to estimate evapotranspiration and root zone drainage. These include WAVES (Water, Atmosphere, Vegetation, Energy and Solutes), developed by CSIRO, and ENSYM (formerly CAT1D), which has been developed by the Department of Sustainability and Environment (DSE) Victoria (Ha *et al*. 2010).

We note that recharge estimates derived from these models have not been shown to match well with estimates derived from groundwater models. For example, ENSYM estimates of recharge were used as inputs to a set of groundwater models developed for the DSE. Each groundwater model covered a complete Catchment Management Authority (CMA) region. The Mallee CMA region model was developed by Aquaterra (2010) and reviewed by AWE (2010b). It was found by the CMA-region modellers that the ENSYM recharge estimates did not agree with prior estimates and that this made calibration of the models difficult. For example, the initial ENSYM drainage estimates show large areas of the Mallee CMA that have no recharge at all. While some of these areas are under native vegetation, much is cleared land and some is irrigated. The ENSYM estimates in the northern Mallee CMA differed significantly in rate and pattern from estimates obtained using other methodologies such as (i) those used in Cook *et al*. (2004), (ii) those typically employed in groundwater modelling of mallee regions, and (iii) the Eastern Mallee 2 groundwater model.

The discrepancy described above demonstrates how a model developed based on agricultural and soil sciences may disagree with models based on saturated zone hydrogeology. These discrepancies are, however, not all bad as they focus attention on identifying gaps in scientific knowledge.

2.4.3 Flux between groundwater and the Murray under pool conditions

The flux between groundwater and the River Murray under pool conditions is difficult to measure directly. It can be estimated using Darcy's Law, which requires an estimate of the hydraulic conductivity of the river bed and bank sediments and the head difference between the river and the floodplain aquifer. The conceptualisation and quantification of what processes affect the river bed conductivity is understood at a general level only. It is possible that the hydraulic properties of the river bed vary metre by metre.

Unfortunately, the river bed conductivity is difficult to measure in the field. AWE (2004) used aquifer test results at Bookpurnong to infer that the river bed conductivity can vary significantly at the kilometre scale.

Numerous numerical groundwater models have been developed to estimate the flux between groundwater and the River Murray. A series of models have been developed which cover the entire Lower Murray: Eastern Mallee 3 (Aquaterra 2010), the Chowilla Floodplain model (Yan *et al*. 2005), the Border to Lock 3 model (Barnett & Yan 2006), the Lock 3 to Morgan model (Middlemis *et al*. 2005), and the Morgan to Wellington model (Yan *et al*. 2010). The modelled results are generally compared or calibrated to datasets including groundwater head, Run of River salt loads, in-stream NanoTEM and Aerial Electromagnetic (AEM) resistivities. The results vary model by model.

In-stream NanoTEM (Telfer *et al*. 2005 and 2006) can be used to infer the salinity of pore-water in the river bed between Wellington and Torrumbarry Weir. The in-stream NanoTEM surveys quantify the resistivity of the river bed which is used to infer whether the river is losing stream (which results in fresh river water in the sediments) or gaining stream (with saline water in the sediments). The in-stream NanoTEM data were extensively analysed and correlated with available geologic, hydrogeologic and in-stream salinity data in Telfer *et al*. (2005). The report concludes that:

> *Correlation of the resistivities with the available geologic and hydrogeologic data illustrates that gaining streams with Run of River salt loads of greater than 2 tonnes per day per kilometre usually have a riverbed resistivity of less than 3 Ωm. Losing streams usually have a riverbed resistivity of greater than 20 Ωm and very low to zero in-stream Run of River salt loads. The low resistivity signals correlated with high in-stream salt loads occur along 6% of the study reach. The high resistivity signals correlated with losing streams occur along 43% of the study reach*.

The NanoTEM data have been compared with the Chowilla model (Yan *et al*. 2004). The comparison (Telfer *et al*. 2005) concluded that:

> *The NanoTEM and Lock 6 modelling comparison demonstrates that high NanoTEM riverbed resistivity values (greater than 20 Ωm) correlate strongly with losing stream conditions and that low resistivity values (less than 3 Ωm) correlate strongly with gaining stream conditions. This reinforces the strong correlations deduced in the preceding Chapter. The causality between NanoTEM and losing/gaining streams could be established by obtaining riverbed sediment porewater salinity data at Lock 6*.

Later work (Berens *et al*. 2007 ; Tan *et al*. 2007) reports on the sampling of riverbed sediments and extracted and measured pore water salinities, and identifies the strong correlation between the NanoTEM/AEM resistivity results and the extracted river-bed pore-water salinities . Key results of the NanoTEM groundtruthing and the correlation with other data at Mildura (Telfer *et al*. 2009) include:

- Areas of low resistivity (high conductivity) are correlated with high pore water salinities. Review of soil texture at these locations indicates that the sediments are predominantly sand, meaning that clay is not likely to have an influence on the NanoTEM signal.
- Areas of high resistivity (low conductivity) are correlated with low pore water salinities.
- Given the correlations between the two datasets at each of the locations discussed above, extrapolation of the NanoTEM throughout the study area could be made with a high degree of confidence.

2.4.4 Floodplain salinity

Regional groundwater salinity data are contained within MDBC (1999). More detailed salinity assessments have been compiled for site or region specific projects (AWE 2009; REM 2005). The detailed assessments show that floodplain salinity values are highly variable at the floodplain scale, however the compilation and analysis of these data are beyond the scope of this project.

A number of Airborne or Helicopter Electromagnetic surveys of the River Murray floodplain have been conducted upstream from, and including, Pike River (Munday *et al*. 2008; Fitzpatrick & Munday 2009; Tan *et al* 2007), and for parts of the highland in South Australia (Brodie *et al*. 2004). A large volume of AEM data had been compiled and analysed, and a large number of derived products prepared based on the data. These datasets provide a large repository of information and interpretation that has not been fully assessed for this study.

The AEM studies provide an indication of floodplain salinity, both in the saturated and unsaturated zones. Advanced vibrocoring technologies permit the drilling and sampling of undisturbed core for unconsolidated saturated and unsaturated sediments in the Murray Trench. Core has been sampled to depths in excess of 25 m on the floodplains. It has also been obtained for saturated sediment at the base of the River Murray. Analysis of core samples shows the relationship between Quaternary sediments and salt for the Chowilla and Sunraysia regions, and confirms that the observed variations on the conductivity shown in inverted helicopter electromagnetic data are primarily a function of the salinity of the contained pore waters rather than being related to variations in the sedimentary texture (Tan *et al.* 2007).

2.4.5 Impacts of flooding and floodplain inundation on groundwater

Most studies of flood impacts on groundwater in the lower River Murray have focused on the Chowilla floodplain.

Jolly *et al*. (1994) present field observations and an analytic model of a 1990 flood. The modelling work is also presented in Narayan *et al*. (1993). Potentiometric head, hydrogeochemistry and soil salt storage were monitored before and after a flood which inundated much of the monitored area. Both the field observations of soil salinity and the modelling suggested that diffuse inundation recharge through the floodplain clays (i.e. overbank recharge) was minimal. Additionally, their model suggests that bank storage alone cannot account for the long period of declining in-river salt loads (the salt recession) following the flood. Unfortunately, the model assumptions and results are not presented, making it difficult to evaluate this result. The authors postulate that the long post-flood salt recessions are instead due to a different process:

> *localised recharge in locations remote from the floodplain streams occurs during floods which, over a period of several months, displaces in situ groundwater into the streams*.

They recommend that their hypothesis be tested. We note that Akeroyd *et al*. (1998) supports the idea that inundation recharge is negligible, as paired pre- and post-flood soil salinity profiles at the same site suggests that infiltration did not occur. The hypothesis regarding localised recharge has not been tested in any field studies of which we are aware. Jolly *et al*. (1994) notes that “diffuse recharge” is relatively unimportant as the low permeability of the sodic surface Coonambidgal Clay means that infiltration rates are very low.

Charlesworth *et al*. (1994) simulate flooding and a proposed salt interception scheme at Chowilla using a two-dimensional SUTRA model. The model is density-dependent and includes the simulation of solute transport. The model shows that salt loads peak during the flood recession period. Both diffuse and localised inundation recharge were simulated and there was little difference between the resulting salt loads over time.

Armstrong *et al*. (1999) use a MODFLOW/MT3D model to estimate groundwater flow and salt loads to the Loxton reach of the River Murray under various management scenarios. The model has been calibrated to match 1997 heads. Salt loads to the river peak 13 years after root zone drainage rates peak. A decline in groundwater salinity due to irrigation drainage does not compensate for the increasing flux the irrigation causes, so total salt loads are predicted to rise. Flood modelling shows large changes in groundwater salinity. Salt loads are presented with reservations as there are no available historical data on the floodplain’s initial conditions for salinity. The authors conclude that:

> *Serious reservations now exist regarding the value of predictions of groundwater flow in the floodplains [by models of Loxton not simulating floods], due to the absence of any flood events in setting up of initial conditions*.

We note that most groundwater models calculating salt loads for the River Murray have ignored this conclusion and have assumed pool levels for simplicity (Middlemis *et al*. 2005; Barnett & Yan 2006; Yan *et al*. 2010; AWE 2010d).

Richardson and Evans (2004) consider the Tri-State region near the borders of New South Wales, Victoria and South Australia, which includes Chowilla. Salt accessions and floodplain wetland conditions are reviewed, with potential salt accession hot-spots identified and ranked. The hot-spots within the Lower River Murray are the Wallpolla Creek, Lake Victoria, Ned's Corner, Lindsay River, the Chowilla Floodplain, Murtho and Ral Ral Creek. Key data are combined into a GIS database. The report recommends coordinated monitoring of the next flood and a study of groundwater processes.

Overton *et al*. (2005) considers the impact of a proposed weir at Chowilla. The weir is proposed to manipulate river levels to cause artificial floods with the aim of improving vegetation health. The WINDS model is used to estimate the impact of flooding on vegetation health and soil salinity. The salinity impacts on the River Murray are calculated using a Department of Water, Land and Biodiversity Conservation groundwater model described in greater detail in Yan *et al*. (2005). The MODFLOW model uses monthly changes in river level based on records from 1977 to 2005. Surface hydrological models provided flood inundation zones and creek levels. Recharge zones and rates are based on soil type, vegetation and soil temperature, and whether the weir is in operation. The model was a poor match to Chowilla Creek salt loads (Overton *et al*. 2005).

REM (2009) report a desktop study on the effects of weir pools on floodplain hydrology and hydrogeology. An uncalibrated two layer (Monoman and Parilla Sands respectively) MODFLOW model was developed to examine the effect of weir pool elevation changes at Lock 7. Riverbed resistance for the River Murray and backwaters was set to a very high number so as not to impede river-groundwater interaction. The model will therefore overestimate the impact of the weir pool manipulations on the groundwater levels in the floodplain. Sensitivity analysis was not undertaken to evaluate the sensitivity of the model to inclusion of riverbed resistivity or the presence of confining Coonambidgal clays.

A groundwater flow and solute transport model was developed by AWE (2009) for a cross-section passing through the floodplain near Lock 2 and Waikerie. River stage records were examined and three flood records were selected for simulation: one small, one medium and one large. The MODFLOW/MT3D model simulated series of floods of different sizes and frequency to gauge the fluxes and salt loads between the River Murray and the groundwater during floods and inter-flood periods. Included were both variations in river stage and floodplain inundation. Solute transport was simulated to evaluate the importance of the freshening of groundwater by river waters during the flood.

The model simulates floods as occurring only within the river, or within the river plus floodplain inundation. The river-only and river plus floodplain inundation models (Figure 2.4) produce similar groundwater recharge during the flood and discharge following the flood recession, except that in the floodplain inundation model:

- the bank storage volume (recharge from river to bank) is ~ 30% smaller, and therefore the freshwater lens volume protecting the river will be similarly smaller
- the post-flood groundwater flux (direct from bank to river) is ~10% larger, indicating the overbank flow contributed only a small incremental increase to the volume of water discharging back to the river. However the salinity of the water will be higher because there is a smaller freshwater lens to buffer the saline groundwater inflows
- around 30% of the overbank flow that entered the groundwater on the floodplain was returned to the river via the floodplain water bodies as the flood moved off the floodplain
- the remainder of the overbank flux was lost from the floodplain through evapotranspiration.

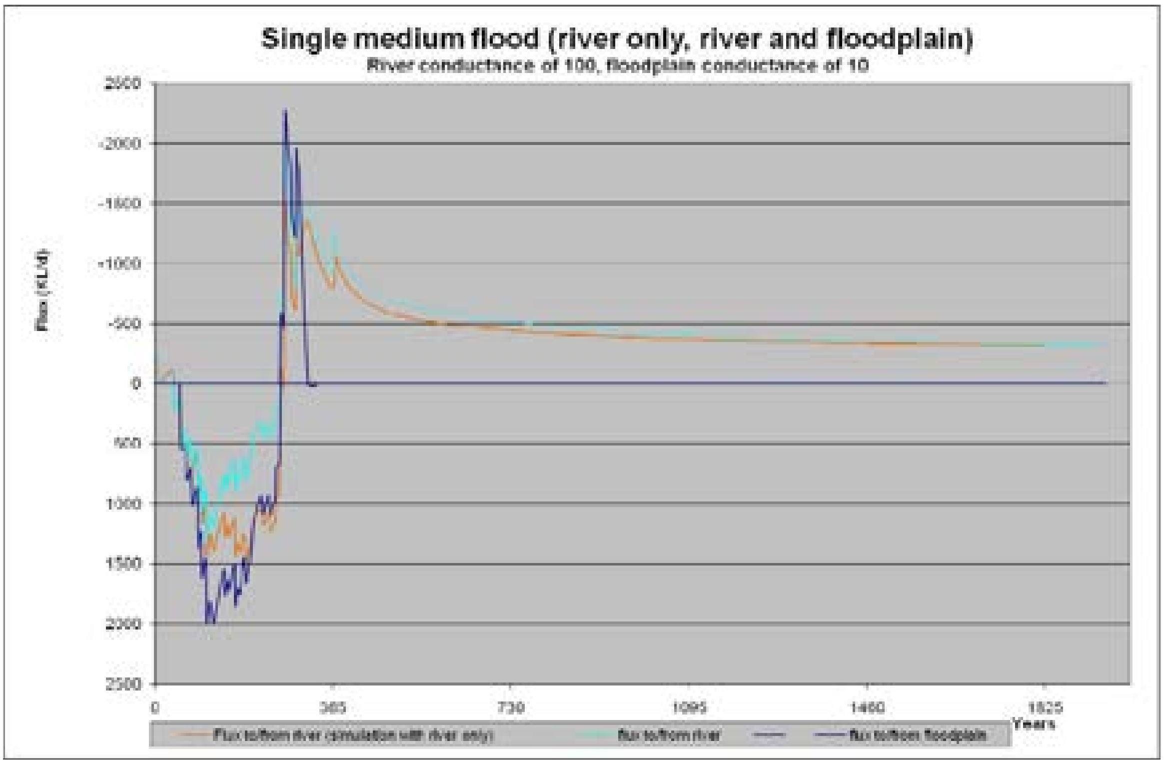


Figure 2.4: Narrow Floodplain Model – Flux to and from river

The net result is that whilst flow returned via groundwater to the river only increased by 10%, only some 60% of it was due to the return of bank storage. The other 40%, induced by overbank flooding would displace the near river groundwater that existed before the flood. If in a section of gaining stream where near river salinity is expected to be high, this additional return would also be high, having a significant salinity impact on the river. If in a losing stream section, the additional return may well be low salinity water but would tend to diminish the size of the fresh water lens.

Figure 2.5 shows the same model, this time testing the sensitivity of floodplain inundation groundwater recession flows to the vertical permeability of the Coonambidgal Clays. Within the range tested (ie k'v = 10-1 to 10-3) the floodplain permeability has little influence on the size of the groundwater inflow. However, examination of the model results during the flood shows that when the floodplain clay is tight (ie FPc=1, which is equivalent to a k'v of 10-3) the volume of water entering the floodplain through the bank is larger than when the clay is more permeable (k'v = 10^{-1}). Conversely, less water enters via the floodplain soils when it is less permeable than when it is more permeable.

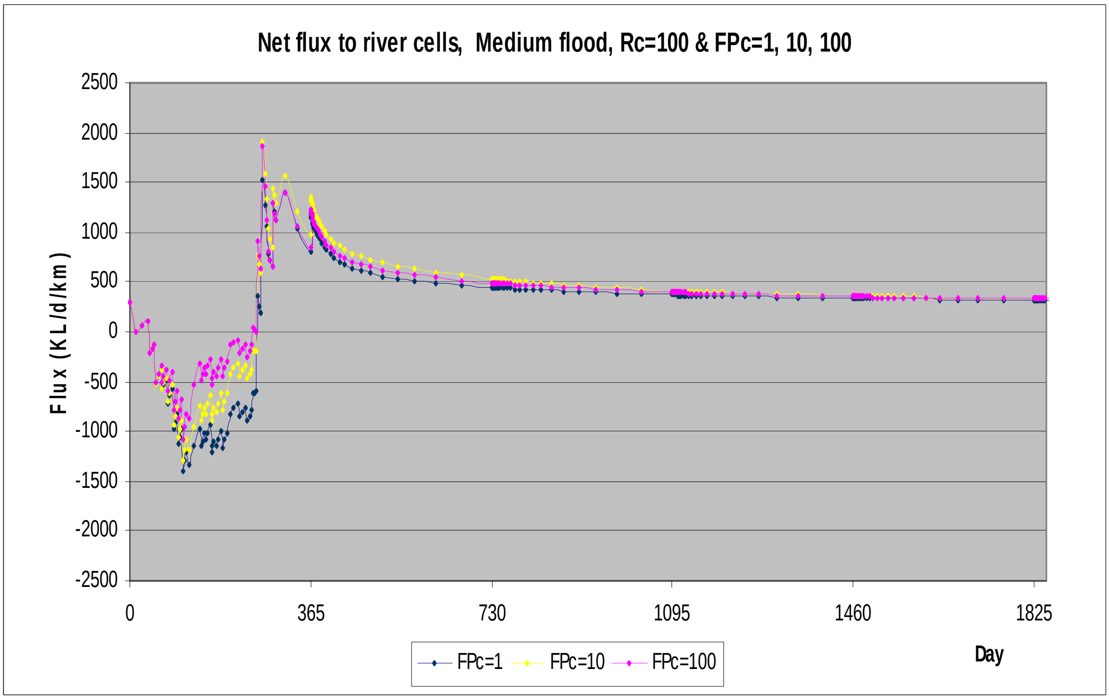


Figure 2.5: Narrow Floodplain Model – Flux to river – impact of Coonambidgal permeability

In summary, the model results for a narrow (1 km wide) floodplain indicates that:

- There is little impact on the size of the floodplain inundation groundwater recession when a flood is modelled with and without overbank inundation. However, the groundwater salinity is expected to be more saline when the overbank flows are included in the model.
- The groundwater recession flux to the river from an overbank event was not affected by changes in Coonambidgal Formation permeability within the range tested. However, there was clearly infiltration to the floodplain from the overbank flows because the quantum of bank storage reduced with increasing floodplain permeability. This suggests that head increases in the near-river aquifer (ie from bank storage processes) can propagate through the confined Monoman aquifer and raise the head by addition of water from below.

Jolly and Rassam (2009) review the modelling of groundwater and surface water interactions in arid and semiarid floodplains. They conclude that “future advances in this discipline are not so much limited by either computing power or solution methods, but rather by the availability of suitable data needed to parameterize, calibrate and validate current-day models.” This indicates the importance of data gaps when estimating groundwater impacts on River Murray salinity.

Yan (2010) gauges the relative impact of in-channel water level changes (via bank storage) to floodplain inundation recharge for Chowilla. A MIKE-FLOOD model was used to calculate the inundated area for every five day stress period and inundation recharge rates were estimated from the RiM-FIM model discussed in Section 2.3.2 (Overton *et al*. 2006). Recharge zones and rates were derived from the product of MIKE-FLOOD and FIM results and used as input to a MODFLOW model based on Howe *et al*. (2007). The model found that changes to river/creek level are more important than inundation recharge.

A groundwater flow model was developed by AWE (2010c) for Murtho in South Australia, extending from the Pike River to the western part of the Chowilla floodplain. The model refined and extended the methodology employed for the Lock 2 simulation undertaken by AWE (2009). Instead of simulating individual events, the Murtho model simulated river stages during the benchmark period (1975-2000) and the following decade of lower flows (2000-2009). River stages for each timestep were interpolated from stages recorded downstream of Locks 5, 6 and 7 and from backwater curves. Flooding of the floodplain was simulated (as a first approximation) using topographic data and calculations of the closest river kilometre. The impact of a proposed salt interception scheme (SIS) east of the river at Murtho was considered. The model shows the patterns of flux between the River Murray and the groundwater under variable flow condition. It shows how the water balance within the floodplain aquifer responds to these changes, particularly in terms of evapotranspiration. Results suggest that the majority of water that recharges the floodplain during a flood is subject to evapotranspiration, reducing the flux available to the River during a groundwater recession. Groundwater flux to the River is, similar to the Waikerie model results, sensitive to riverbed conductivity but not to floodplain sediment conductivity in the parameter range used. The proposed SIS reduces the impact of groundwater recessions but does not intercept all of the additional flow. The solute transport calculations show that salt loads are reduced by a third due to freshening of groundwater during floods (bank storage). More detailed modelled results are presented in Chapter 9 to illustrate groundwater recession processes.

It is also worth noting that the Murtho model example has both gaining and losing stream fluxes at the same time within the Lock 6 to Lock 5 reach. This highlights that gaining and losing streams can and do both occur within the one reach. Other floodplains will have different balances between gaining and losing stream components.

The AWE (2009) and AWE (2010c) models provide templates for further studies of surface and groundwater interaction during different river conditions. The salinity of the River Murray and the water balances of floodplains respond dynamically to changes in river stage and groundwater level induced by flooding. Salt loads cannot be accurately calculated without adequate solute transport modelling, due to freshening of the floodplain aquifer. Further improvements to the model would include the investigation of density effects on freshwater lenses and buffer zones in the floodplain, an improved representation of surface water flows and better representation of evapotranspiration processes.

2.4.6 Density effects

A few studies have considered the impact of density on floodplain processes. River water is fresher and less dense than saline groundwater in the lower River Murray.

A rare field study demonstrating density effects is Berens *et al*. (2009), using the experimental design of Telfer and Philp (2005). A production well near the River Murray at Bookpurnong induced a growing freshwater lens. The lens shape was curved, with fresher water above saline groundwater (Figure 2.6, from Berens *et al*. 2009). The results are based on contouring of salinity measurements in screened bores. The river is at the left hand side of the sections and B25 is the production bore.

Groundwater discharge will preferentially be attracted to the deepest parts of the river because density differences between the groundwater and river water mean that the pressure at the base of the deep pools is less than the pressure at a similar elevation below the river surface in the adjacent shallower river because the shallow river section includes lighter fresh water and denser saline water while the deep pool contains only lighter fresh water (Telfer 1989). Pools of saline groundwater occur in local deep “holes” in the river bed because the denser saline groundwater is retained in the pools at low flows, with only the top surface of the saline pool entrained into the laminar flow passing over the top of the pool. Under more turbulent higher flows, the pools are partially or completely scoured. This process has been noted at Woolpunda (Telfer 1989), in the Wimmera River (Anderson & Morison 1989), in the Lindsay-Wallpolla anabranch (Dudding 1992), and at many other locations within the main stem of the river in South Australia.

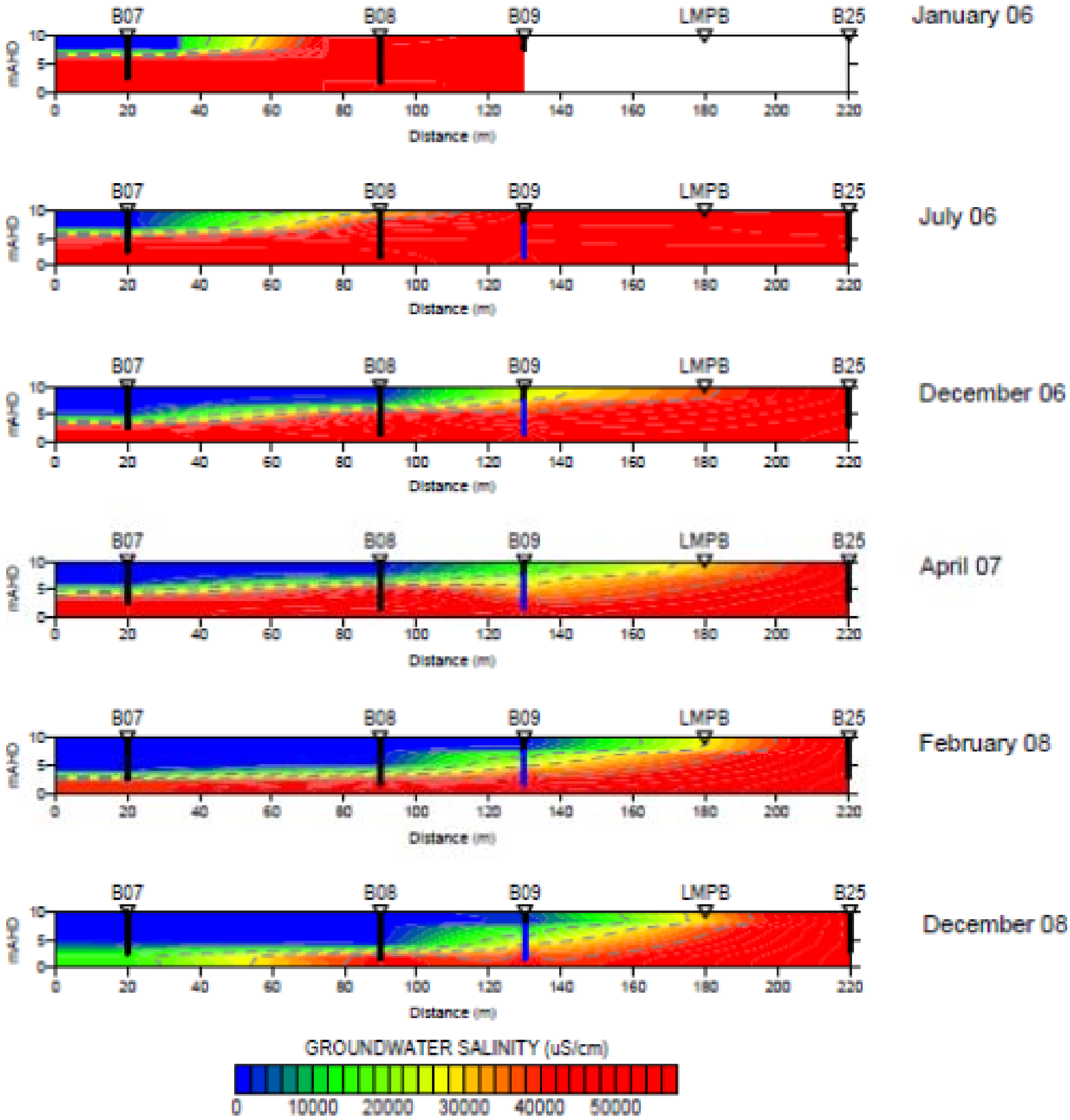


Figure 2.6: Growth of a freshwater lens in the floodplain aquifer at Bookpurnong

Jolly *et al*. (1998) simulate with SUTRA a cross-section through Chowilla that includes:

- the River Murray, Chowilla Creek and Monoman Creek
- changes in density, river and creek level
- diffuse recharge
- solute transport
- unsaturated-saturated zone flow.

The model is calibrated to hydrographs considering Coonambidgal hydraulic properties and thicknesses. The match to salinity is not presented but is reported as *"not exactly replicating"* observations. Data presented show groundwater influx to the bed of Monoman Creek on the flood recession. Modelled scenarios with and without diffuse recharge (2 mm, 5 mm) shows increased salt loads with diffuse recharge a kilometre north of Monoman Creek. The model shows the greatest fluxes are at the base of creek. The authors suggest that long groundwater recessions are due to localised recharge (i.e. preferential recharge through a "hole" in the floodplain sediments rather than diffuse recharge through all sediments) but this is not supported or refuted in the text.

Cartwright *et al*. (2010) examine in detail a freshwater lens in the Colignan-Nyah region of Victoria. The lens extends below the Blanchetown Clay, indicating that its vertical conductivity is not particularly low. The lens has shrunk during the present drought.

2.5 Soil salinisation and mobilisation

Rainfall, irrigation, inundation and high watertables provide water and salt to soils. Evapotranspiration removes some of the water, concentrating the salt. This salt may sit on the ground surface and within the soils, or it may leach down further into the profile through the unsaturated zone and perhaps to the watertable. The salt stored on the surface and in the unsaturated zone may be mobilised during flooding.

Soil salinity is usually measured using an aqueous extract from a soil sample. A number of methods have been developed to give a measure of soil salt concentration with the most common being the EC_e paste extract method or the $EC_{1:5}$ soil water extract method (Spies & Woodgate 2005). $EC_{1:5}$ conductivities are lower than EC_e results and conversion factors based on soil texture properties can be applied to compare the two (Spies & Woodgate 2005). The table below is an example of soil salinity classification based on EC_e results.

Table 2.1: Soil salinity classification (from Spies & Woodgate 2005)

Soil	EC_e (dS/m)
Non-saline	<2
Slightly Saline	2 – 4
Moderately Saline	4 – 8
Very Saline	8 - 16
Extremely Saline	>16

The quantum of salt exported from surface washoff from River Murray floodplain soils is assumed to be low (AWE & URS 2007; Jolly 2004). Dudding (1992) concludes that floodplain wash-off during flood events from the Lindsay floodplain introduces between 80 and 360 t/d during the event.

Weisbrod and Dragila (2006) present a conceptual model which suggests that surface-exposed fractures could be the main source of aquifer salinisation under arid conditions where there are thick unsaturated zones of low permeability. Evapotranspiration, enhanced by convective air circulation in the fractures, leaves the salt behind in the soil profile, where it remains until washed downwards to the aquifer during a wet season or period. Lab and field work of these processes have been conducted in the Negev Desert (Weisbrod *et al*. 2000). These processes could be expected to occur in an active floodplain but may not have been verified experimentally.

Jolly *et al*. (1993) developed a steady-state analytical model of the evapotranspiration-driven movement of salt from the watertable to the ground surface. Under these conditions, the time taken for the "salt front" to reach the surface varied from 4 to 17 years. The model relies on the assumption that the soil profile was fully leached of salt after the 1956 flood; as far as we are aware this assumption has not been tested, despite other studies at the same time and later (Narayan *et al*. 1993; Ackeroyd *et al*. 1998) documenting that infiltration of floodwaters is negligible or restricted to 1 m penetration. The assumption regarding fully leached 1956 soil conditions was, and is still, used in WINDS and WAVES models used to assess floodplain health.

A subsequent study by Thorburn *et al*. (1995) using a refined version of the same model calculated times from 4 to 40 years for the salt front to reach the surface. The model simulates plant water uptake using a coupled water and solute model, assuming (i) plants take water from a "plane of evaporation", (ii) no reflux of salt from the profile, except by diffusion which is <0.007 mm/d (i.e. 1 to 5% of upward flux). It considers leaching through flooding, but not the evidence that flooding doesn't change the salinity profile.

McEwan *et al*. (2003) document the results of a soil and groundwater sampling program in the River Murray floodplain from the South Australian border to Lake Alexandrina. The data include water table depth, groundwater salinity, soil texture and salinity at 206 sites. Vegetation data were also collected and reported separately.

Jolly (2004) provides a useful review of South Australian studies which guided later work by REM in the Sunraysia region of Victoria (REM 2005, 2009). Field observations have shown that soil salt storage is highly variable; the mean is 43.2 t/ha with a standard deviation of 19.1 t/ha. An exponential relationship between groundwater salinity and salt storage is found in the data (R^2 of 60%) suggesting that groundwater salinity may be a reasonable surrogate for salt storage.

Overton and Jolly (2004) also present a graph showing a linear relationship between flow and salt load at Chowilla, suggesting the number of recent prior floods is not a significant control of flood salt load. The data sources for the salt loads are not identified, nor is the methodology used for calculating them. The authors conclude: *"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 *et al*. (2005) included an updated version of the relationship between salt load exported from the Chowilla floodplain and the maximum flow of the preceding flood. Size of flood, rather than flood return interval, was identified as the major control on salt load, as shown in Figure 2.7.

Sinclair Knight Merz (2005) describes a monitoring system developed for the Mallee CMA region, including initial data from monitoring transects and a vegetation health survey. They considered the use of geophysical techniques to estimate sub-surface conductivity and salinity profile. This information was used to estimate patterns of the salt stored in the unsaturated zone. Points closer to the river show lower salt concentrations at one location (Iraak South) but at King's Billabong the major salt stores were close to the river, which could be potentially mobilised during floods.

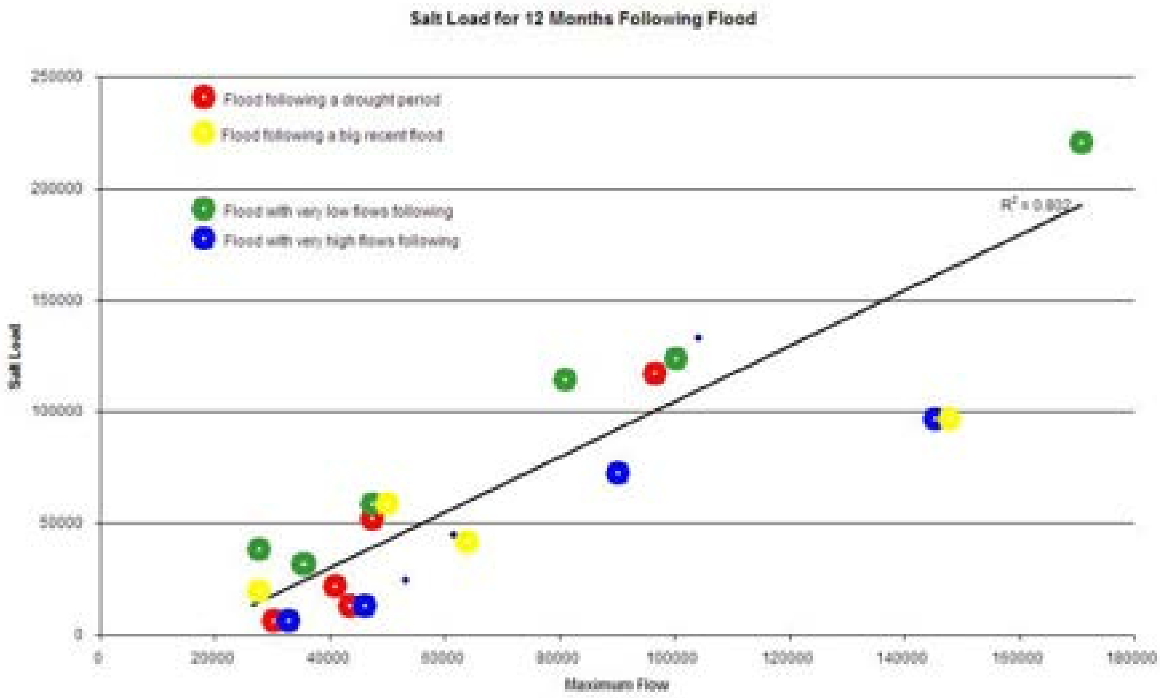


Figure 2.7: Linear relationship between salt load (tonnes per day) and river flow (ML/day) for Chowilla (from Overton et al. 2005)

2.6 Salt interception schemes

The importance of SISs can be demonstrated with reference to MDBA 2009b, which states:

"The construction and management of salt interception schemes (SIS) is a major investment component of the BSMS. Salt interception schemes along the River Murray play a critical role in maintaining water quality for agricultural, environmental, urban, industrial and recreational uses. The BSMS identified a target for SIS to reduce average salinity by 61 EC at Morgan by 2007. The timeframe for meeting this target is now 2011-12.

Since 1988, nine SIS have been constructed. These schemes prevent entry of approximately 450,000 tonnes of salt into the River Murray each year. A further eight SIS are in the pipeline, with five under construction and three under investigation.

Figure 2.8 shows that the actual recorded salinity at Morgan throughout July 2008 to June 2009 varied between 421 and 624 EC (grey line). The peak level is considerably less than last year (785 EC). The highest salinity level occurred in late September 2008 and the lowest occurred in mid-June 2009. The modelled 'no further intervention' (green line) indicates that management actions are responsible for salinity reductions of between 295 and 831 EC."

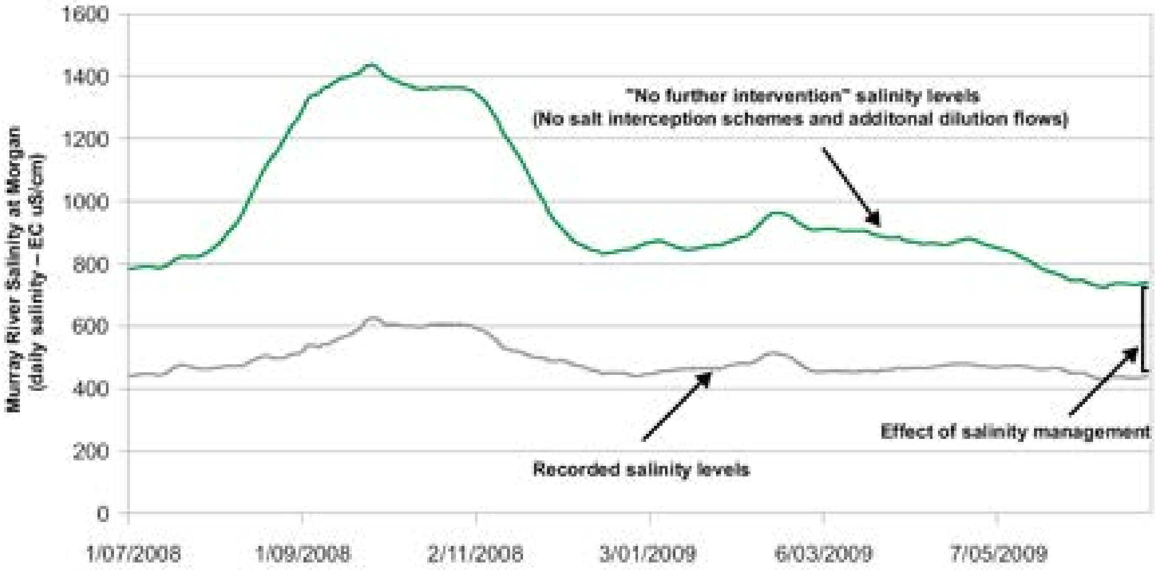


Figure 2.8: The effect of salinity management in the Murray–Darling Basin at Morgan, South Australia (daily salinity July 2008 to June 2009) (after MDBA 2009b).

Part 2 - Data

3 Floodplain characteristics

This section examines key regional datasets for the River Murray floodplain from Euston to Wellington. The river and floodplain is divided into five major reaches and each reach is further divided into sub-reaches. Key floodplain characteristics are assembled for each reach using the key regional datasets.

Floodplain characteristics that contribute to defining and analysing salt inflows are summarised in Table 3.1, and detailed analysis of the major characteristics is reported in the following sections.

The main data sources used are:

- BIGMOD: the calibration input file data and key output data enumerating flows and salinity through the River Murray.
- River Murray Floodplain Inundation Model (RiM-FIM): GIS output from the Overton *et al*. (2006) model of floodplain inundation by flow for the River Murray.
- In-stream NanoTEM: In-stream NanoTEM resistivity data and interpretations from Wellington to Torrumbarry (Telfer *et al*. 2005, 2006, 2007, 2009);
- Basin in a Box (MDBC 1999): The most recent compilation of groundwater data across the basin.
- Salt interception scheme data: data and GIS coverages developed by AWE for SIS projects.

3.1 Reaches

The five major reaches are bounded by stations with long-term salinity records (Appendix Figure A1). Up to seven sub-reaches occur in each major reach. The major reach and sub-reaches boundaries are shown in Appendix Figure A2 and key details are summarised in Table 3.2 and Table 3.3. The delineation of the reach boundaries across the floodplain takes into account the reach into which the surface water and groundwater will flow. This is particularly important where anabranches circumvent locks, for example at Chowilla, where groundwater from the floodplain upstream of Lock 6 discharges into the Chowilla Creek anabranch, but the anabranch rejoins the river downstream of Lock 6. The major reaches generally align with BIGMOD salinity reaches.

Table 3.1: Description of floodplain characteristics

Characteristic	Data source	Description
River reach	MDBA/ BIGMOD	The five major reaches are bounded by stations with long-term salinity records. The major reaches generally align with BIGMOD salinity reaches. Up to seven sub-reaches occur in each major reach.
Gaining/losing floodplain	Basin in a Box	Assessment of where the floodplain is gaining, losing or flow-through with respect to the regional groundwater, using the nomenclature of Section 0.
Regional /floodplain groundwater salinity	Basin in a Box	The regional and floodplain groundwater salinity.
SIS locations	AWE	SIS bore locations indicating where river salt loads have been reduced by SIS implementation.
NanoTEM riverbed resistivity	AWE	Riverbed resistivity derived from four in-stream NanoTEM surveys, stitched together to display the most recent data in each reach.
Murray trench area	AWE GIS	In SA reaches only where AWE has assessed the extent of the Monoman Formation, which in some cases is wider than the 1956 flood extent.
Flooded area	FIM	The area of floodplain inundated for flows of 5, 20, 40 ,60, 80, 100, 120, 150, 200, and above 200 GL/day.
Off stream wetland area	AWE GIS	Permanent inundated floodplain area connected to the river at minimum flow: anabranch, backwater.
River surface area	BIGMOD	Used in BIGMOD for the calculation of evaporation
River surface area	AWE GIS	Area of the main river channel from GIS
Dead water volume	BIGMOD	The volume which at zero flow is held in weir pools or lakes. It is used to differentiate between the travel time for flow changes and solute transport.

Table 3.2: Major reach details

Major reach	Description	River distance upstream (km)	River distance downstream (km)	River length (km)
1	Euston to Mildura	1117.2	885.5	231.7
2	Mildura to Lock 9	885.5	765.1	120.4
3	Lock 9 to Lock 5	765.1	562.1	203.0
4	Lock 5 to Morgan	562.1	315.0	247.1
5	Morgan to Murray Bridge	315.0	115.3	199.7
	Total	**1117.2**	**115.3**	**1001.9**

Table 3.3: Sub-reach details

Sub reach	Description	River distance upstream (km)	River distance downstream (km)	River length (km)
1.1	Euston to Wemen	1117.2	1063.6	53.6
1.2	Wemen to Chalka	1063.6	1028.6	35.0
1.3	Chalka to Colignan	1028.6	993.6	35.0
1.4	Colignan to Lock 11 weir pool	993.6	935.5	58.1
1.5	Lock 11 weir pool to Red Cliffs	935.5	910.1	25.4
1.6	Red Cliffs to Lock 11	910.1	885.5	24.6
2.1	Lock 11 to Old Mildura	885.5	877.5	8.0
2.2	Old Mildura to Merbein	877.5	871.0	6.5
2.3	Merbein to Curlwaa	871.0	846.5	24.5
2.4	Curlwaa to Wentworth	846.5	825.1	21.4
2.5	Wentworth to Anabranch	825.1	801.2	23.9
2.6	Anabranch to Lock 9	801.2	765.1	36.1
3.1	Lock 9 to Lock 8	765.1	725.7	39.4
3.2	Lock 8 to Lock 7	725.7	696.6	29.1
3.3	Lock 7 to Lindsay Mouth	696.6	654.0	42.6
3.4	Lindsay Mouth to Lock 6	654.0	619.8	34.2
3.5	Lock 6 to Lock 5	619.8	562.1	57.7
4.1	Lock 5 to Berri	562.1	526.0	36.1
4.2	Berri to Lock 4	526.0	516.2	9.8
4.3	Lock 4 to Lock 3	516.2	431.4	84.8
4.4	Lock 3 to Woolpunda PS	431.4	411.0	20.4
4.5	Woolpunda to Waikerie PS	411.0	383.0	28.0
4.6	Waikerie PS to Lock 2	383.0	362.1	20.9
4.7	Lock 2 to Morgan	362.1	315.0	47.1
5.1	Morgan to Lock 1	315.0	274.2	40.8
5.2	Lock 1 to Swan Reach Ferry	274.2	252.3	21.9
5.3	Swan Reach to Mannum PS	252.3	149.8	102.5
5.5	Mannum PS to Murray Bridge PS	149.8	115.3	34.5
	Total	**1117.2**	**115.3**	**1001.9**

3.2 Gaining, through-flow and losing floodplain classification

The regional groundwater contours and flow paths are shown in Appendix Figure A3, based on data from MDBC (1999). The groundwater contours and flow directions have been used to classify the floodplains into gaining, through-flow and losing floodplains using the floodplain classification nomenclature in Section 0.

Gaining floodplains occur in two localised areas around Mildura (from Mallee Cliffs to Psyche Bend and from Lock 11 to Merbein Common) and in the lower half of the study reach from Lock 6 to the Lower Lakes. The groundwater is sourced from regional groundwater mounds (e.g. Woolpunda) and from irrigation induced groundwater mounds. (e.g. Mildura, Loxton, Waikerie).

The regional hydrogeological maps indicate that the floodplain between the Darling Anabranch and Lock 9 (Wallpolla Island) is a losing floodplain.

The remaining floodplains are through-flow floodplains, i.e. most of the river upstream of Lock 6. The through-flow floodplains occur between Euston to Mallee Cliffs, Psyche Bend to Lock 11, from Merbein Common to the Darling Anabranch, and from Lock 9 to Lock 6.

In the absence of any losses in a floodplain, gaining floodplains would be expected to contain gaining rivers. However, losses do occur, and river management practices also affect the direction of groundwater flow in relation to the river.

Floodplain evapotranspiration causes groundwater losses from the floodplain. The magnitude of these losses will tend to increase with increasing floodplain width, and if evapotranspiration losses from the floodplain exceed net water gains (e.g. regional groundwater inputs, floodplain rainfall, floodplain irrigation), then the river can become a source of water for the floodplain. The NanoTEM data discussed below indicates some 50% of the river downstream of Lock 6, where gaining floodplains are ubiquitous, are losing river reaches. The stream classification (i.e. gaining or losing) can vary over time. Floodplain inundations will tend to replenish groundwater levels and increase the length of river where gaining stream conditions occur and extended drought will tend to increase the length of river where losing stream conditions occur. These general trends can be further modified by factors such as depth to water table, seasonality, floodplain inundation, floodplain irrigation and rainfall.

The presence of weirs and associated weir pools usually result in losing stream conditions upstream of a weir and gaining stream downstream (Telfer *et al*. 2005). The exception is the downstream pool at Lock 4 where the Bookpurnong Irrigation Mound drives groundwater into the lower pool of Lock 4.

3.3 Irrigation and salt interception scheme locations

Irrigation areas and the SIS borefields in the study area are shown in Appendix Figure A4.

The regional groundwater heads and flow directions are influenced by an overprint of irrigation induced groundwater mounds. Irrigation has usually resulted in the development of drainage water induced groundwater mounds which in turn displace saline groundwater into the floodplain and river. Impacts can take many decades to become evident. Irrigation practices have improved over the last two decades resulting in reduced drainage volumes. The presence of irrigation can create gaining floodplain conditions where through-flow conditions existed previously (e.g. in the Sunraysia area), or significantly increase the magnitude of gaining floodplain conditions (e.g. at Loxton and Waikerie).

Many salt interception schemes have been installed since 1979 to prevent saline groundwater flows entering the river. They have been placed in the high risk areas and reduce the in-river salinity impact. The SISs are continuing to be built, with Murtho and Pike SIS currently under construction.

3.4 Groundwater salinity

Regional and floodplain salinities (MDBC 1999) are shown in Appendix Figure A5. The floodplain boundary is indicated by the shaded area labelled the River Murray trench. Floodplain groundwater salinities are lower than regional groundwater salinities upstream of Lock 6. Floodplain salinities are similar to regional salinities from Lock 6 to around Loxton, and between Overland Corner and Murray Bridge. Floodplain salinities are higher than regional salinities between Loxton and Overland Corner.

More detailed salinity assessments have been compiled for site or region specific projects (e.g. AWE 2009; REM, 2005). The detailed assessments show that floodplain salinity values are highly variable at the floodplain scale, however the compilation of these data is beyond the scope of this project.

A number of Airborne or Helicopter Electromagnetic (AEM) surveys of the River Murray floodplain have been conducted upstream from and including Pike River.

A single unified approach and coverage has not been compiled previously, however a draft compilation has been prepared for this report using data from approximately the water table elevation from four different studies (noting that the individual coverages use different resistivity colour stretches and resistivity scales and different vertical intervals – the datasets have not been rectified (Appendix Figure A6).

The AEM resistivity distribution data provide an indication of groundwater salinity trends in the floodplain. The AEM data have been plotted against available bore salinity data in the Sunraysia reach, with good correlations observed (Munday *et al*. 2008). Tan *et al*. (2007) confirm that the observed variation on the conductivity shown in inverted helicopter electromagnetic data are primarily a function of the salinity of the contained pore waters rather than being related to variations in the sedimentary texture.

The AEM data illustrate broad patterns of floodplain salinity variability. Much work has been done on interpretation to date. Additional analysis is likely to assist in discriminating between the numerous, spatially and temporally complex, salt delivery, storage and mobilisation processes discussed in the Floodplain Salt Conceptual Model. Development of a consolidated map of floodplain salinity distribution using AEM data, point data and existing mapped distributions is recommended, to provide baseline data from which to deduce process and improve understanding of floodplain salt.

Comparison of the floodplain salinity patterns (Appendix Figure A5) with the Floodplain Classification (Section 0) infers the following about the regional groundwater and floodplain process interactions:

- Floodplain salinity tends to be lower than the regional groundwater salinity where through-flow or losing floodplain conditions occur. This pattern suggests that the dilutive effect of inputs of fresh water from the river and anabranches is stronger than the concentrating effect of evapotranspiration.
- Where gaining floodplain conditions occur, the floodplain groundwater salinity tends to be similar to or higher than the regional groundwater salinity. This pattern is consistent with the floodplain evaporative capacity being stronger than the dilutive effects of losing rivers and anabranches, leading to concentration of regional groundwater salinities in the floodplain.
- The relationship between high resistivity fresh water adjacent the river and through-flow to losing stream reaches, and the reduced width or absence of high resistivity fresh water in the gaining floodplain reaches.

3.5 NanoTEM riverbed resistivity

In-stream riverbed NanoTEM data are included in Appendix Figure A8. The riverbed NanoTEM data can be used to infer the location of saline and/or fresh water in the river bed (Berens *et al*. 2007; Tan *et al*. 2006). The NanoTEM data have been collected in inter-flood periods only – the bed resistivity patterns may vary during floods due to changes in the direction of groundwater-river flux. Therefore the NanoTEM patterns represent inter-flood periods only. The NanoTEM data have been analysed in detail by Telfer *et al*. (2005, 2006, 2007) compared to the Run of River data. Telfer *et al*. (2005) classifies the NanoTEM data into three classes, based on the correlations between the NanoTEM resistivity and the Run of River salt load inputs to the river, as follows:

- high resistivity NanoTEM values in the riverbed (>20Ωm) are interpreted as fresh water in river bed sediments, correlating with losing stream conditions - resistivity values greater than 20 Ωm are broadly correlated with salt loads of zero to less than 1 t/d/km
- medium resistivity NanoTEM values in the riverbed (3 to 20Ωm) are broadly correlated with salt loads of 0.5 to 2 t/d/km and gaining to losing stream conditions
- low resistivity values of less than 3Ωm are strongly associated with salt loads of greater than 2 t/d/km.

The NanoTEM riverbed resistivity data have been evaluated according to the resistivity criteria outlined above for the major reaches (Table 3.4 and Figure 3.1) and the subreaches (Figure 3.2). The sub-reach analysis indicates the major zones of saline inflow to the river are Colignan to Merbein, Lock 6 to Berri and Lock 4 to Morgan. Note that the NanoTEM riverbed resistivity results reflect conditions after salt interception schemes have been implemented – for instance the riverbed resistivity in the Woolpunda reach pre-SIS is anticipated to have been largely low resistivity (e.g. red in Figure 3.2) whereas post-SIS it is largely moderate resistivity (e.g. yellow). The NanoTEM results for backwaters and anabranches are not included in the data because not all anabranches have had NanoTEM surveys. NanoTEM surveys have been conducted on parts of Chowilla, Pike and Lindsay-Wallpolla anabranches.

The NanoTEM patterns (Appendix Figure A8) correlate with the AEM patterns (Appendix Figure A6).

Table 3.4: Major reaches – inferred saline Inflow and freshwater lens lengths per reach

Major reach	Description	<3 Ωm: Saline groundwater	3-20 Ωm: Medium resistivity	>20 Ωm: Fresh groundwater
		km	km	km
1	Euston to Mildura	10.3	109.8	111.6
2	Mildura to Lock 9	2.9	62.5	55.0
3	Lock 9 to Lock 5	2.8	69.4	124.4
4	Lock 5 to Morgan	24.4	192.2	36.9
5	Morgan to Murray Bridge	0.1	52.8	146.8
Total		40.5	486.7	474.7

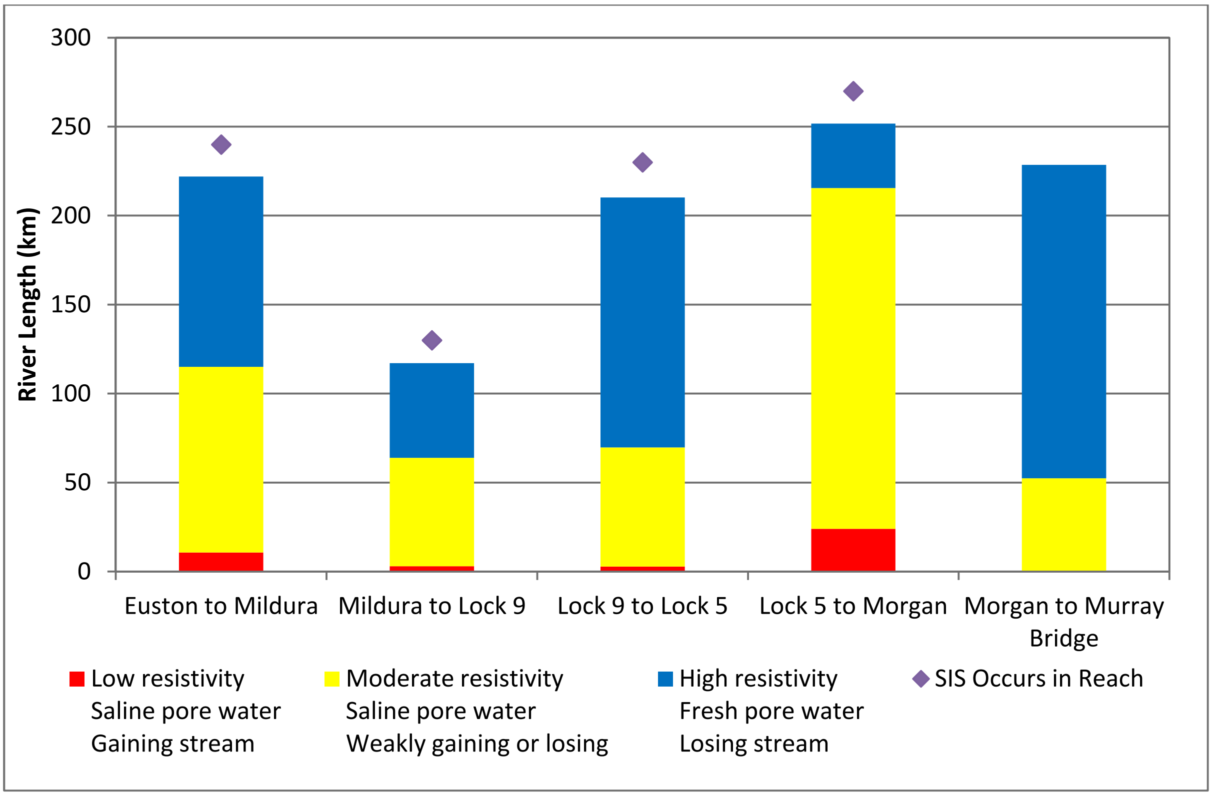


Figure 3.1: Major reaches – Saline inflows and freshwater lenses inferred from NanoTEM data

(Note: Does not include key anabranches which may have saline inflows.)

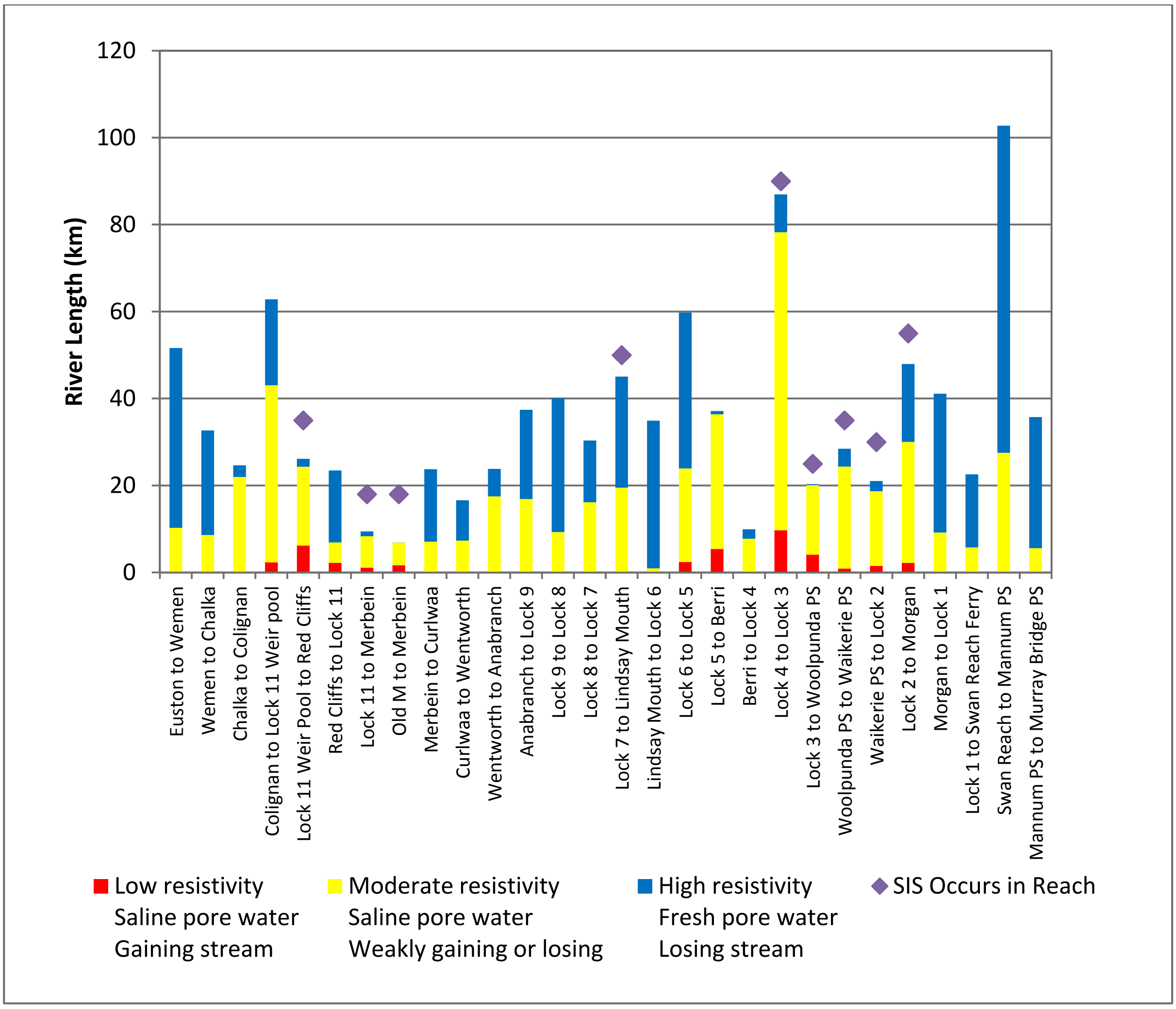


Figure 3.2: Key reaches – saline inflows and freshwater lenses inferred from NanoTEM data

3.6 Surface area of permanent water bodies

Surface waters have been segregated into river channel area and permanent wetland areas. The permanent wetlands are further divided into backwaters and anabranches. The key surface water body parameters for each major reach are summarised in Table 3.5.

The surface area of the river channel was obtained from both BIGMOD and the GIS shapefile of the river. The results compare favourably. The permanent wetland areas are derived by calculating the difference between the river channel area and the FIM inundation area for flows less than 3,000 ML/day. The area of permanent wetland varies from 7% in the Euston to Mildura reach where only one weir occurs, to 178% in the Lock 5 to Morgan reach where the whole reach is influenced by weir pools.

Table 3.5: Surface area of permanent water bodies

No	Description	River channel area (km^2)	Backwater area (km^2)	Anabranch area (km^2)	Wetland area / channel area (%)
1	Euston to Mildura	30.90	2.11	0.00	7%
2	Mildura to Lock 9	18.53	3.23	0.00	17%
3	Lock 9 to Lock 5	31.76	11.82	4.53	51%
4	Lock 5 to Morgan	37.98	59.75	7.90	178%
5	Morgan to Murray Bridge	34.91	46.17	0.00	132%
	Total - Reach Euston to Murray Bridge	**154.08**	**123.08**	**12.43**	**88%**

Note: Table excludes Lake Victoria but includes Chowilla Creek and Lindsay River anabranches in the Lock 9 to Lock 5 reach.

3.7 Floodplain inundated areas

The FIM data (Overton *et al*. 2006) are used to illustrate inundated areas by flow range (Appendix Figure A7). The database associated with the FIM have been analysed to obtain inundated areas for the reaches used in this project. Downstream of Lock 7, FIM delineates inundated areas for all flows. Upstream of Lock 7, inundation areas for flows above 100,000 ML/day are not well defined in the FIM model.

Figure 3.3 and Figure 3.4 show two different representations of the additional area of inundation for each major reach for various flow ranges. Figure 3.3 illustrates that the floodplain inundated area is minor at flows less than 40 GL/day, and that ~45% of the floodplain is inundated by the time flows reach 100 GL/d.

Figure 3.4 shows that while a relatively small proportion of the floodplain is inundated by flows in the 40 to 60 GL/d flow range, most of the inundated area occurs in the Lock 9 to Lock 5 reach. Analysis of the reach (Appendix Figure A7) shows that this inundation occurs in the Murtho reach. The Murtho area is the first area to significantly inundate on the rising limb of a flood downstream of Euston: it will also inundate more frequently than the rest of the study reach. It can therefore be anticipated that the Murtho area may pose a higher risk to river salt loads from groundwater salt inputs from floodplain inundation than the rest of the study area. The Chowilla floodplain, by contrast, does not flood extensively until flows exceed 60,000 ML/d.

Most of the Lock 5 to Morgan floodplain is inundated by flows less than 100 GL/d – in the Euston to Lock 5 reach only half to one third of the floodplain is inundated by flows less than 100 GL/d. In the 60 to 80 GL/d flow range, significant areas of floodplain are inundated between Lock 9 and Morgan.

The inundation areas for sub-reaches from Lock 9 to Morgan for flows less than 100 GL/d is shown in Figure 3.5. Figure 3.5 illustrates that the most significant inundation in this flow range occurs in the Lock 6 to Lock 5 region (Murtho area), with a smaller area inundated in the Chowilla reach.

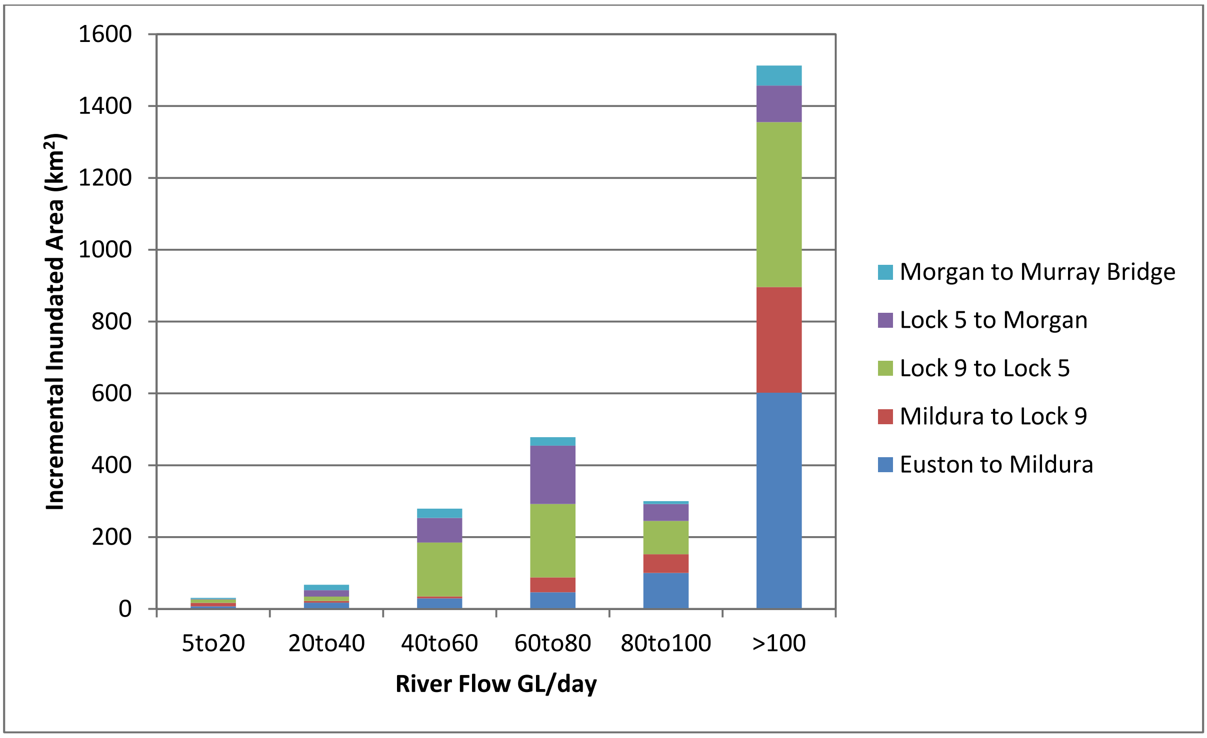


Figure 3.3: Major reaches – incremental inundated area by flow range for major reaches

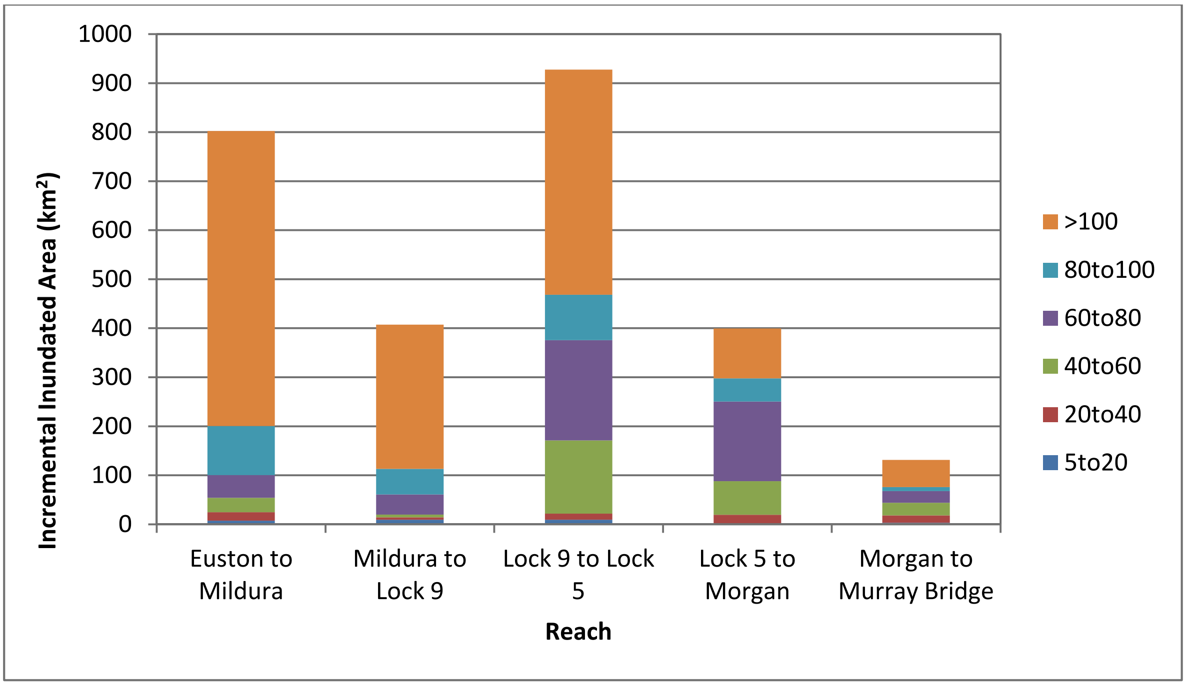


Figure 3.4: Major reaches –incremental inundated area by major reach for key flow ranges

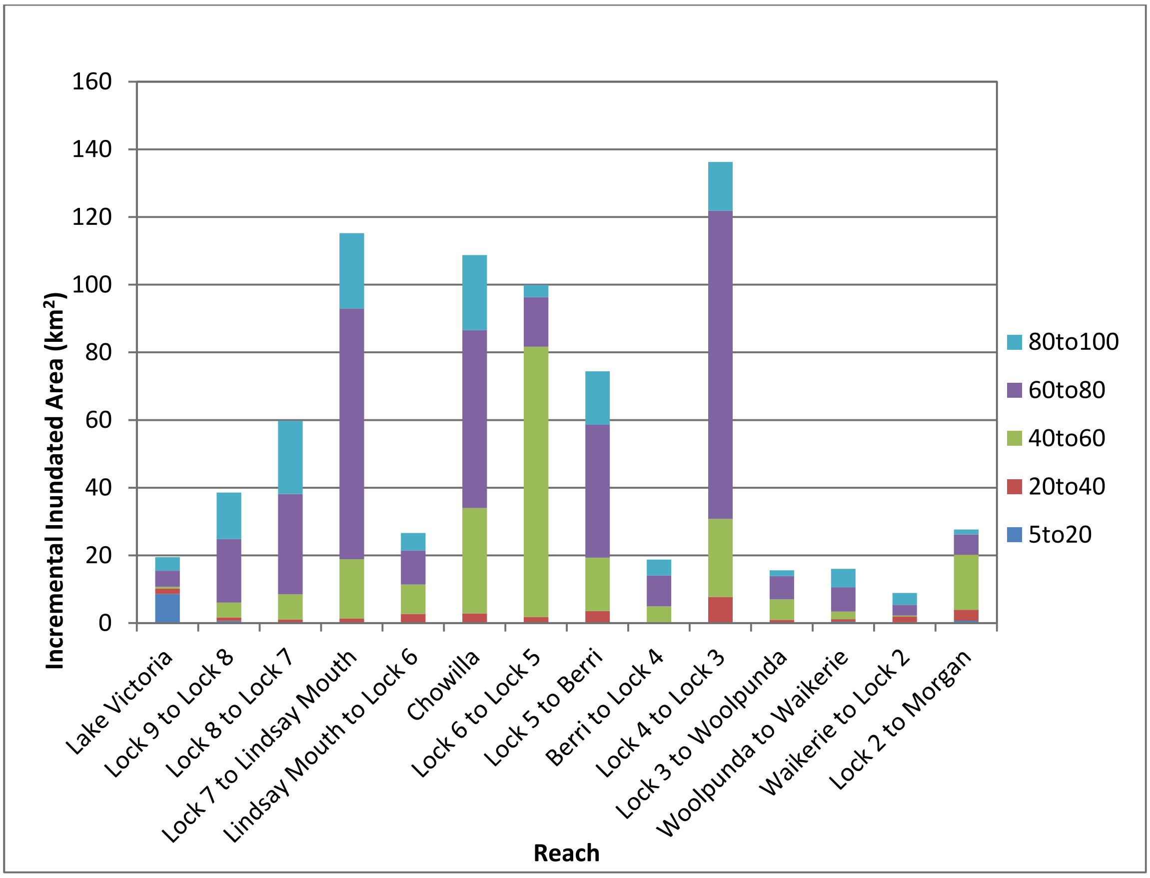


Figure 3.5: Sub reaches - incremental inundated area Lock 9 to Morgan for key flow ranges

3.8 Dead storage volume

The river downstream of kilometre 936 (i.e. just upstream of Mallee Cliffs) is a series of pools at low flows. In these weir pools, the transmission of a change in flow rate is much faster than the transmission of the water and salt molecules. The MDBC (2002) describes how BIGMOD uses "dead storage volumes" to compensate for the different travel times of flow and salinity. The dead storage volume for the various reaches is the main method for calibrating the travel time for salinity. The dead storage volumes and the corresponding average depth of the dead water are shown in Table 3.6.

Table 3.6: Dead storage volumes

Reach no	Description	BIGMOD dead storage volume (GL)	River channel surface area (km^2)	Average depth (m)
1	Euston to Mildura	51.1	30.90	1.65
2	Mildura to Lock 9	48.0	18.53	2.59
3	Lock 9 to Lock 5	80.7	31.76	2.54
4	Lock 5 to Morgan	129.6	37.98	3.41
5	Morgan to Murray Bridge	192.9	34.91	5.53
	Total – Reach Euston to Murray Bridge	**502.3**	**154.08**	**3.26**

Part 3 - Analysis

4 In-stream salinity and flow data

4.1 Observation network data

There is a considerable volume of in-stream salinity and flow data for the period of interest for this study since July 1970. Most of the major sites have continuous daily data for both salinity and flow. During the period many additional monitoring locations have been added and the frequency of readings increased.

For the project, MDBA supplied a full suite of the available observed data for monitoring stations throughout the Basin. The observed salinity and flow data have been a constant reference point against which to plan the project, observe patterns, test ideas and formulate understanding. The key datasets of salinity at the major stations of Euston, Mildura, Lock 9, Lock 5 and Morgan and flow at Euston and Lock 1 are shown in Figure 4.1, and in larger format in Appendix Figures A9 and A10.

4.2 BIGMOD Estimates

The MDBA BIGMOD model is described in Section 2.3.1. It is a daily model routing flow and salinity from Hume Dam and Menindee Lakes to the barrages at the Murray Mouth. Its calibration is reasonable given the overall uncertainties regarding salinity processes in the lower River Murray.

The vast amount of data against which calibrates and the model's output of salt inflow provides a comprehensive dataset to assess the temporal and spatial variability of salt load inputs to the river.

To facilitate this study, MDBA ran MSM_Bigmod for the period July 1970 to June 2009 in the history match mode to provide the best match to the historical flow and salinity data. The datasets used in this report differ from the datasets used in the calibration mode. Andy Close (MDBA, 2010, pers. comm.) notes that:

> *The BIGMOD model used to calculate salt inflows (i.e. the results used for this report) is considerably different to the calibration run for MSM_Bigmod because:*

- historical flows are substituted for the modelled flows (in the current study) wherever good flow data exists
- historical diversions are used (in the current study) rather than modelled diversions
- historical salinities are substituted (in the current study) at the upstream end of every reach over which salt load calculations are made.

> *By comparison, in the MSM_Bigmod calibration run, all the allocations, diversions, storage operations and flows are modelled. In the case of 1982-83, the low modelled salinity at the peak was caused by a modelled spill event from Menindee Lakes. In practice this spill did not occur because two years previously the operators released more water than the rules adopted in the model.*

> *The process that BIGMOD uses to calculate salt loads is as follows:*

- A marker is established at the upstream site every day and assigned the observed salinity at that site.
- That marker is routed downstream and its salinity is adjusted for evaporation and the impact of known salt inflows such as tributaries and monitored drains. However no adjustment is made for the unknown salt inflows.

- Additional records are kept for each marker of the time elapsed since the marker left the upstream site and the increase in salinity that would result from salt inflows of 1 tonne/day per kilometre.
- At the downstream site, the unknown salt inflow (ie unaccounted salt input) is calculated using the equation: Salt inflow = Number of kilometres*(Downstream Measured salinity – Modelled salinity)/Increase in salt load for 1 t/d/km
- The salt load is attributed to the date that the marker reached the downstream site less than half the modelled travel time.

To test the reliability of Bigmod to make this calculation you would need to examine its calibration when all flows and diversions are fixed as above. In this calibration, the key output is the ability of the model to match the travel time of salinity peaks.

In this study, salt load inflows were calculated for long reaches (e.g. Lock 5 to Morgan) due to data availability constraints, but calibration comparisons for salinity were done at a number of intermediate locations in this long reach (eg at Lock 3, Lock 4, Woolpunda and Waikerie) including Morgan. The comparisons between observed and simulated salinity at intermediate sites indicate the model adequately represents the salinity patterns in the river for the purposes of this report, providing some assurance that the calculated salt load inflows are reasonable.

BIGMOD incorporates known “accounted” salt loads, which are the product of flow and salinity from tributaries and drains, and the extraction for consumptive use (irrigation, stock and domestic uses). For example, in the reach downstream of Euston, accounts for flows and associated salt loads for flows in the main river, the Darling River and anabranch, flows to and from Lake Victoria and Lake Bonney and flows from metered irrigation drains in Victoria. The model also accounts for the flow and salt impact of rainfall, evaporation, seepage and consumptive extractions.

It does not specifically account for many discharges that are either un-regulated or not measured, such as discharges from evaporation basins in South Australia (e.g. Disher Creek Basin and Berri Basin) and outflow from anabranches and lagoons (e.g. Wachtels Lagoon, Gurra Gurra Lakes, Pike River).

The model uses unaccounted salt inflow to achieve the best fit to the observed salinity data and thus “unaccounted” salt inflow includes all groundwater inflows and unaccounted surface water discharges.

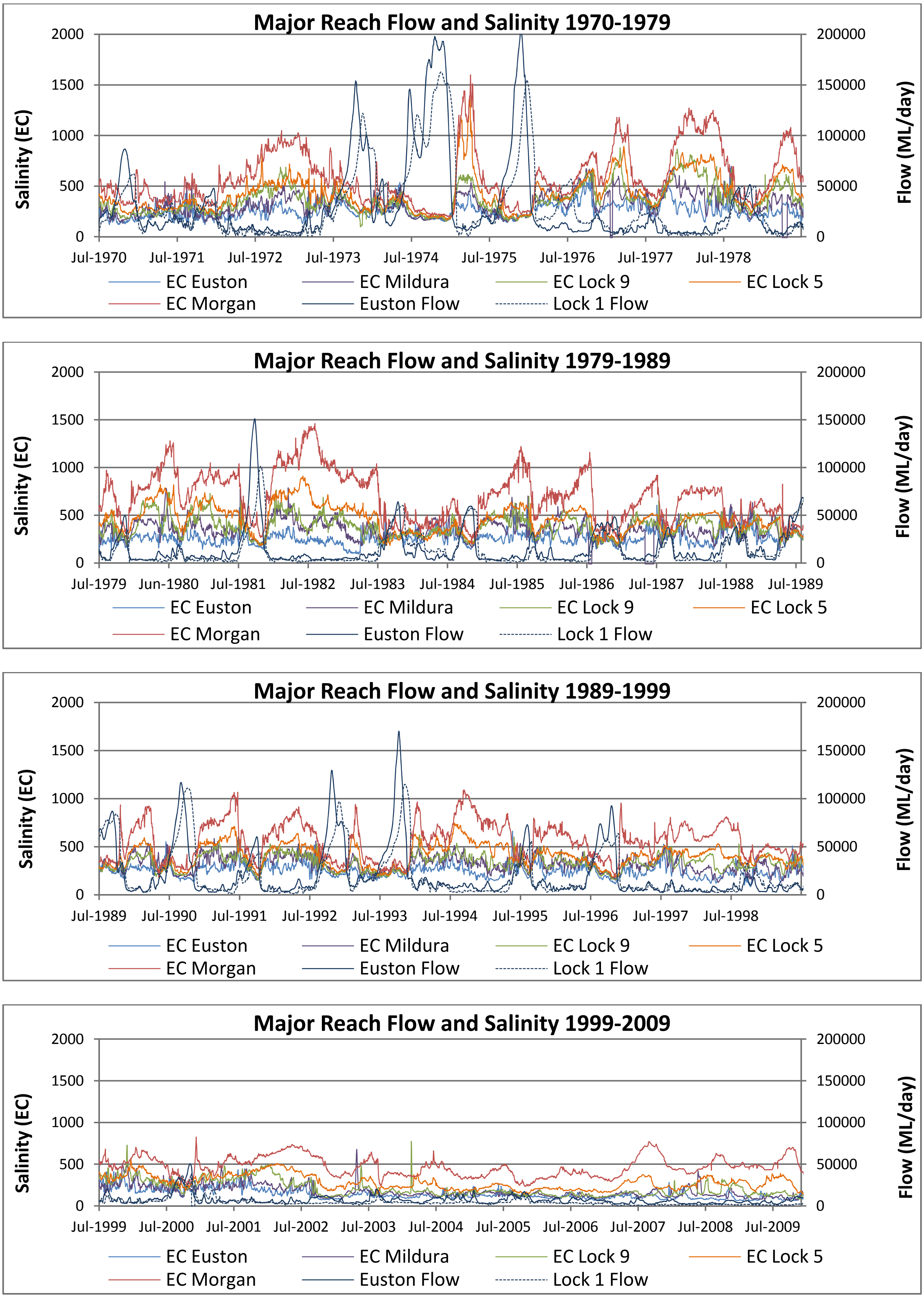


Figure 4.1: Major reach flow and salinity data

4.2.1 Accounted and unaccounted salt loads

A summary of the total accounted and unaccounted quantities for flow and salt are given in Table 4.1. The quantities are for the study reach from Euston to Morgan over the 39 year period from July 1970 to June 2009.

Table 4.1 illustrates that 62.1% of the salt enters the reach via inflow in the River Murray at Euston, and inputs from the Darling River. Of the salt loads added in the reach in addition to these river inputs, 2.4 million tonnes is from accounted sources and 25.3 million tonnes from unaccounted sources. Thus unaccounted sources add 10 times more salt than the accounted sources. These unaccounted salt loads are 35% of the total salt load in the river. The unaccounted salt loads are thought to derive almost entirely from floodplain sources. This demonstrates the importance of understanding floodplain processes that contribute to the unaccounted salt inflows.

4.2.2 BIGMOD unaccounted salt inflow estimates

The modelled monthly unaccounted salt inflow for the major river reaches are provided in the MDBC technical report (MDBC 2002), with separate values for with ("post SI") and without ("pre SI") the impact of salt interception schemes (SIS). Data for the five major reaches targeted in this study are shown in Figure 4.2 (note that the vertical scale varies between graphs). The graphs show the highly variable nature of salt inflows, the major differences from reach to reach and demonstrate the change in relationship between salt inputs and river flow. Key items to note are:

- the Lock 9 to Lock 5 reach has low background salt inflow levels, and is characterised by long lasting groundwater recession following the flood
- Lock 5 to Morgan has higher background salt inflow levels, the peak flood salt inflow is some 3 times higher than the Lock 9 to Lock 5 reach, with peak salt inflow generally occurring during the high river flows rather than after the flood recession.

This markedly different pattern of unaccounted salt inflow between these two adjacent reaches suggests that peak salt inflow in the Lock 5 to Morgan reach is driven by different processes to those driving salt inflow in the Lock 9 to Lock 5 reach. These differences are analysed in later chapters.

Table 4.1: Accounted and unaccounted flow and salt quantities

Inflows - Source	Flow		Salt	
	GL (,000)	**%**	**Tonnes** (,000,000)	**%**
Murray at Euston (1)	265	83.4%	35.2	49.3%
Darling River(1)	55.4	17.4%	8.6	12.0%
Lake Victoria (2)	-2.2	-0.7%	1	1.4%
Lake Bonney (2)	-1	-0.3%	0.1	0.1%
Irrigation drains in Victoria (2)	0.55	0.2%	1.3	1.8%
Unaccounted salt loads (3)	0	0.0%	25.3	35.4%
Total	317.8		71.5	
Outflows - Destination	Flow		Salt	
	GL (,000)	%	**Tonnes** (,000,000)	%
Murray at Morgan (1)	241.8	76.1%	59.8	83.6%
Evaporation less rainfall (4)	25	7.9%	0	0.0%
Extraction and seepage (5)	51	16.0%	11.7	16.4%
Total	317.8		71.5	

Notes:

(1) Calculated from raw flow and salinity data

(2) BIGMOD Accounted accounted flow and salt load

(3) BIGMOD Unaccounted unaccounted salt load – flow would equate to 1,200 GL if salinity is 20,000 mg/L and is less than 0.3% of total inflow.

(4) Net loss to evaporation (evaporation - rainfall) has been estimated at 33% of total (evaporation plus diversions plus losses) based on MDBC Technical Report (MDBC 2002) appendix K.

(5) Extraction and seepage has been calculated to balance inflows and outflows, average salinity of extraction and seepage calculates to 384 EC which is considered reasonable.

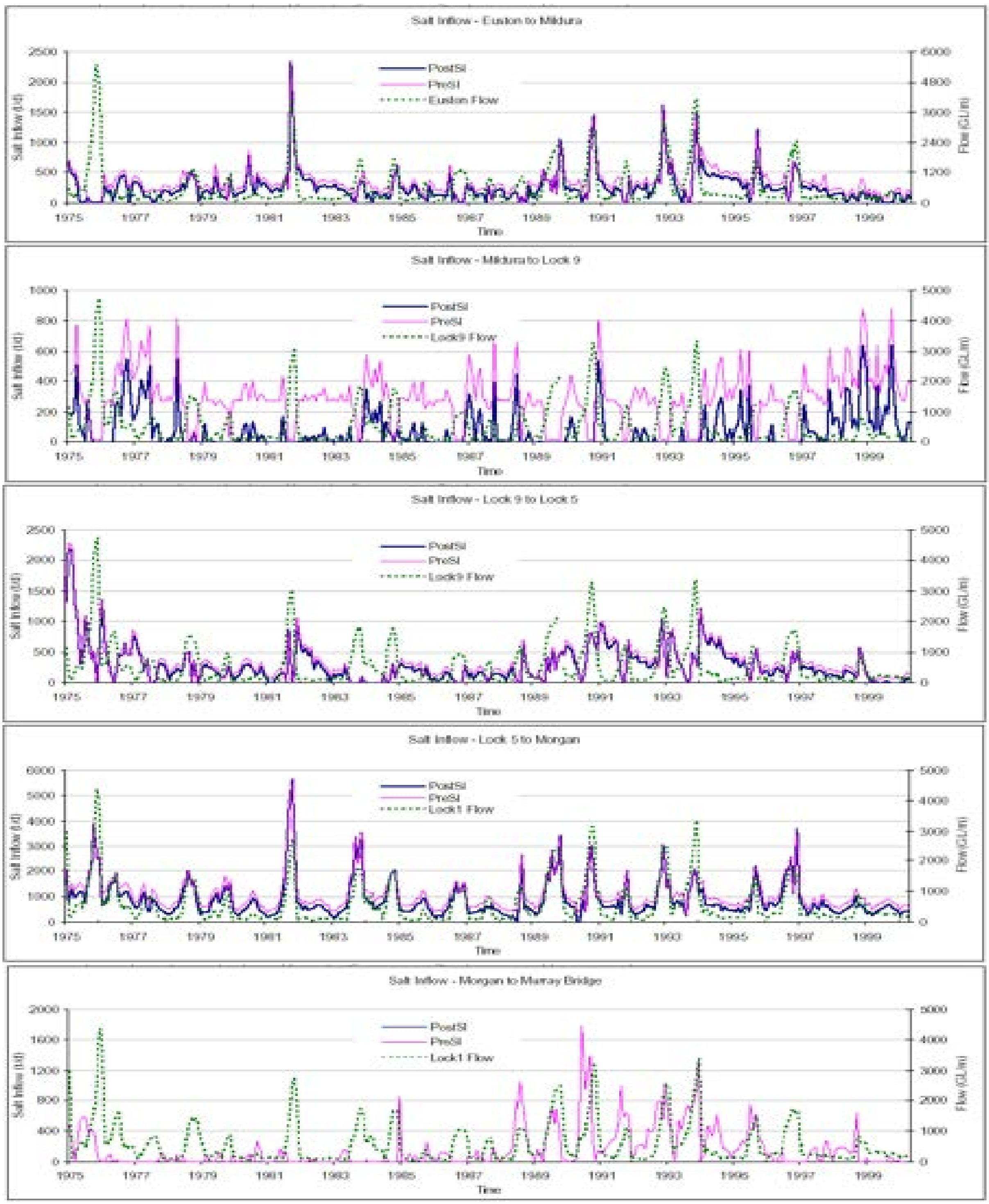


Figure 4.2: BIGMOD salt inflow – major reaches

5 River salinity analysis

This chapter describes our analysis of in-stream salinity, and the interrelationship between river flow and in-stream salinity.

5.1 Relationship between Morgan salinity and flow

In-stream salinity is strongly affected by stage and river flow. Figure 5.1 shows daily data, for the period 1970 to present, of the flow at Lock 1 and the salinity at Morgan. The figure illustrates that the highest salinities occur at low river flows and that at high flow the salinities are low. At the very low flows the travel time between Lock 1 and Morgan can be some days but would not significantly impact the correlation. Broadly speaking, these data indicate that flow is a dominant control on in-stream salinity at Morgan.

Figure 5.2, which zooms in to the low flow range of Figure 5.1, shows that flow is generally below 5,000 ML/d when the 800 EC benchmark at Morgan is exceeded.

The total number of days when EC exceeded 800 at Morgan represents 16.5% of the entire record. The events (290 days) when salinity exceeded 800 EC and flow was also over 5,000 ML/day represent 2.5% of the record and are discussed in more detail below.

There are also many periods when flow is below 5,000 ML/day and salinity remains low. The data in Figure 5.2 have been sorted into decades in Figure 5.3. Of the low flow/low salinity events that have salinity less than 500 EC and flow less than 5,000 ML/day, 97% occurred in the period since 2000.

The salt load entrained in the river at low flows also has a significant impact on the timing of exceedances. Figure 5.3 illustrates that the frequency of 800 EC exceedances at Morgan reduced in the 1990s and 2000s compared to the previous two decades, and that there has been only one exceedance in the past decade. This indicates that there is now less salt in the river at flows <5,000 ML/d than there was in the earlier decades. This “salinity holiday” in the 2000s can be attributed to a range of salt load reduction mechanisms, including implementation of salt interception schemes (SISs), drought-induced salt storage in the floodplains, improved irrigation efficiencies, and low salinity surface water inputs from the Hume Dam.

Woolpunda and Waikerie SISs, which represent around less than half of the total salt interception capacity prevent 280 t/day of salt from reaching the River Murray (MDBA 2009b). Figure 5.4 demonstrates the impact on salinity if the Woolpunda and Waikerie SISs had not been built, and the 280 t/day were entering the river at all flows in the last decade. The results indicate that these two schemes alone have had a major impact on reducing peak salinity levels at Morgan. Without these two SISs, exceedances above 800 EC increase from 0% to 39% of the record for the last decade. In the last two decades, SIS implementation appears to have contributed significantly to the reduction in peak salinities, as well as reducing average river salinity levels. The other potential contributors to the salinity holiday are discussed later, and it is concluded that SIS operation is a significant contributor.

The EC at Morgan exceeds 800 EC when flow at Lock 1 exceeds 5,000 ML/day on 290 days. The timing of these moderate flow/high salinity occurrences is shown in Figure 5.5, which shows that 220 (76%) of these events occur on the rising limb of a high flow event immediately following a period of low flow with salinity exceeding 800 EC. Most of the remaining 24% of events where flow exceeds 5,000 ML/day and salinity is over 800 EC occur on a sharp falling limb of a flood.

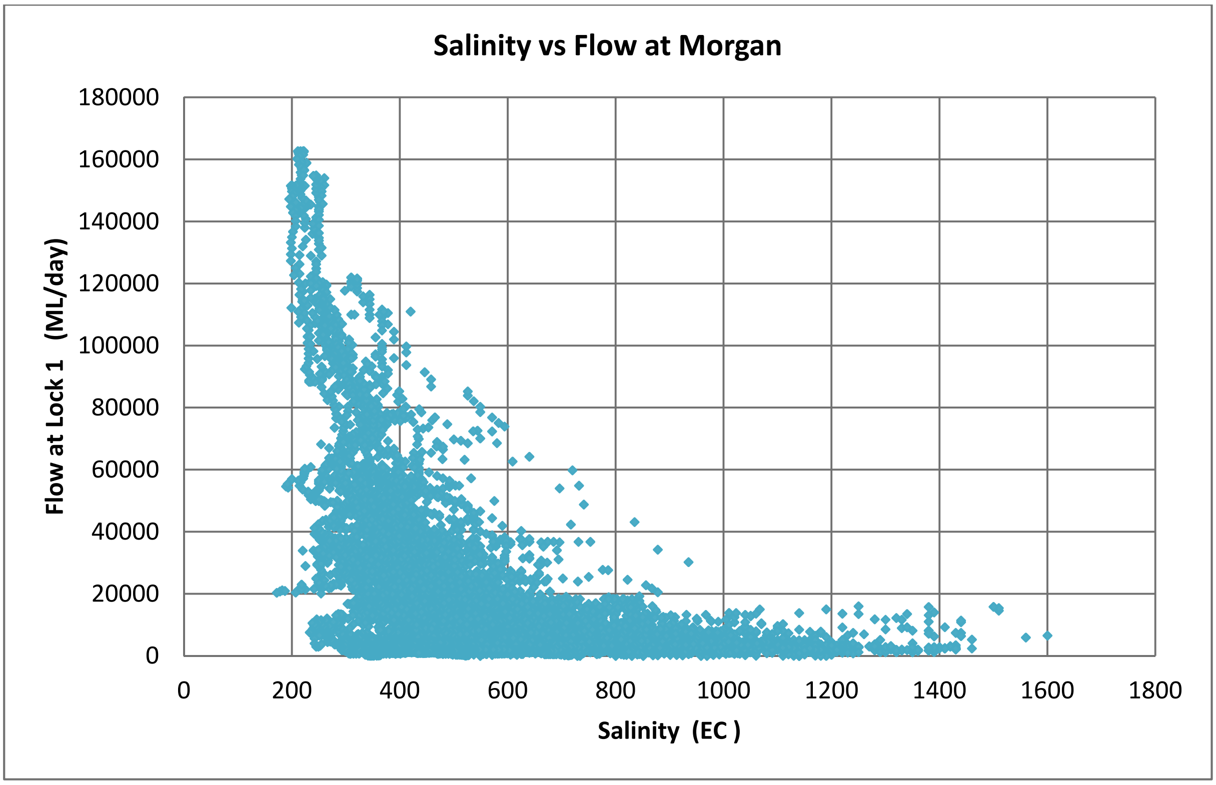


Figure 5.1: Morgan salinity vs flow

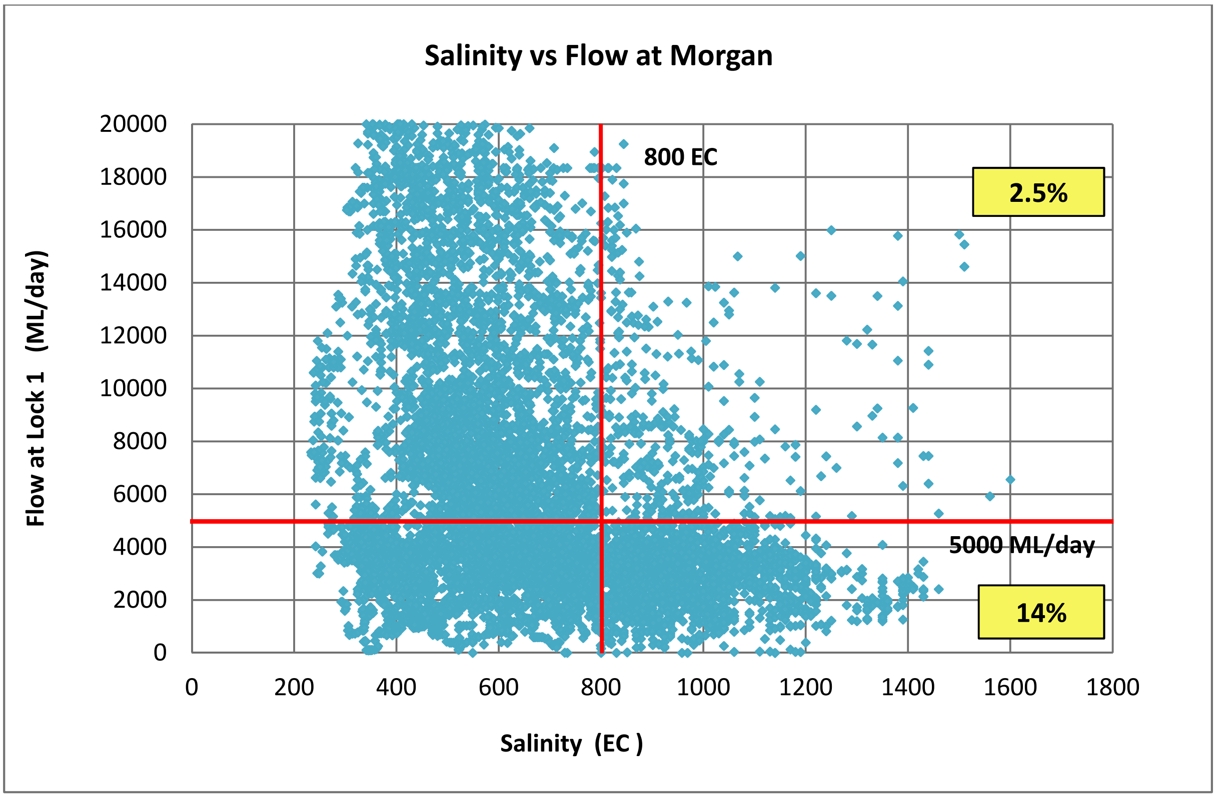


Figure 5.2: Morgan salinity vs flow – for flow less than 20,000 ML/day

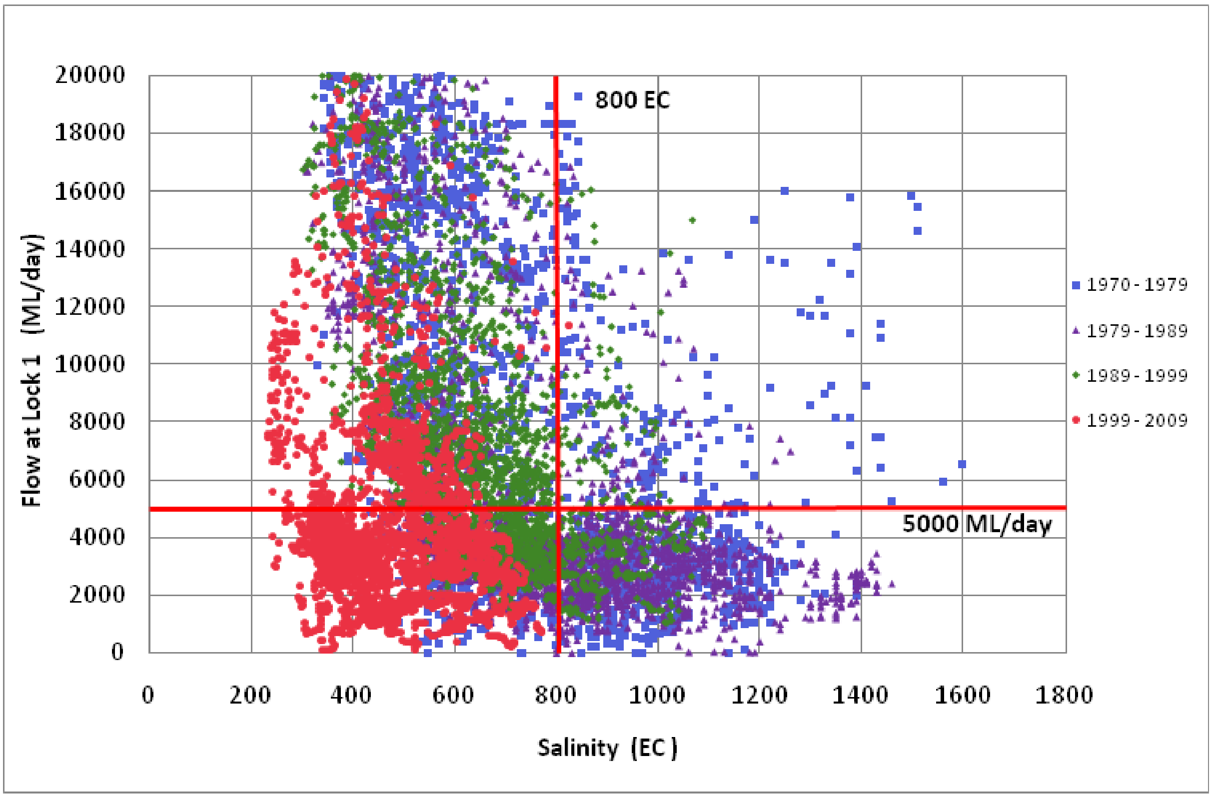


Figure 5.3: Flow and salinity by decade

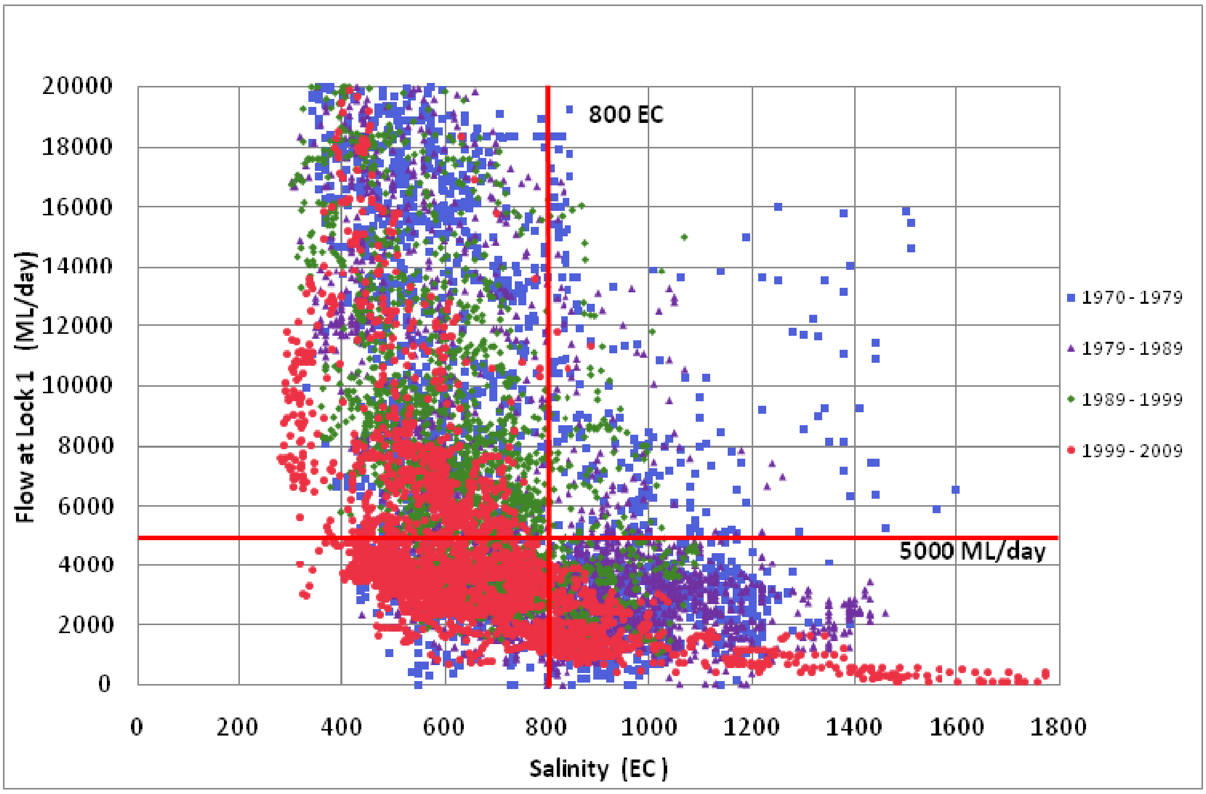


Figure 5.4: Flow and salinity by decade without key salt interception schemes

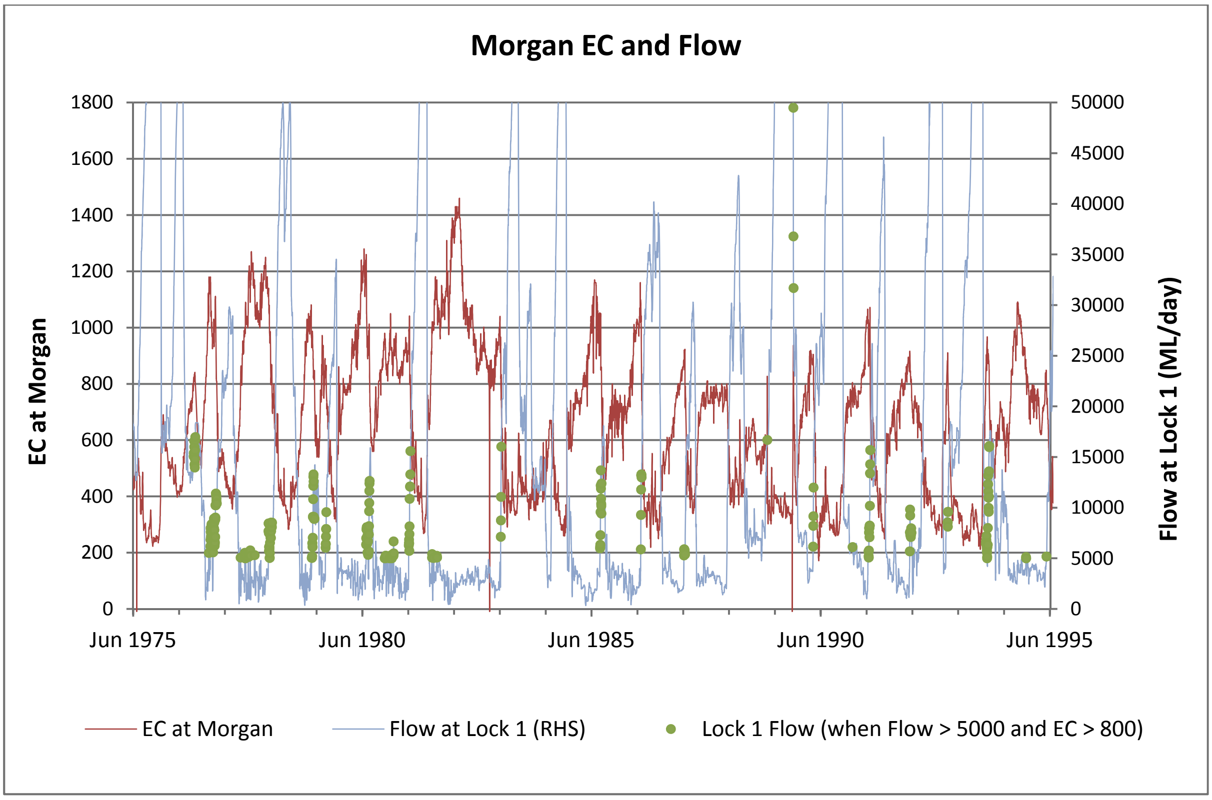


Figure 5.5: Morgan salinity – days when Flow exceeds 5,000 ML/day and salinity exceeds 800 EC

The salinity exceedances on rising limbs are discussed in this paragraph and the salinity exceedances on sharp falling limbs in the following paragraph. The River Murray is highly regulated, and at low flows the river becomes a continuous series of weir pools between Lock 9 and Lock 1. The MDBA calibrated model BIGMOD (MDBC 2002) routes flow and salinity in the river and accounts for the impact of the weir pools by using dead storage volumes in each weir pool. The dead storage volumes allow calibration to the observed pattern of the flow pulse moving downstream at a much faster rate than the water body itself. Data in Appendix D of the report (MDBC 2002) indicate that whilst the travel time for flow rate transfer from Lock 5 to Morgan is 2.87 days for flows of 5,000 ML/day and 10,000 ML/day, the dead storage volumes result in the water body travelling between Lock 5 and Morgan over a period of approximately 29 days at flows of 5,000 ML/day and 16 days at flows of 10,000 ML/day. Thus the initial days of a high flow event at Morgan contains water that has flowed through the upstream reaches at a much lower rate providing low levels of dilution to incoming salt loads. Therefore the initial days of a flow event exceeding 5,000 ML/d following a low flow period will contain river water that was sourced from when the river was slow flowing and had less dilutive capacity. Thus management strategies that address the high salinities at flows below 5,000 ML/day, will also reduce the high flow, high salinity events that occur during the subsequent period of higher flows.

Most of the remaining 24% of events where flow exceeds 5,000 ML/day and salinity is over 800 EC, occur on a sharp falling limb of a flood. These salinity peaks are of generally short duration and occur downstream of Lock 5. This would indicate that the rapid flood recessions are inducing large salt inflows or that sudden flow decrease removes the dilution ability of the river at times when there are still large salt inflows. Careful management of the flood recession flows may be able to limit these occurrences and are discussed further in Chapter 12.

5.2 Salinity at Euston and Swan Hill

Euston, at river kilometre 1117 km, and Swan Hill, which is a further 293 km upstream, were investigated as possible upstream stations for this study. Figure 5.6 shows the 15 day rolling average salinity at Swan Hill, Euston and Morgan. This figure illustrates that the salinity peaks observed at Swan Hill do not generally persist to Euston. Through the 1970s, salinities at Swan Hill peaked over 800 EC at times but these peaks do not persist to Euston. For much of the post-1980 record, the Swan Hill and Euston salinities have similar trends and magnitudes, but again salinity peaks at Swan Hill do not persist downstream to Euston.

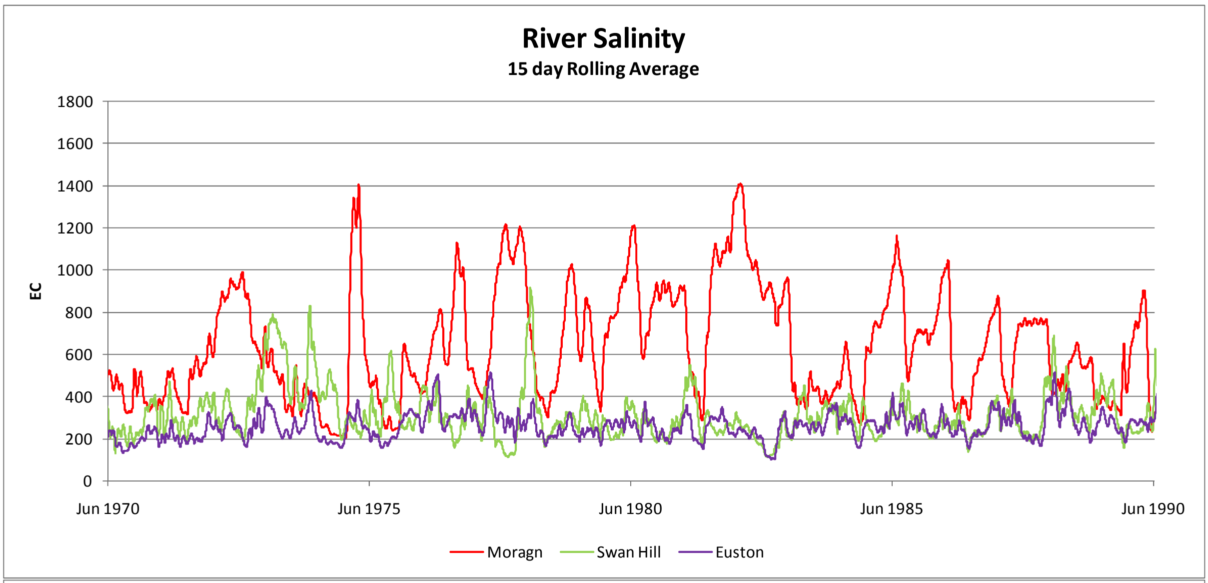
Possible reasons for the salinity peaks at Swan Hill not persisting to Euston include:

- Dilution of the River Murray salinities inflows from lower salinity tributaries between Swan Hill and Euston, such as the Murrumbidgee and Wakool rivers
- The River Murray may be poorly mixed at Swan Hill and the EC meter sited in a location that has above-average salinities. There are several inflows upstream of Swan Hill that are at times highly saline (e.g. Barr Creek, Loddon River and Little Murray River). The Little Murray River enters the main channel at Swan Hill some 1.8 km upstream of the salinity recording station. A review of BIGMOD output, which accounts for the dilution impact of flows from the Murrumbidgee and Wakool, indicates that over the 39 year study period, the average unaccounted salt inflows between Swan Hill and Euston is negative 184 tonnes per day. This consistent and large negative salt inflow indicates that there are data errors which on balance are most likely erroneously high EC readings at Swan Hill, possibly due to poor mixing at the location of the EC recorder. Further investigation would be required to confirm the cause.

When evaluating salt inputs downstream, Euston provides a better reference point against which to compare increases in salinity and assess salt loads than Swan Hill, and will be used as the reference point for this study.

Figure 5.6 also shows that salinity at Euston averages around 225 EC, moving within a band between 200 to 400 EC from 1970 to 2000 and in the last decade moving between 50 and 200 EC. It rarely reaches 600 EC. It follows that the major driver of salinities at Morgan exceeding the 800 EC benchmark are salt inputs between Euston and Morgan. During 1984, the salinity at Morgan is only marginally above that at Euston, because of the large fresh Darling River flows.

Using daily data, the EC exceedances curves at Euston and Morgan are compared in Figure 5.7 for the period 1970 to present. Morgan exceeds the 800 EC threshold in around 15% of the record. The salinity at a given exceedance percentage is around 2.5 times higher at Morgan than it is at Euston. The exceedance curve at Swan Hill is also shown in Figure 5.7 and demonstrates that Swan Hill has many more high salinity events than Euston, with values above 400 EC being 14.1% at Swan Hill and only 2.6% at Euston. The exceedance curve at Murray Bridge is practically identical to the Morgan curve and is not shown.



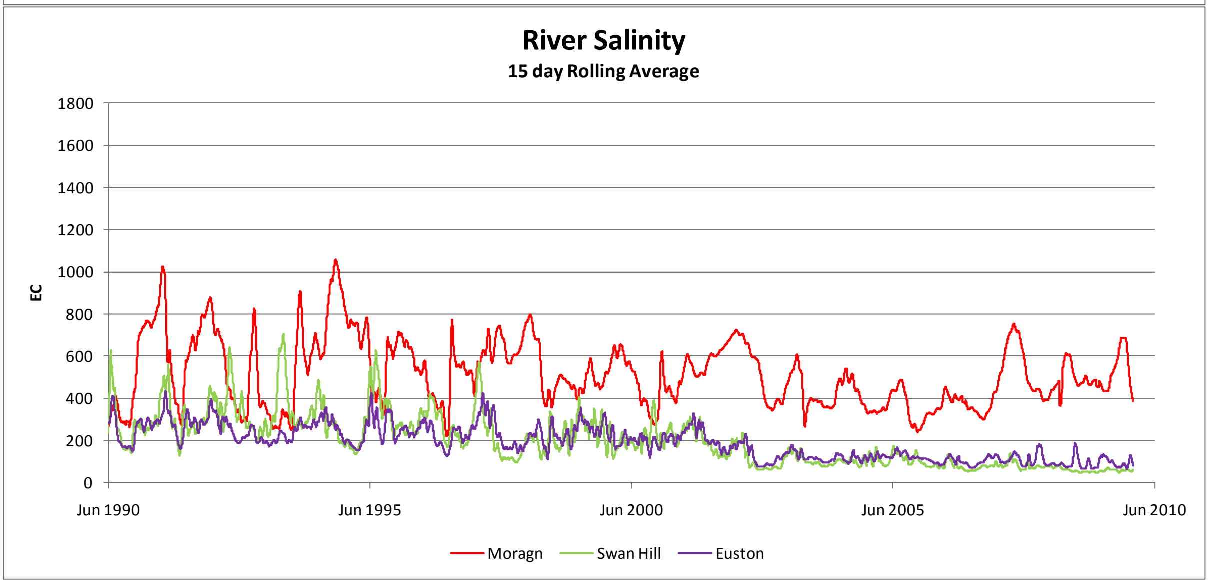


Figure 5.6: Salinity at Swan Hill, Euston and Morgan

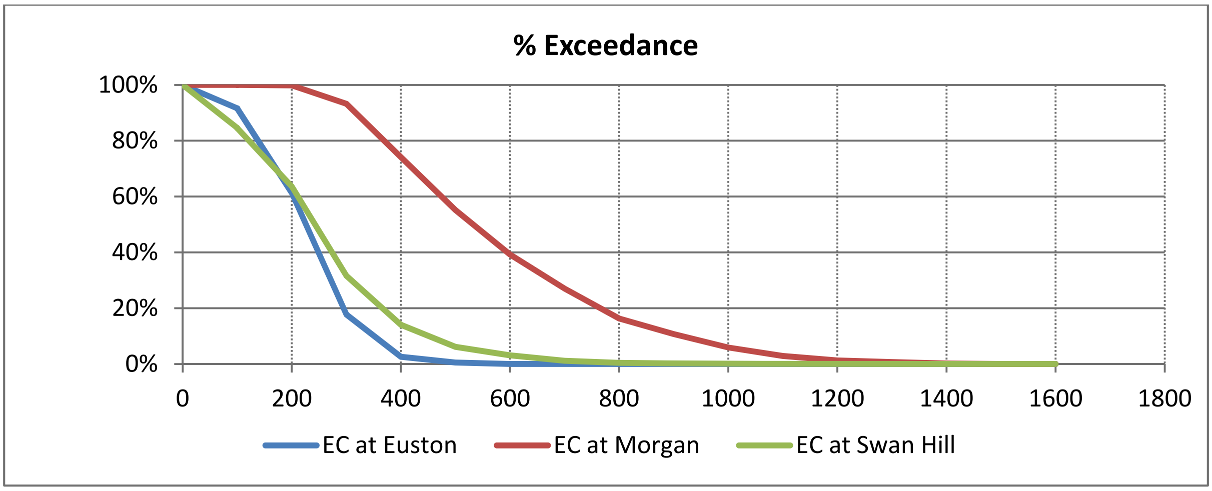


Figure 5.7: Salinity % exceedance – Swan Hill, Euston and Morgan

6 Analysis of BIGMOD unaccounted salt inflow

Daily output data of flow, salinity and salt inflow from the MSM_Bigmod history match run have been used in the following detailed analysis.

The daily data are highly variable due to the difficulty in modelling such a large, complex and dynamic system. There are many negative numbers for salt inflow in the output which indicates that the calibration, when done on a daily basis and over relatively short reaches, is very difficult to achieve. However, the aggregation of the daily figures over longer time spans and longer reaches produces meaningful results that adequately reflect the salinity records for this report’s purposes. In the analysis, rolling averages of the daily values have been used to smooth the data to enable graphical presentation and interpretation. The rolling average data have been plotted at the centroid of the averaging period and the period of averaging varied depending on the analysis being undertaken.

The BIGMOD output analysis provides insight into the temporal and spatial patterns of salt inflow to the River Murray. From these patterns possible causative processes can be conceptualised. However the outputs of themselves do not discriminate between the various processes leading to the unaccounted salt inflow.

6.1 Key aspects of analysis technique

Key aspects of the analysis technique are summarised in the following sections.

6.1.1 Check against observed salinity data

The overview of how well BIGMOD matches the observed salinity for the benchmark period is given in Section 2.3.1. During the detailed analysis there have been many occasions when the observed salinity data have been used to confirm modelled salt inflow for specific events and to check the veracity of BIGMOD results. In most instances the pattern identified by BIGMOD has been supported by the observed salinities.

6.1.2 Flow ranges

Division of the flow record into flow ranges assists in the understanding of salt inflow and characterisation of processes. Flows have been separated into the following categories.

- Floods – Flows greater than 40,000 ML/day. Very little overbank inundation occurs at flows below 40,000 ML/day, so 40,000 ML/day has been used as a threshold to indicate a flood event.
- Transition Flows – 7,000 to 40,000 ML/day.
- Flows Less than 7,000 ML/day - Fully regulated river flow downstream of Euston is below 7,000 ML/day and our assessment of the data has indicated that it is reasonable to assess inter-flood flows below this level.

6.1.3 Time periods

The study period can be usefully divided into four shorter time periods for the purpose of analysis. The time periods are the basis of the subdivisions of Figure 4.1 and Appendix Figures A9 and A10. Each period commences on 1 July to make it less likely that flood events straddle the division. BIGMOD salt inflow data are available from 1 July 1970, therefore the first period is nine years and the following periods are 10 years each. Key characteristics of each period are as follows.

- Period 1 (1 July 1970 to 30 June 1979) there were three flood events over 100,000 ML/day in three successive years (1974 to 1976). The events in 1975 and 1976 were both over 180,000 ML/day and represent the two largest floods since 1956. These events make this period highly variable and difficult to assess as a whole. Salinity and flow records are also not as good as in the later years.
- Period 2 (1 July 1979 to 30 June 1989) was a relatively low flow period with four years not experiencing a flood (<40,000 ML/day) and there was only one event over 80,000 ML/day. The start

of the decade is three years after the peak events of 1974 to 1976, so residual impact from these events is minimal. This is a low flow period.

- Period 3 (1 July 1989 to 30 June 1999) was an extended wet period, with a flood (>40,000 ML/d) in seven of the first eight years. During the decade there were four events over 80,000 ML/day.
- Period 4 (1 July 1999 to 30 June 2009) was a period of drought with only one flood event of 60,000 ML/day in 2000. From 2001 to 2009 there were no flows above 15,000 ML/day. This is a low flow period.

Comparing and contrasting these four periods provides insight into changes over time and with variable climate sequences.

6.2 Total salt inflows - reach by reach

The comparison of Euston and Morgan salinity data (Figure 5.6) illustrates that the high salinities at Morgan are due to increases in salinity between Euston and Morgan. The discussion of the accounted and unaccounted salt loads (Table 4.1) illustrates that the unaccounted salt loads, which are attributed mostly to floodplain salt inputs, are a major input to the total salinity increase between Euston and Morgan.

The relative importance of the unaccounted salt load inputs in each reach is demonstrated by the MSM_Bigmod total salt inflow data (Table 6.1). There are negative values in the Mildura to Lock 9 reach which are much more pronounced at high flows.

The negative salt loads in the Euston to Lock 9 reach suggest persistent data errors. The negative salt inflows may be due to erroneous EC measurement, most likely at Mildura, however additional analysis is required to identify the likely cause before analysis of the temporal and spatial trends.

The data in Table 6.1 are graphed in Figure 6.1, noting that the reaches Euston to Mildura and Mildura to Lock 9 have been combined to eliminate the negative values.

Table 6.1: Unaccounted salt inflows for major reaches (t/day) - BIGMOD output

Reach No	Description	Salt inflow 1970 to 2009 average tonnes/day	Salt inflow 1970 to 2009 total kilotonnes	Salt inflow % of total
1	Euston to Mildura	361	5142	20%
2	Mildura to Lock 9	-25	-356	-1%
3	Lock 9 to Lock 5	311	4430	17%
4	Lock 5 to Morgan	1063	15142	60%
5	Morgan to Murray Bridge	64	912	4%
	Total	1774	25270	100%

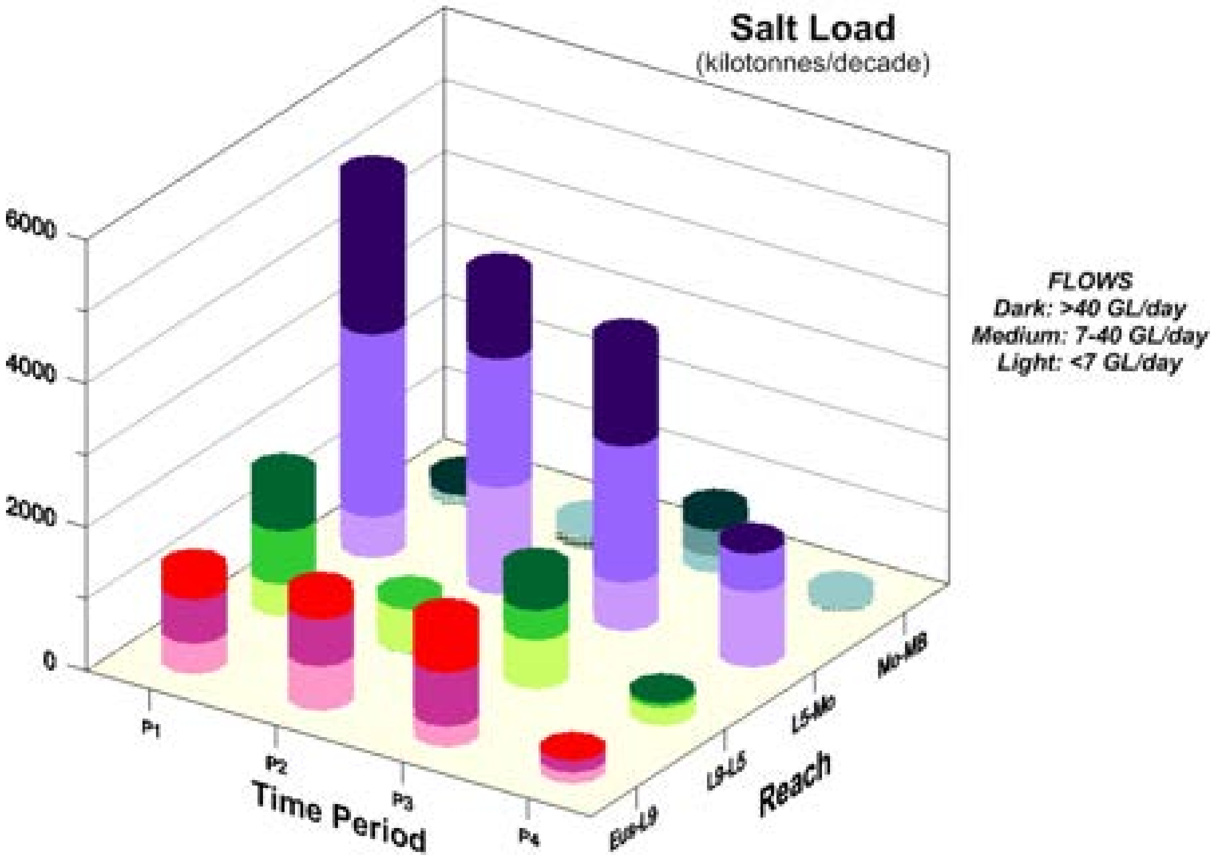


Figure 6.1: Salt inflows, by reach, by time period, by flow range

The key patterns emerging from Table 6.1 and Figure 6.1 are:

- The pattern of salt inflow varies by period, by reach and by flow range - there is not one repeated pattern in the entire dataset. This provides an indication of the spatial and temporal variability in salt inputs to the river, which suggests significant spatial, temporal and magnitude variability in the processes and delivery mechanisms delivering salt inflow to the river. Unravelling the variability and complexity is no trivial task.
- The Lock 5 to Morgan (L5-Mo) reach has the highest salt inflows and accounts for 60% of the total salt inflow downstream of Euston. Lock 9 to Lock 5, and Euston to Mildura account for most of the remaining salt inputs.
- The Lock 9 to Lock 5 (L9-L5) reach shows the greatest variability between the time periods, with higher salt inflows in the two wetter periods (P1 – 1970's and P3 – 1990's). It also has the highest proportion of salt inflows at flows <7,000 ML/d (i.e. comparatively more salt during the inter-flood periods than during the transition and flood periods). This suggests that salt delivery processes differ, or are relatively more active in this reach during the inter-flood periods compared to the other reaches.
- The Euston to Lock 9 reach deserves analysis, but observed potential errors and budget constraints prevent analysis herein. The analysis of this reach should include detailed analysis of raw salinity data on a reach by reach basis to identify the likely causes of the negative values.
- Salt inputs in the Morgan to Murray Bridge reach are relatively minor.

In the remainder of this Chapter, the Lock 9 to Lock 5 data are interrogated to determine the processes delivering salt in the inter-flood period and the Lock 5 to Morgan data have been interrogated to determine the salt delivery processes active in the highest salt input reach.

This study has not exhausted the value that can be mined from this dataset and significant potential remains for gleaning additional insights from the data. This additional work includes analysis of the other reaches to identify the major patterns of salt delivery and hence indicate the major salt delivery processes, and more detailed analysis of all reaches, to extract additional information.

6.3 Detailed analysis - Lock 9 to Lock 5

6.3.1 Unaccounted salt inflow trends over time

The salt inflows to the Lock 9 to Lock 5 reach and sub-reaches are shown in Figure 6.2 to Figure 6.5. Each figure spans ten years, with salt inflows presented as average salt inflow per day plotted at monthly intervals. The salt inflow shown is cumulative, with salt inflow for each station being that between the start of the major reach and the station, i.e. Lock 9 to Lock 8, Lock 9 to Lock 7, Lock 9 to Lock 6, etc.

An analysis of the salt inflow through time on a reach by reach basis assists the identification of mechanisms driving the salt inflow, specifically during and following periods of high flows. Key observations from the review of the data are:

- During flood events there are consistently high readings at Renmark that do not persist downstream to Lock 5. This indicates a local salt input immediately upstream of the Renmark station, which is more completely mixed by the time the water reaches Lock 5. Mixing usually occurs within 3 km of the point of inflow (Barry Porter, pers. comm., SA Department for Water). Ral Ral Creek (Figure 6.9) has an upstream entry and downstream exit immediately upstream of the Renmark station in the Lock 5 weir pool. Flows in the anabranch are therefore low, because there is little hydraulic gradient in the anabranch, so salt inputs and evaporative concentration will tend to generate higher salinities in Ral Ral Creek than in the adjacent river. In flood events, flows would be expected to increase as flow in the main channel increases, exporting accumulated salt into the river and affecting the readings at the Renmark station.
- Significant post-flood salt inflows occur in the Lock 6 to Templeton reach following the 1981, 1989, 1990 and 1993 floods. The 1993 post-flood salt inflows is cut short by the next flood. These are all flood events above 80,000 ML/day. The inflows are not so pronounced for the smaller floods. The Lock 6 to Templeton reach receives salt inputs from Chowilla Creek and from the Upper Murtho floodplains. For the smaller flood events, the correlation between flood size and salt inflow is not as pronounced as for the larger events.
- The salt inflow often drops to zero on the rising limb of the flood, indicating that groundwater inflows are suppressed and that no significant salt inflow is occurring from other sources (e.g. flushing of salt from surface water bodies) during the rising limb of a flood.
- The 1992 post-flood salt inflow appears to still be influenced by the tail of the large 1991 flood, because the post 1992 salt inflow is larger than would be expected for a flood of that size. It is possible that the recession of the major 1991 flood event influences the initial inflows of the 1992 post-flood period, because Figures 6.6 and 6.7 illustrate that salt loads persist for more than 12 months following the end of a flood.
- In the period since 2001, when there have been no floods, there still seems to be an annual cycle of salt inflow variation with the low inflows corresponding with the end of summer when groundwater levels would be lowest at the end of the high evapotranspiration period.

6.3.2 Analysis of inter-flood salt inflows

The BIGMOD unaccounted salt inflows for the 23 inter-flood periods during the study period for Lock 9 to Lock 5 sub-reaches were analysed. The inter-flood period was nominated to have commenced once flows dropped below 20,000 ML/day and end once flow again reached flood flows of 40,000 ML/day. The average values are shown in Figure 6.6. The salt inflow is plotted against the number of days since the flow dropped below 20,000 ML/day. The salt inflow shown is cumulative, with salt inflow for each station being that between the start of the major reach and the station, i.e. Lock 9 to Lock 8, Lock 9 to Lock 7, Lock 9 to Lock 6, etc.

The graph demonstrates that the unaccounted salt inflow between Lock 9 and Lock 6, averaged over the 23 inter-flood events, is relatively constant at 100 t/day. While significant variability in the salt inflows have been observed (Dept for Water, pers. comm., December 2010) between Lock 7 and Lock 6 due to flows from Lindsay River, Rufus River and Lake Victoria, the relatively constant average over the 23 inter-flood periods indicates that flood events are not a key driver of the reported variations. Additional work could be undertaken to evaluate the causative processes or factors that are controlling the individual salinity events.

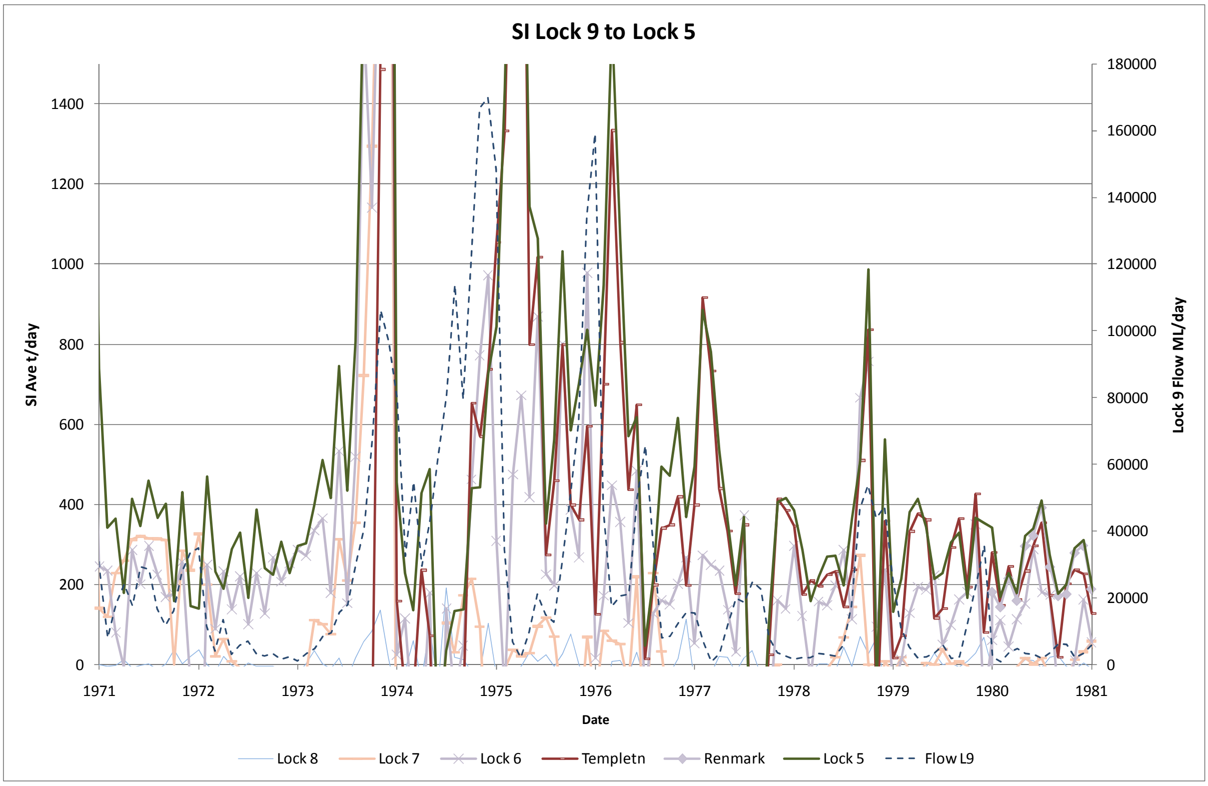


Figure 6.2: Salt inflow 1971 to 1981 – Lock 9 to Lock 5

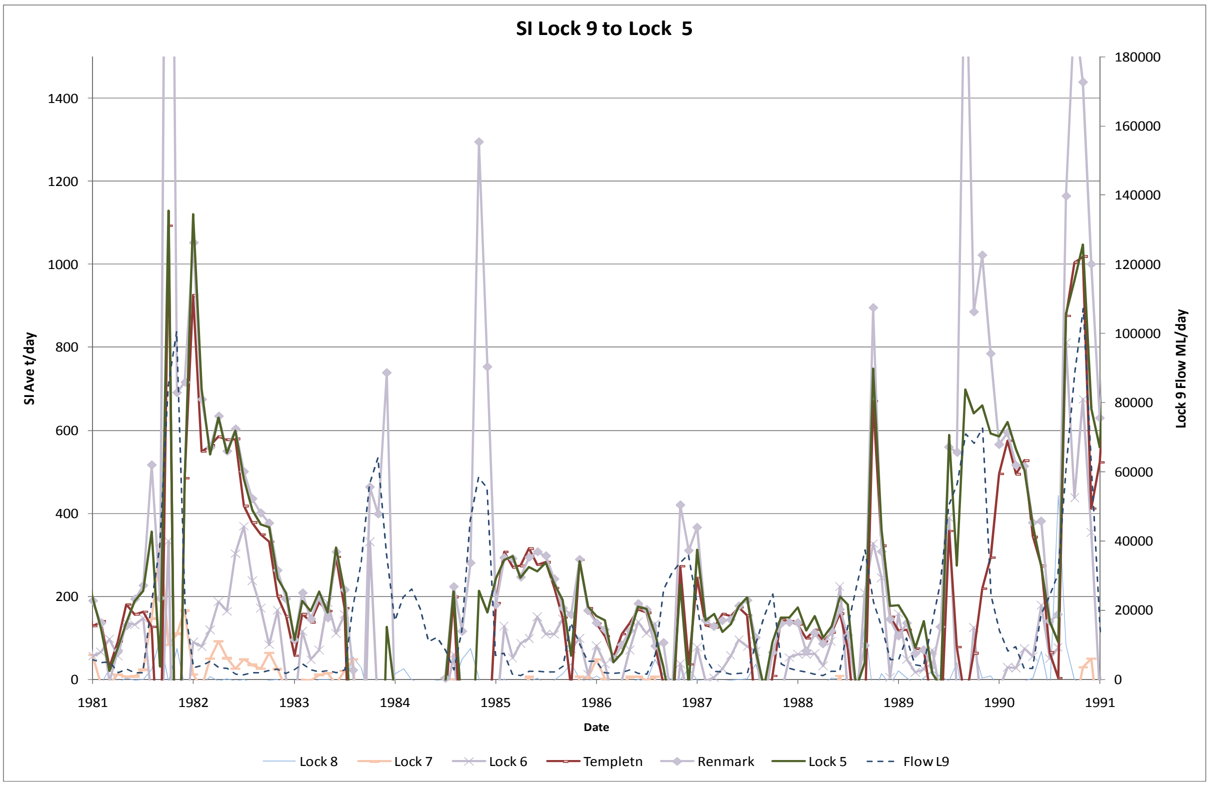


Figure 6.3: Salt inflow 1981 to 1991 – Lock 9 to Lock 5

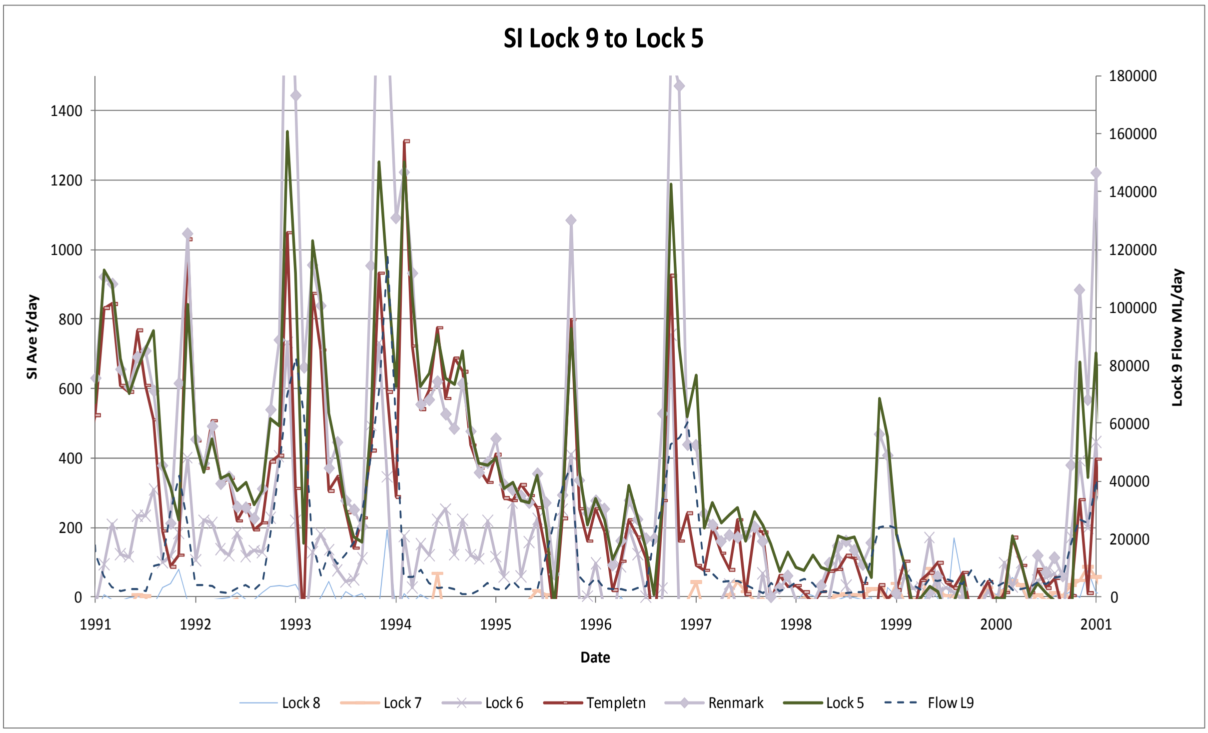


Figure 6.4: Salt inflow 1991 to 2001 – Lock 9 to Lock 5

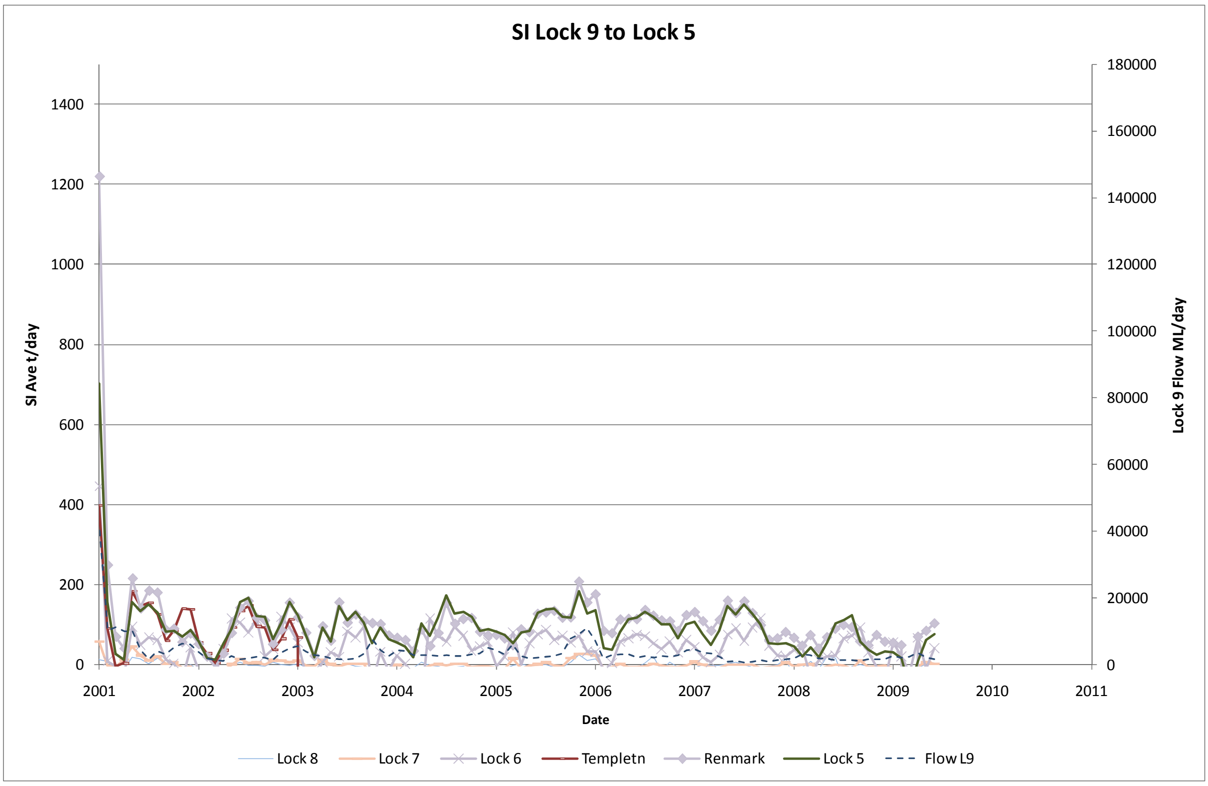


Figure 6.5: Salt inflow 2001 to 2009 – Lock 9 to Lock 5

The difference between the Lock 6 average salt inflow and the Templeton salt inflow value in Figure 6.2 shows there is a major salt input in the Lock 6 to Templeton reach. The reach includes the outfall of Chowilla Creek which is a major anabranch flowing through the Chowilla floodplain and part of the Murtho floodplain. The graph shows the salt inflow in this reach is greatly influenced by flooding, peaking at some 550 tonnes per day, 25 days after flow drops below 20,000 ML/day. There is an asymptotic decline, with rapid declines during the first 120 days from 500 tonnes per day to 200 tonnes per day. There appears to be an ongoing slow decline between 120 and 300 days.

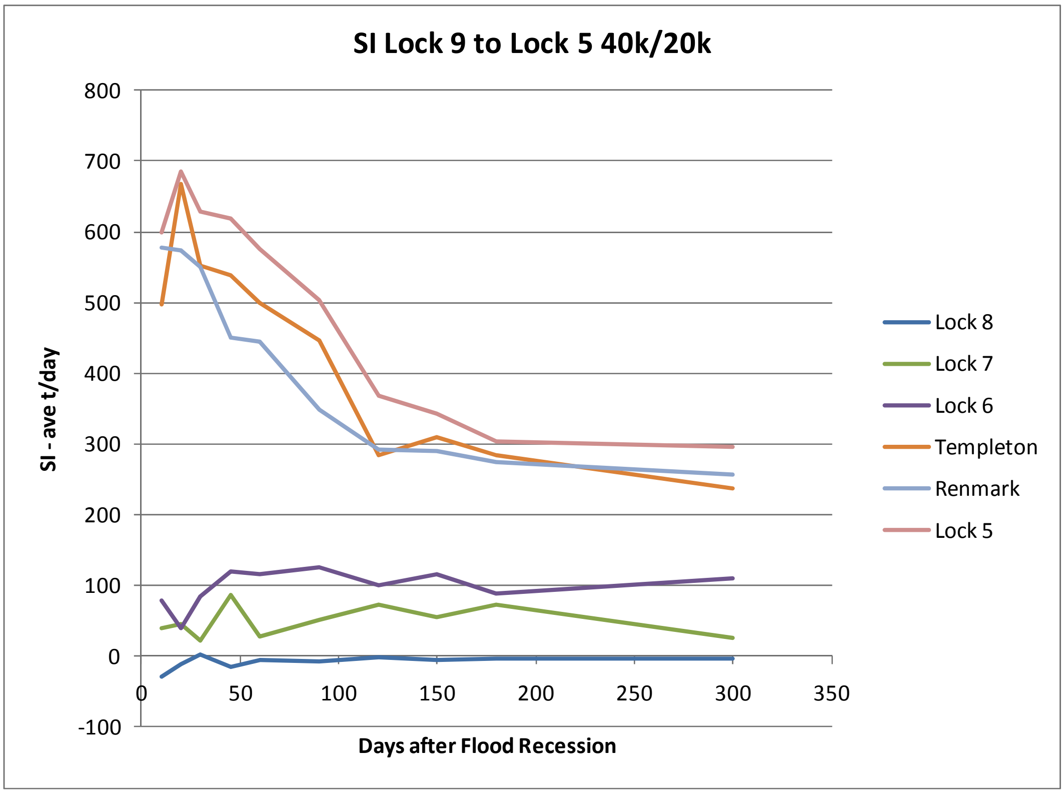
Downstream of Templeton the cumulative salt inflows rise only slightly, if at all, indicating modest salt increases. The increases are perhaps less influenced by time elapsed since the flood recession.

Post-flood salt inflow for 1981, when flows remained below 7,000 ML/day for more than 500 days, is shown in Figure 6.7. The plot shows a similar pattern to the average of the 23 floods shown in Figure 6.6. Following the 1981 flood, the salt inflow continued to fall throughout the 500 day inter-flood period, dropping to around 100 t/d at the end of the period. It is considered likely that the progressive reduction of salt inflow during the 500 day period is contributed to by the cumulative effects of net floodplain losses (i.e. excess of evapotranspiration over inputs) causing groundwater levels to continue to fall during the period.

The unaccounted salt load data have been analysed to assess the relationship between salt inflow and flood peak size (Figure 6.8). Results for the overall reach (Lock 9 to Lock 5) and for the largest salt inflow reach (Lock 6 to Templeton) are provided. The data, and the comparison between the two datasets, illustrates that there is a correlation between salt inflow and flood size, particularly for floods above 70,000 ML/day. Additional analysis of the data, examining the relationship between salt inflows and with flood duration, and salt inflows and time since previous flood have been analysed, but no correlation was observed. This finding is consistent with Overton *et al*. (2005), where size of flood rather than flood return interval was identified as the major control on salt load from the Chowilla floodplain (Figure 2.7). The Chowilla Floodplain salt loads are introduced to the River Murray between Lock 6 and Templeton.

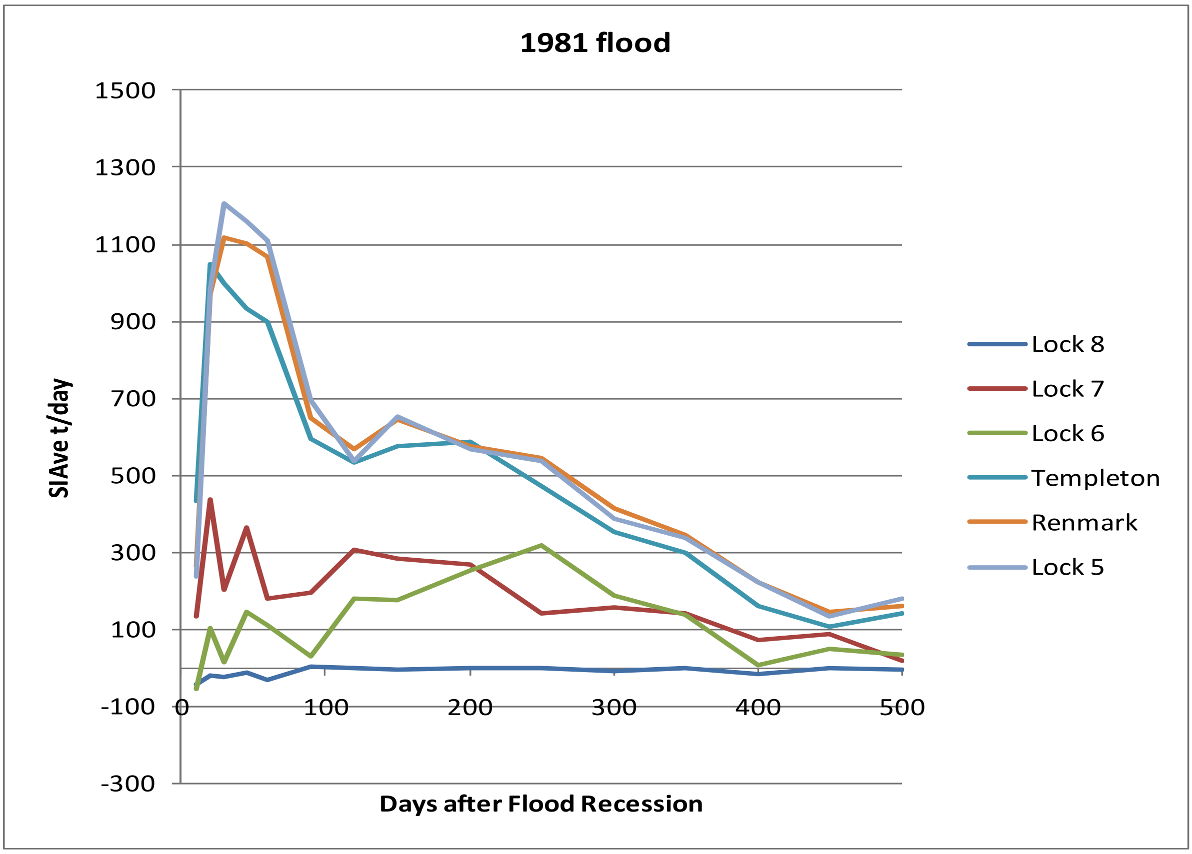
Additional analysis of the data plotted in Figure 6.8 and the antecedent conditions for each flood, reveals that:

- The two largest floods, (1974 and 1975) with flows around 180,000 and 160,000 ML/day respectively, were 12 months apart. The second flood had considerably reduced salt inflow. The earlier flood was preceded with an 18 month period where flows did not drop below 20,000 ML/day and included during this period two other peaks of 120,000 and 60,000 ML/day.
- The two outliers in flows at around 60,000 ML/day have non-typical preceding events. The high side outlier had a flood of 112,000 ML/day in the preceding year, and the low side outlier followed a period of four years without a flow above 40,000 ML/day. Whether these preceding flow events are the cause of the outliers has not been established, however the correlation deserves attention.



Note: Salt inflow cumulative from Lock 9 to the graphed station (e.g. Lock 6 is the sum of all salt between Lock 9 and 6)

Figure 6.6: Average flood recession salt loads Lock 9 to Lock 5 – sub-reaches



Note: Salt inflow cumulative from Lock 9 to the graphed station (e.g. Lock 6 is the sum of all salt between Lock 9 and 6)

Figure 6.7: Salt load recession Lock 9 to Lock 5 – sub-reaches 1981 flood

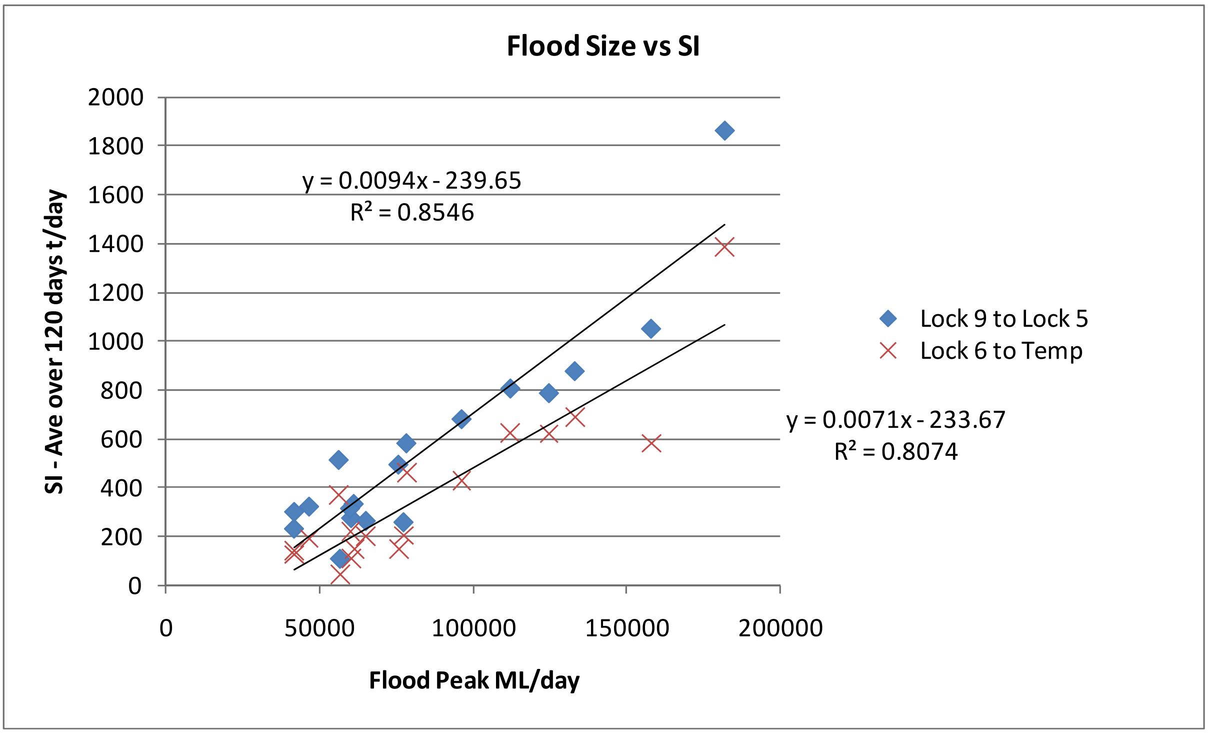


Figure 6.8: Salt inflow vs flood size – Lock 9 to Lock 5

6.3.3 Potential salt sources during the post-flood recession in the Lock 6 to Lock 5 sub-reach

The Lock 6 to Templeton sub-reach demonstrates the most significant post-flood salt inflows. The area covered by and contributing to salt inputs in this reach is shown in Figure 6.9, which also shows areas inundated at various flows. The Chowilla Creek Drainage zone flows out through the Chowilla Creek anabranch and enters the river 10 kilometres downstream of Lock 6.

Extensive inundation occurs between Lock 6 and Lock 5 (Murtho) at flows less than 60,000 ML/d. The Chowilla area has only minor inundation areas at these flows, but is largely inundated by the time flows reach 80,000 ML/day.

The Chowilla area has been the focus of much attention for it salt inputs to the river. However, it is noted that the salt loads attributed to Chowilla could also be driven from the Upper Murtho floodplain, because the salt loads for the initial Chowilla studies were calculated using the Templeton station which is mid-way along the Murtho floodplain.

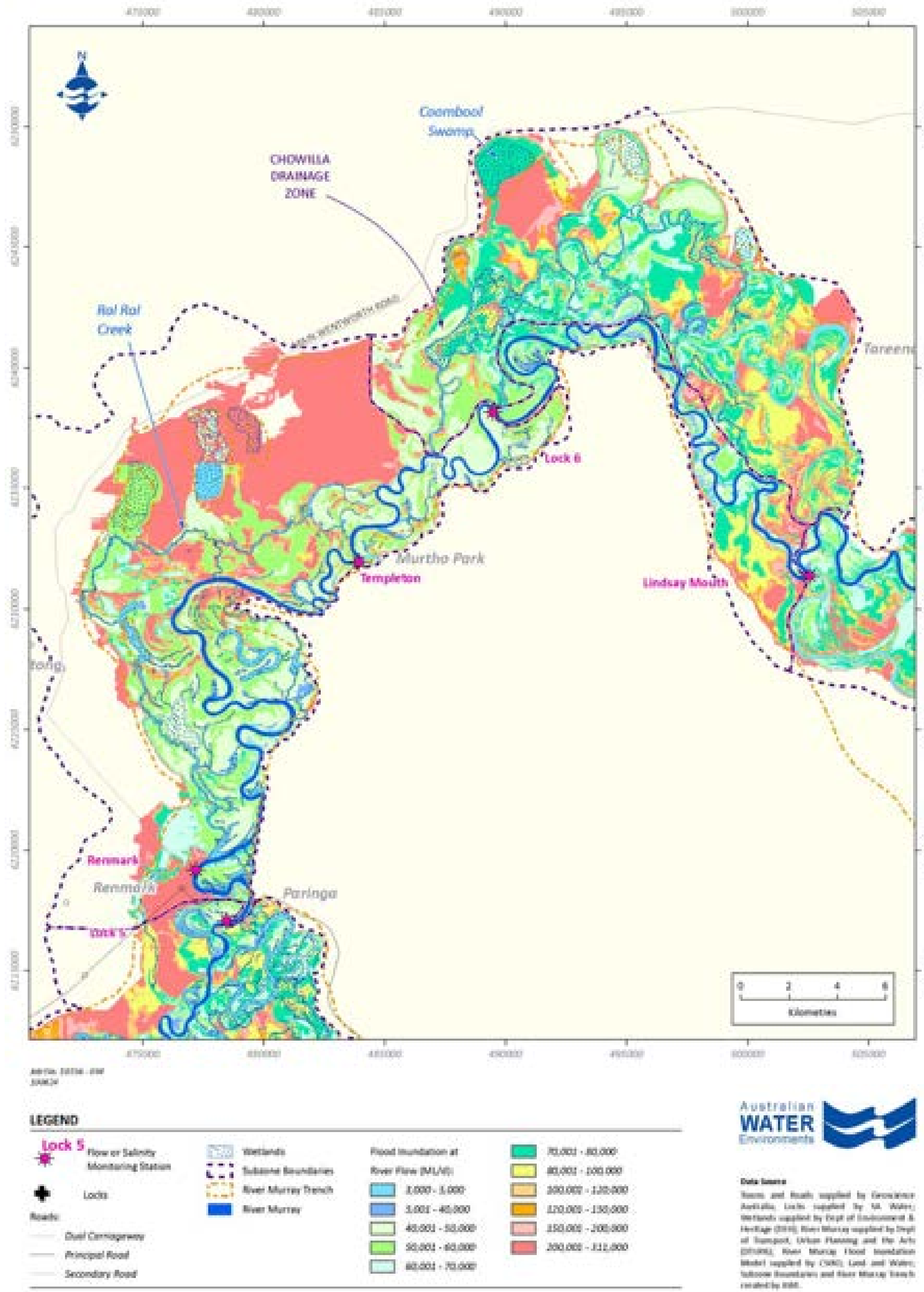


Figure 6.9: Lock 6 to Lock 5 reach including Chowilla – inundation areas

Plots of salt inflow for all inter-flood periods since 1970 for Lock 6 to Templeton are shown in Figure 6.10. The plots start once flows fall below 20,000 ML/day. The plots are terminated when flow enters the next flood period (i.e. exceeds 40,000 ML/day). A 30 day rolling average has been used to smooth the data. The BIGMOD output contains several instances of negative values which reflect the difficulty in modelling the flow through the Chowilla anabranch and possible errors in measuring flow and salinity. The Templeton salinity station was removed in January 2003; hence reference to the Lock 6 to Lock 5 EC reach assists interpretation. The Templeton salinity station was replaced by pontoons upstream and downstream of Chowilla in 2002 with the intention being to capture changes in salinity deriving from the Chowilla area. These stations are currently not in BIGMOD.

The modelled salt inflow for the 1983 flood indicates negative values for some 160 days. The raw salinity data for this time period has been assessed and EC instrument error is considered to be the cause. The period July 1983 to October 1984 has therefore been excluded from the following analysis.

There have been six flood events during the study period with flows over 80,000 ML/day which correspond to the six highest post-flood salt inflow peaks. The six events, shown in Figure 6.11, have a salt inflow peak some 25 days after the flow falls below 20,000 ML/day and have an extensive recession.

Salt inflow following these six large flood events is significantly different to salt inflow following the smaller floods. The smaller floods have much lower salt inflow peaks and do not exhibit the delay until the peak occurs. It is considered that there may be a threshold event occurring at flows above about 75,000 ML/day.

Coombool Swamp is implicated in the major flood recession salt loads at Chowilla. Coombool Swamp does not fill until flows exceed approximately 75,000 ML/d due to a sill on the inlet channel, based on LiDAR data, the FIM model and backwater curves. This same sill prevents the swamp draining, and over a metre of water is held in the swamp after floods based on LiIDAR elevation data. The BIGMOD unaccounted salt load analysis illustrates that there is a significant difference in the character of the salt recession for floods greater than approximately 75,000 ML/d. We suggest that the cause of the major flood salt inputs from Chowilla illustrated in Figure 6.11 is driven by recharge to the floodplain aquifer from the ponded and isolated Coombool Swamp (Figure 6.12). Given the floods usually occur in mid-summer and the water depth is greater than 1 m, evaporation losses are not likely to dry the swamp out in the summer period. The swamp can continue to add water to the water table from summer through winter into spring. The recharge from the swamp can be anticipated to emplace a fresh water lens beneath and adjacent the swamp. However the water inputs from the swamp will drive groundwater into the anabranches and the river. This model of Chowilla behaviour is consistent with the analysis of Jolly *et al*. (1994).

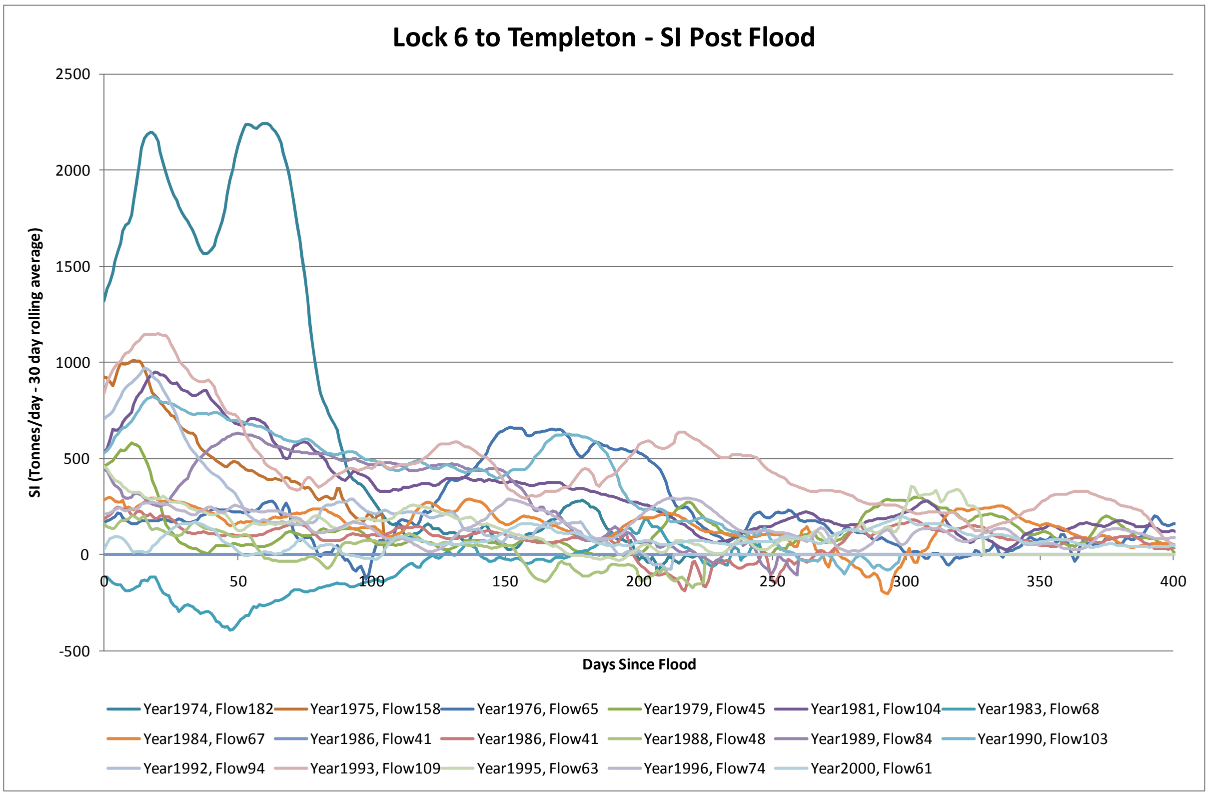


Figure 6.10: Salt recession Lock 6 to Templeton – 30 day rolling average

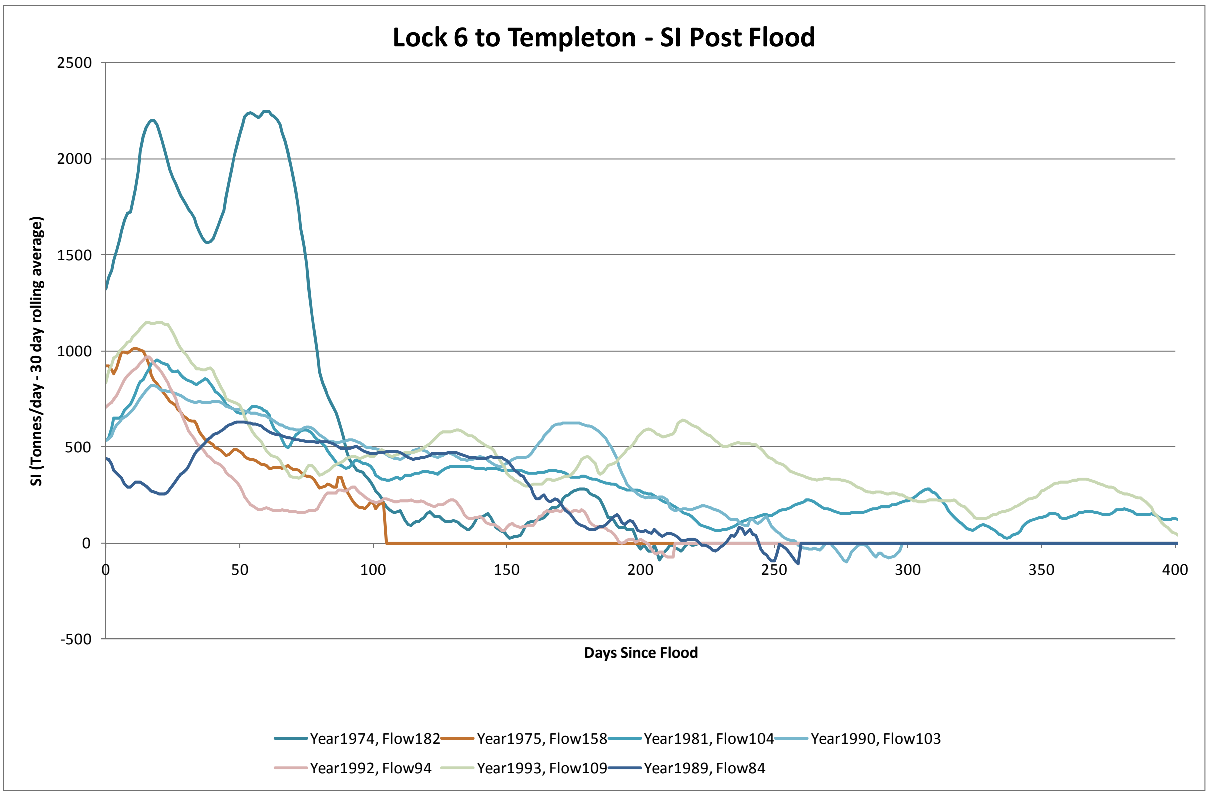


Figure 6.11: Salt recession Lock 6 to Templeton – floods over 80,000 ML/day

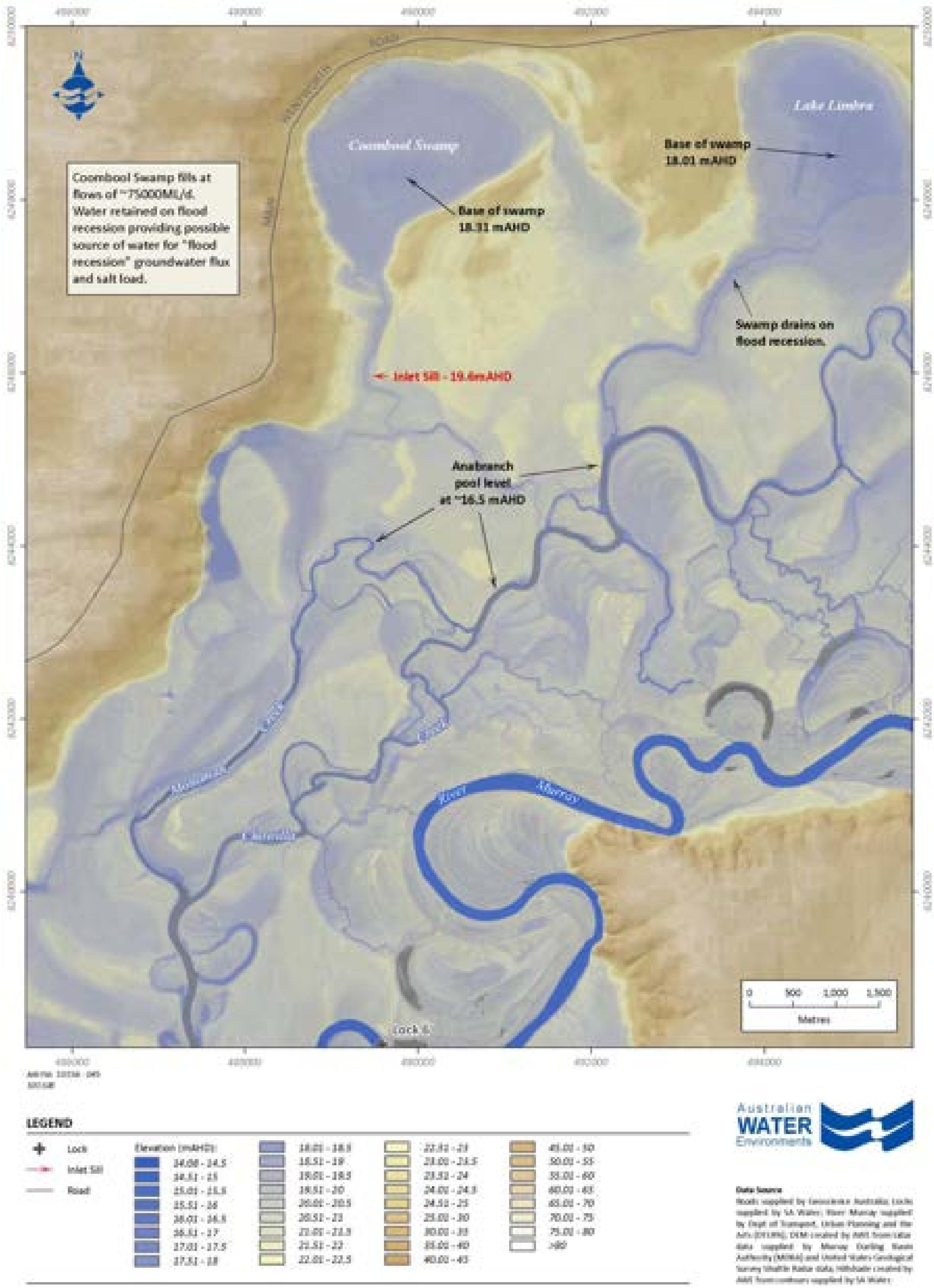


Figure 6.12: Chowilla Floodplain and Coombool Swamp

This deduced model of system behaviour needs testing, both with groundwater and water budget monitoring of environmental watering events, and through groundwater flow and solute transport modelling to test the validity of the hypothesis. If proven correct, additional work to assess the likely sites where this process occurs elsewhere would prove a valuable input to the prioritisation and siting of environmental water activities. It may also provide opportunities for very targeted but very cost effective salt interception options.

The salt inflow after the 1974 flood (Figure 6.11) is significantly higher than all the other salt inflow peaks. There appears to be another threshold process that was triggered by this event. Investigation of the raw salinity data confirms the event is not a modelling issue and the resultant “twin” salinity spike is observed all the way downstream to Morgan. The 1974 flood was the largest flood in the study period (Figure 6.2). Flows were above 70,000 ML/day for 255 days and prior to the flood flows had not been below 25,000 ML/day for 495 days. The twin peak in the salt inflow appears to be driven by the flow in the river. Flow initially dropped from 20,000 ML/day to 6,000 ML/day over 20 days when the first salt inflow peak occurs. Flows then increased over the next 26 days to 13,000 ML/day with a resultant decrease in salt inflow. Flows then dropped back to 5,000 ML/day when the second inflow peak occurs. Using mass balance calculations of salinity from salt inflow and river flow, the salt inflow peaks are calculated to cause increases in river salinity of 610 EC for the first peak into 6,000 ML/day flow and 760 EC for the second peak into 5,000 ML/day. These calculated salinity increases are a very good match to those observed in the raw data (Figure 4.1) and confirm the veracity of the BIGMOD outputs. The twin salinity peaks extended to Morgan and caused the two highest salinity peaks observed at Morgan during the study period. The cause of the major salt inflows and salinity peak has not been isolated by this study. Further investigation of the event may provide insight into what threshold events could have contributed to this very large salt inflow.

The average daily salt inflow and total salt inflow for the Lock 6 to Templeton reach are shown in Table 6.2 and Table 6.3 respectively (1999-2000 is for Lock 6 to Lock 5 as the Templeton EC station was decommissioned in 2003). These tables confirm that the average daily salt inflow during flood events is lower than at other times (Table 6.2), and that overall salt inflow during floods is a minor component of total salt inflow (Table 6.3). The wetter decade of 1989 to 1999 has a much higher overall salt inflow, double the two previous decades and demonstrates that a wetter regime is responsible for an overall higher salt inflow, with the salt being exported during flows of <7,000 ML/d following the floods. The drought period of 1999-2009 produced the lowest salt inflow and, while the data for that period are not directly comparable to the others owing to the closure of the Templeton station, the data for the 1999 to 2009 reach are from a longer reach and therefore the calculated salt load presented in Table 6.3 will be a little higher than that of the shorter reach (Lock 6 to Templeton).

Table 6.2: Lock 6 to Templeton (Lock 5) salt inflow for flow ranges by decade

Period	Salt inflow – Daily average (tonnes/day)			
	Flow range (ML/day)			
	<7,000	7,000 to 40,000	> 40,000	All flows
1970-79	212	135	-12	120
1979-89	145	50	129	122
1989-99	235	248	170	227
1999-2009	42	68	48	45

Note: 79-89 excludes data for 500 days from July 1983 due to salinity instrument error. 1999-2000 is for Lock 6 to Lock 5 as the Templeton EC station was decommissioned in 2003.

Table 6.3: Lock 6 to Templeton (Lock 5) – total salt inflows

Period	Salt inflow – Gigatonnes / period			
	Flow range (ML/day)			
	<7,000	7,000 to 40,000	> 40,000	All flows
1970-79	0.20	0.21	-0.01	0.39
1979-89	0.33	0.04	0.02	0.38
1989-99	0.45	0.26	0.11	0.83
1999-2009	0.13	0.03	0.00	0.16

Note: 1979-1989 excludes data for 500 days from July 1983 due to salinity instrument error. 1999-2009 is for Lock 6 to Lock 5 as the Templeton EC station was decommissioned in 2003.

In summary, in the Lock 6 to Templeton reach, salt inflow is generally suppressed during a flood (Table 6.3), peaks some short time after the flood has ceased (Figure 6.6) and continues for up to 500 days (Figure 6.7) or until the next flood event occurs. This is in stark contrast to the Lock 5 to Morgan reach where salt export is some four times higher during the floods (Section 6.4).

6.3.4 Salt stored in the floodplain

The total mass of salt stored in the Chowilla/Lock 6 to Lock 5 floodplain is considered to be in the order of 11 megatonnes. This conservative (low), coarse assessment of the total mass of salt stored in the floodplain has been calculated using the following parameters:

- a floodplain area of 183 km^2 from GIS information
- a Monoman aquifer thickness of 16 m
- aquifer porosity of 0.15
- average floodplain groundwater salinity of 30,000 mg/L.

During the decade 1999 to 2009 there was some 0.7 megatonnes less salt exported in the Lock 6 to Templeton reach than in the previous wetter decade (Table 6.3). The decrease in export represents some 7% of the total mass stored.

The mechanism and location of the additional salt stored is not well understood. The flux entering the floodplain is expected to be similar and not significantly influenced by the low river flows. The flux to the floodplain is most likely being consumed by evapotranspiration from the wide floodplain. It is thus likely that the additional salt is distributed across the floodplain. If it is stored by increasing the average salinity of the groundwater (e.g. by 7%) the salt inflows to the river from future floods would not be significantly different to previous similar sized floods. It is difficult to envisage a process whereby the storage of the additional salt would result in it all being exported during the next flood. A further detailed assessment of floodplain groundwater is needed to properly account for floodplain salt storage.

6.4 Detailed analysis - Lock 5 to Morgan

During the study period, this reach had the highest salt inflow (Figure 6.1). The salt inflow has reduced significantly over time with the construction of SISs and improved irrigation practices.

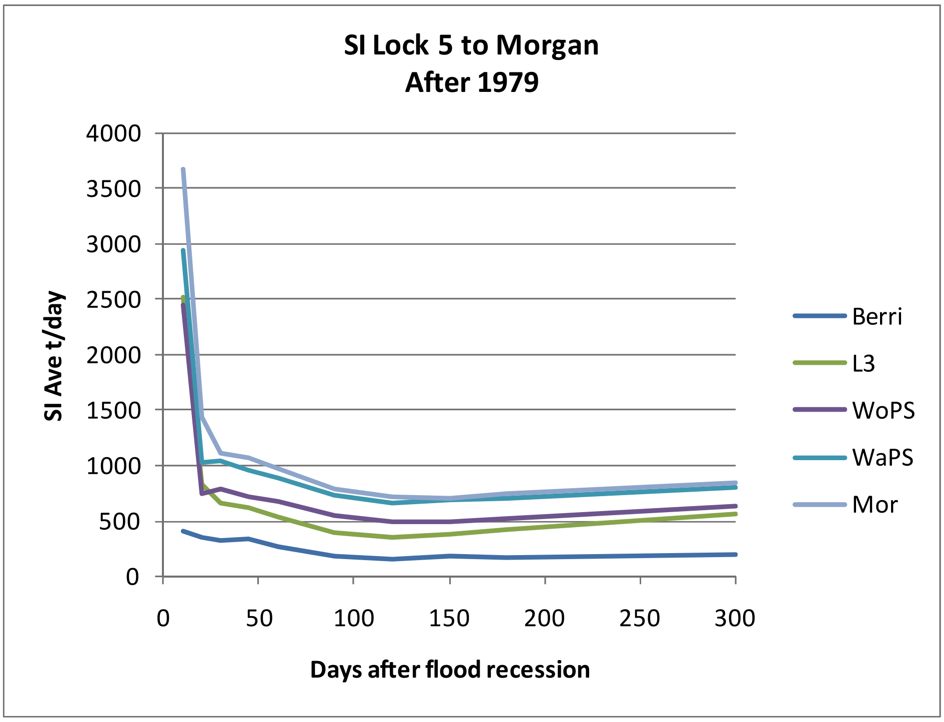
6.4.1 Floods and salt recessions

Salinity records are available for five sub-reaches of the Lock 5 to Morgan reach from 1979 onwards. The intermediate stations are Berri Pump Station (PS), Lock 3, Woolpunda PS and Waikerie PS.

The cumulative salt recessions since 1979 are shown in Figure 6.13. Each sub-reach has a similar shape. In marked contrast to the Lock 6 to Templeton reach, the Lock 5 to Morgan reach exhibits very high salt inflow values, around 3,000 tonnes per day, for the 15 days following a flood. Salt inflow then decreases to about 1,000 tonnes per day and slowly continues to fall over the next 100 days. There also appears to be an increase in salt inflow, particularly in the Berri to Lock 3 reach, after about 130 days, which may be due to seasonal factors and/or increased river flows following minimum entitlement flows of May and June. Further investigation of correlations between river hydrology and flow patterns and the observed salt inflow patterns would enhance the understanding of processes influencing salt inflows.

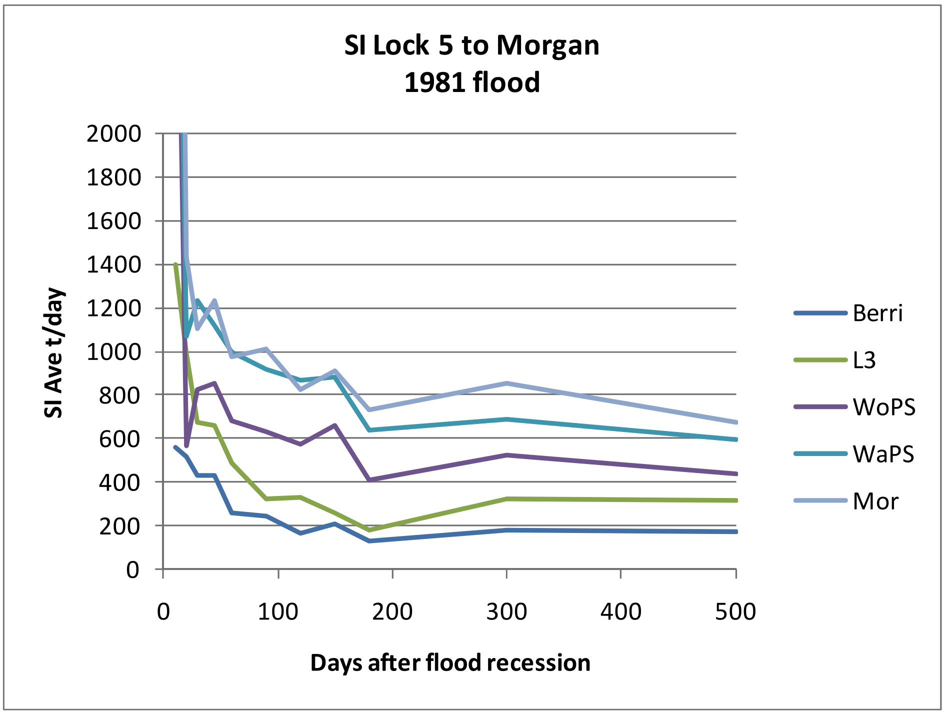
There has been implementation of major SISs in the Lock 5 to Morgan reach during the period 1979 to 2009, namely Woolpunda SIS in 1991, Waikerie SIS in 1993 and 2002, and Bookpurnong in 2005.

The 1981 salt recession shown in Figure 6.14 indicates that most of the post-flood salt impact for that flood was upstream of Lock 3, which is expected because the floodplain is on average 5.0 km wide between Lock 5 and Lock 3 and only 1.6 km wide between Lock 3 and Morgan. Most of the flood-influenced salt inflow has dissipated within 180 days. Similar to the pattern observed in the overall averages, there appears to be an increase in salt inflow between 180 and 300 days, followed by a slow reduction up to 500 days.



Note: Salt inflow cumulative from Lock 5 to the graphed station (e.g. Lock 3 is the sum of all salt between Lock 5 and Lock 3)

Figure 6.13: Salt recession – sub reaches Lock 5 to Morgan 1979 to 2009



Note: Salt inflow cumulative from Lock 5 to the graphed station (e.g. Lock 3 is the sum of all salt between Lock 5 and Lock 3)

Figure 6.14: Salt recession – Lock 5 to Morgan 1981

Daily salt inflow data for the 100 days following the 19 flood events in the Lock 5 to Morgan reach are shown in Figure 6.15. The data have not been averaged and the plot commences the day after flows fall below 40,000 ML/day. The plot shows a consistent pattern between all floods, irrespective of size. The peak salt inflow is some six times the base flow and occurs within eight days after the flows fall below 40,000 ML/day. The salt recession effects last less than 30 days. The peak salt inflow does not appear to be related to flood size.

The salt inflow versus flood size graph (Figure 6.16) for the flood events in the Lock 5 to Morgan reach during the study period does not show the same clear correlation as in the Lock 6 to Templeton reach (Figure 6.8). This may, in part, be attributed to the higher salt inputs during the inter-flood period in the Lock 5 to Morgan reach (e.g. 750 t/d, Figure 6.13) compared to the Lock 6 to Templeton reach (300 t/d, Figure 6.6). As there is a high base load salt inflow, the relative impact of flood recession on the salt inflow may be reduced.

The base load salt inflow has changed considerably over the study period, with construction of SISs and changed irrigation drainage practices, possibly influencing relationships between salt inflow and flood size.

There does, however, appear to be a relationship between total salt inflow during a flood event and the total flow. The 14 flood events since 1979 are shown in Figure 6.17. The 1981 event has a very large salt inflow at the beginning of the flood in the section upstream of Berri. A similar but smaller event occurred in the 1986 flood but not the intermediate floods and does not appear to have occurred since. Further investigation would be required to determine the cause of the peak salt inflow, however one possible explanation is a managed discharge from Disher Creek Drainage Disposal Basin prior to the commissioning of the Noora Disposal Basin in 1982. The 1981 flood event has been excluded from the correlation analysis.

Given the many processes influencing salt inflow it is considered that the correlation indicates that there is a relationship between total flow and total salt inflow during the event, with a factor of 31 tonnes/GL. This equates to a constant salinity impact during flood events of 31 mg/L or 52 EC. The salt inflow during a flood event could be contributed to by flushing of higher salinity water from wetlands and anabranches, surface salt wash-off, and possibly groundwater inputs during the flood recession. Processes leading to the high salinity water in the wetlands and anabranches cannot be identified from this analysis.

6.4.2 Lock 5 to Morgan –flows below 7,000 ML/day

BIGMOD time series salt inflow data for flows below 7,000 ML/day are shown in Figure 6.19. The data have been smoothed using a 12 month rolling average so that the base load can be assessed for the impact of SIS and climate variations. The sequence has been separated into Lock 5 to Lock 3 and Lock 3 to Morgan because of differences in floodplain width.

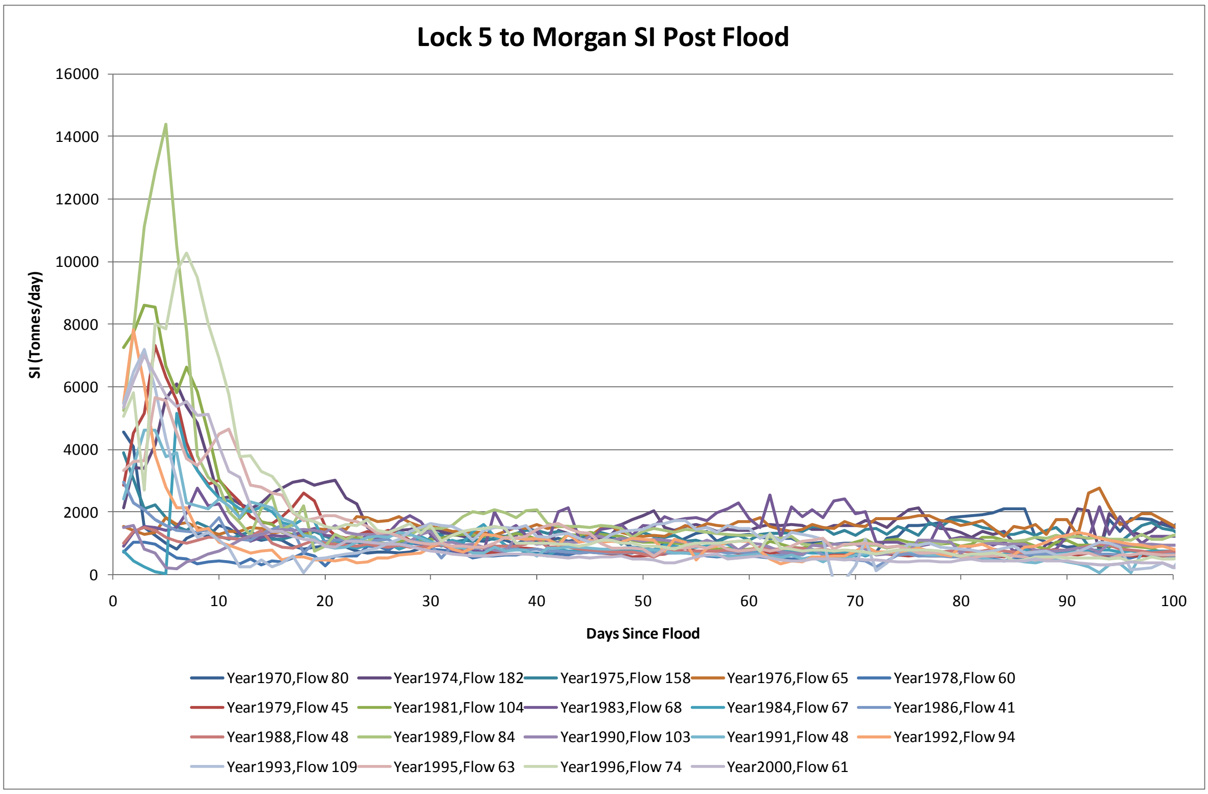


Figure 6.15: Salt recession - Lock 5 to Morgan

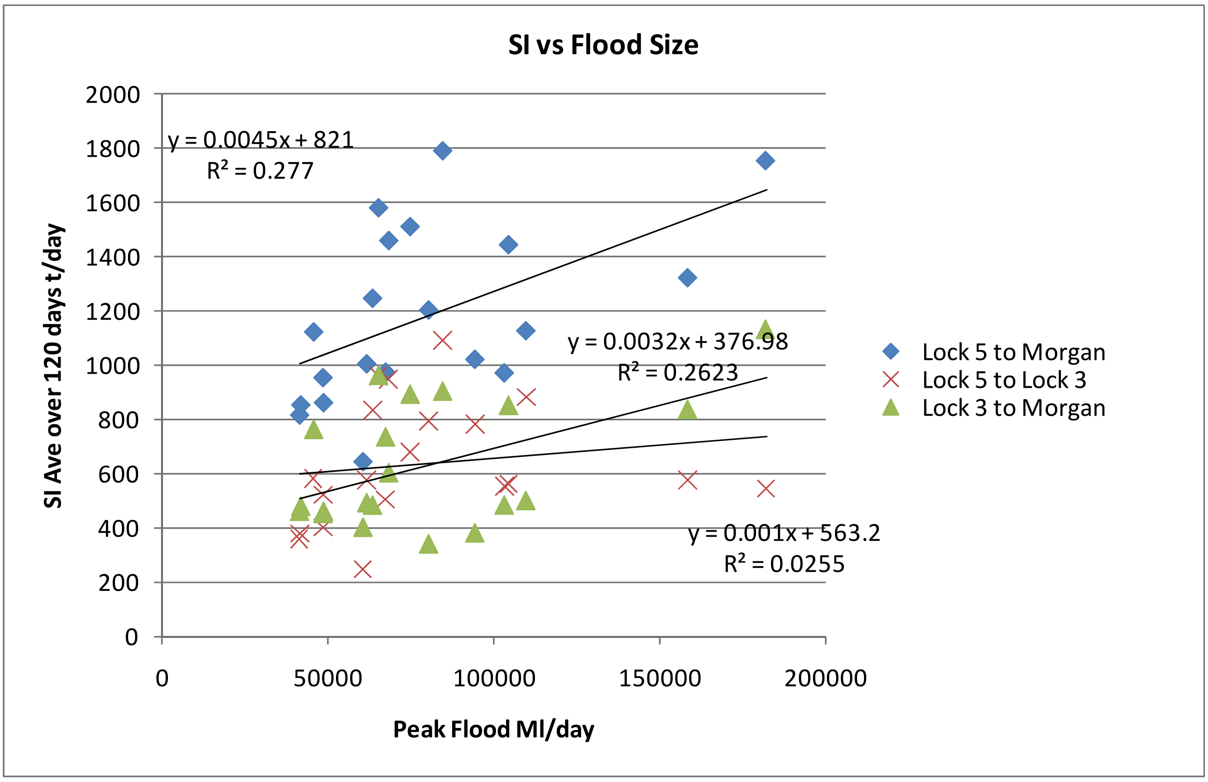


Figure 6.16: Salt inflow vs flood size – Lock 5 to Morgan

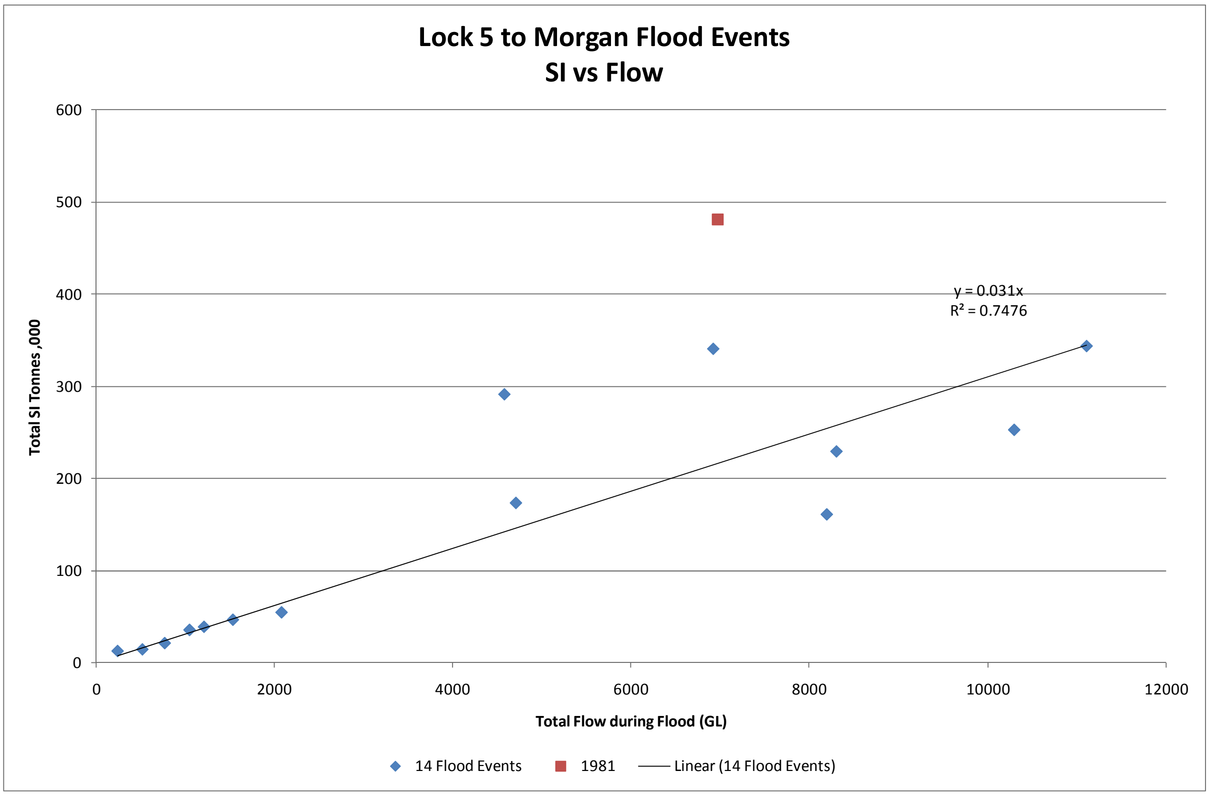


Figure 6.17: Lock 5 to Morgan flood events – salt inflow vs total flow

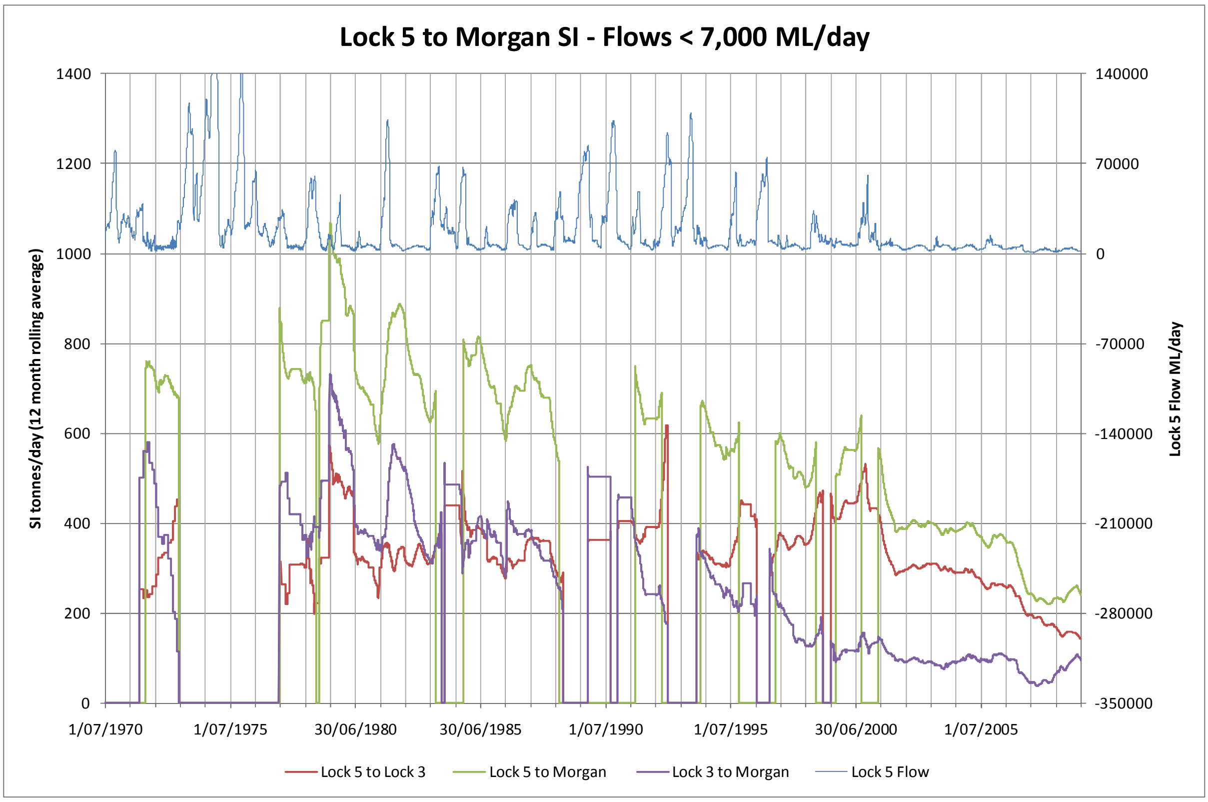


Figure 6.18: Lock 5 to Morgan salt inflow for flows below 7,000 ML/day

Whilst the data represented in Figure 6.18 still clearly show the impact of flooding, the 12 month rolling average salt loads for flows below 7,000 ML/day provide insight into the impact of SISs and the subdued impact of the climate sequence variability between the periods (Figure 6.19). The contrast between the graphs for the sub-reaches “Lock 5 to Lock 3” and “Lock 3 to Morgan” is discussed below:

- The salt inflow for both sub-reaches is similar until 1989.
- The salt inflow for Lock 5 to Lock 3 rises slightly for Period 3 (1989 to 1999), possibly in response to the wetter climate sequence.
- In contrast, the salt inflow for Lock 3 to Morgan reduces through Period 3, correlating with the installation of Woolpunda and Waikerie SISs. The base load at the start of the decade of 380 tonnes per day has reduced to about 100 tonnes per day by the end of the decade. This decline of some 280 tonnes per day equates closely with the assessed and registered impact of the Woolpunda and Waikerie SISs.
- The base load for Lock 5 to Lock 3 continues to be relatively high in Period 4 (1999 to 2009) until 2005 indicating limited impact of the flows <7,000 ML/d and a lack of flooding during the first six years of this period. Salt inflow does decline post 2006 which correlates with the commissioning of the Bookpurnong SIS (2005) and the progressive commissioning of the Loxton SIS since 2007.
- Information from the SA MDB Natural Resource Management Board indicates that during 2007, banks were constructed at several wetlands in this reach to separate them from the main river to reduce impact of evaporation losses on river flow. The lower water levels in the wetlands would lower floodplain groundwater levels and decrease groundwater gradients to the river, decreasing salt inflow. These events may contribute to the salt inflow decrease.

The salt inflow graph for Period 4 is shown in Figure 6.19 and Figure 6.20 using 12 monthly and three monthly rolling averages respectively. Whilst in the12 monthly average trace there is a fairly uniform salt inflow for the period 2002 to 2006, the 90 day average clearly shows there is an annual pattern of variation, with peak salt inflow in August and lowest salt inflow in May. The period of rise is shorter than the period of fall. The low salt inflow corresponds to low river flow which tends to be lowest in May and June. Physical processes that could contribute to the observed annual pattern include:

- The Ramco Lagoon effect is described in Section 2.3.3 and Figure 2.3. The process of summer salt accumulation in the backwater and winter release to the river would be expected to be more pronounced in the upstream reach (Lock 5 to Lock 3) because it has a significantly larger area of wetlands than the downstream reach (the Lock 5 to Lock 3 reach has 61.6 km^2 of wetland compared to 10.2 km^2 in the Lock 3 to Morgan reach). Further data collection of wetlands and the associated hydraulic connections to the river, as well as analysis could provide further insight into the quantum of this salinity impact.

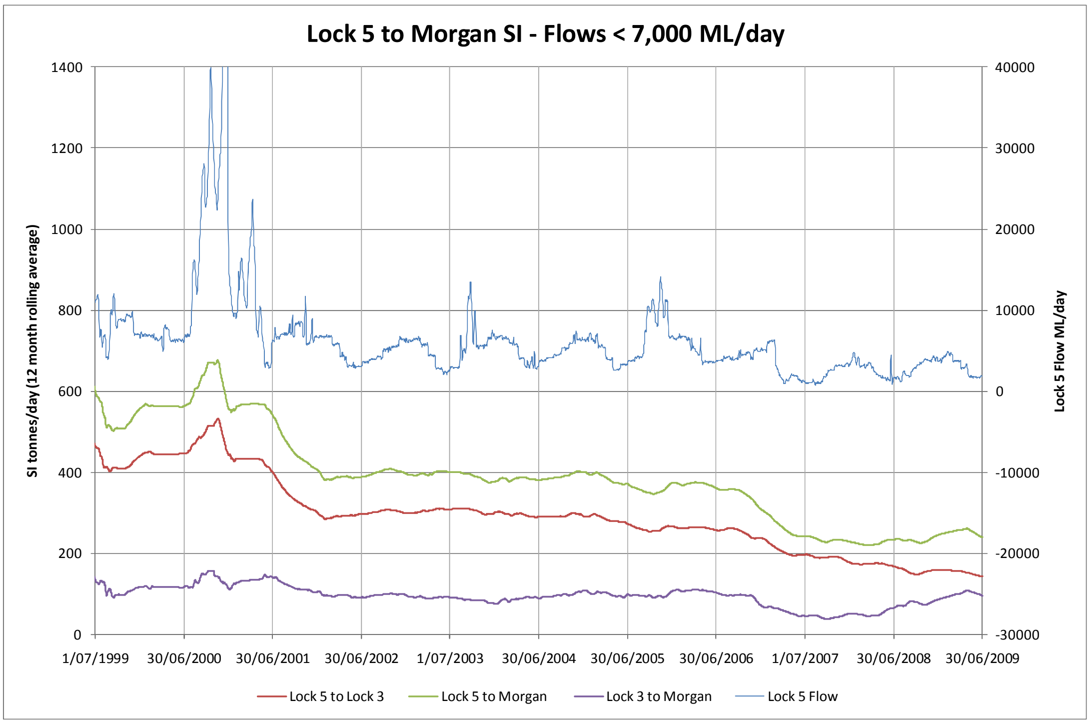


Figure 6.19: Period 4 (1999-2009) Lock 5 to Morgan salt inflow 12 month rolling average flows <7,000 ML/d

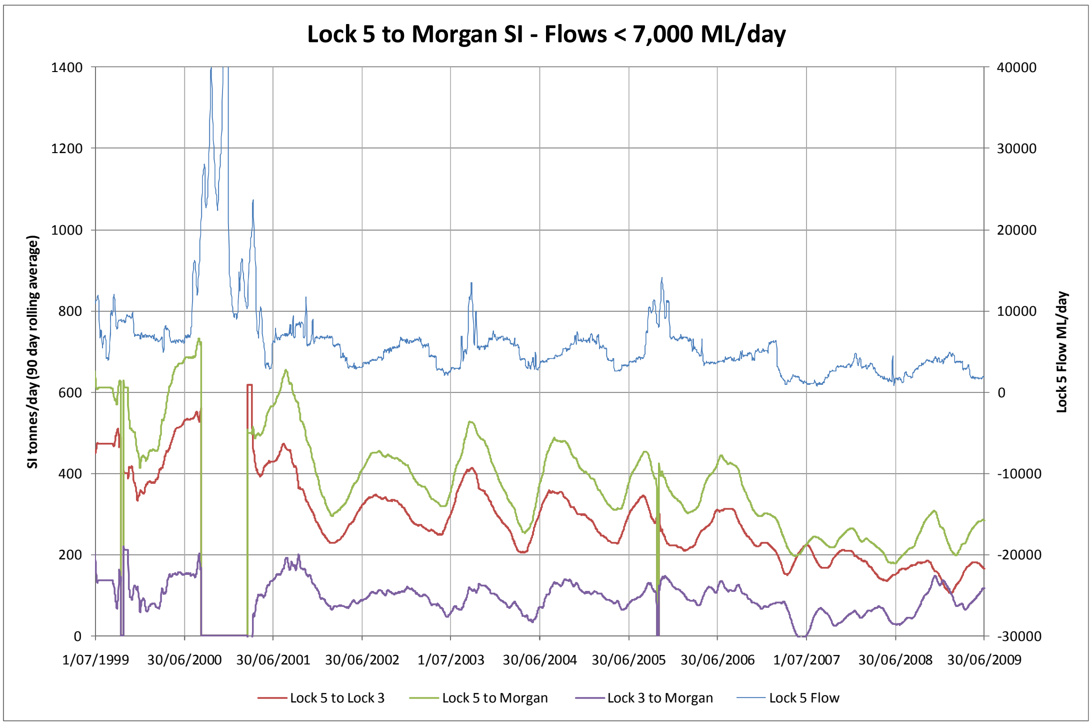


Figure 6.20: Period 4 (1999-2009) Lock 5 to Morgan salt inflow 90 day rolling average flows <7,000 ML/d

- Evapotranspiration from the floodplain produces an annual cycle of groundwater levels that are normally lowest prior to winter and peak after winter. The transient effects of rainfall and flooding events will impact the annual groundwater level cycle. The lower floodplain groundwater levels will tend to reduce groundwater gradients toward the river and hence reduce salt inflow to the river, producing a pattern of salt inflow similar to those observed in the BIGMOD data.

- Small changes in river level will affect the connectivity between backwaters and the river. Increases in river level will increase the cross-sectional area at the connection with the river. This may enhance interchange between the wetland and the river, particularly if wind directions push water toward the connection. The wetland water will probably be more saline than the river due to evaporative concentration and possibly saline groundwater inputs. Rising river levels may therefore mobilise salt. Falling river levels will cause the potentially more saline wetland to drain back to the river.
- If a wetland has a small upstream inflow channel, the evaporation within the wetland will reduce or possibly stop outflow. As river flow increases, and the cross-sectional area of the upstream inlet increases, flow through the upstream inflow channel will increase, moving the potentially more saline wetland water into the main channel.

The balance between these processes can be anticipated to be different for each wetland and it is the combined effect of all wetlands in the reach that contribute to the observed annual salt inflow variation.

6.4.3 Overview of salt export

The average salt inflow for the key periods and key flow ranges for Lock 5 to Morgan are summarised in Table 6.4.

Table 6.4: Lock 5 to Morgan salt inflow for flow ranges by decade

Period	Salt inflow – Daily average (tonnes/day)					
	Flow range (ML/day)					
	<7,000	7,000 to 40,000 (transition flows)			> 40,000	All flows
	Low Flows	20 Days pre flood	20 days post flood	Other	Floods	
1970-79	783	2039	3297	1290	2440	1591
1979-89	753	1662	3049	1108	3067	1193
1989-99	609	1404	3412	797	2039	1081
1999-2009	357	684	4119	666	1615	442

The key outcomes from the analysis are summarised below and discussed in detail in the following sections:

- The average salt inflow during low flow (<7,000 ML/day) has decreased from over 750 tonnes per day prior to 1989 to less than 400 tonnes per day since 1999. The construction of several major SIS schemes in the reach and improved irrigation management practices are likely to be the major influencing factors.
- Average daily salt inflow during floods is some three to four times the average daily salt inflow during periods of flow less than 7,000 ML/day.
- At transition flows (7,000 to 40,000 ML/day) salt inflow is highest immediately post flood in the period that lasts for some 20 days after flows drop below 40,000.

- At transition flows (7,000 to 40,000 ML/day) salt inflow on the rising limb is also higher than the average rate for the 20 days immediately preceding the flood as flows increase towards 40,000 ML/day.

The key outcome from the observations above is that as flows increase and water levels rise, we are not observing a decrease in salt inflows but an increase. This is in stark contrast to the pattern observed in the Lock 6 to Lock 5 reach discussed in Section 6.3. As flows increase rising river levels would be expected to decrease groundwater inflows and the associated salt inflow directly from groundwater. It is speculated that the observed pattern of high salt inflows in this reach during the rising limb of a flood event is therefore due to other processes, most likely:

- surface water processes such as the flushing of wetlands, anabranches and saline deep holes as flow increases
- managed discharges from drainage basins, taking advantage of the higher flows to export salt from the basin.

These processes do not require floodplain inundation to occur to trigger the salt inflows, which is consistent with them also being responsible for salt inflow increases that are observed at all levels of flow increase.

Following the flood peak, as water levels drop, the draining of backwaters and groundwater returning or displaced by bank storage would also contribute to salt inflow. The rapid decay of salt inflow in this reach following the flood also indicates that a key process is likely to be the draining of surface water bodies, which decreases rapidly as river levels stabilise. It is possible that some of the response is also due to short-term pressure release groundwater responses. Further work is required to determine the relative importance of actual processes causing the observed salt inflow patterns.

Simplified salt inflow vs flow relationships for Periods 2, 3 and 4 are shown in Figure 6.21. The salt inflow/flow relationship represented in Figure 6.21 equates to a constant EC rise (52 EC) during flows of over 40,000 ML/day in the reach due to saline inflows. At lower flows the EC increase is higher. On a flood recession, if the decrease in salt inflow is delayed by several days relative to the change in flow, a short term salinity spike is produced similar to those observed on some flood recessions.

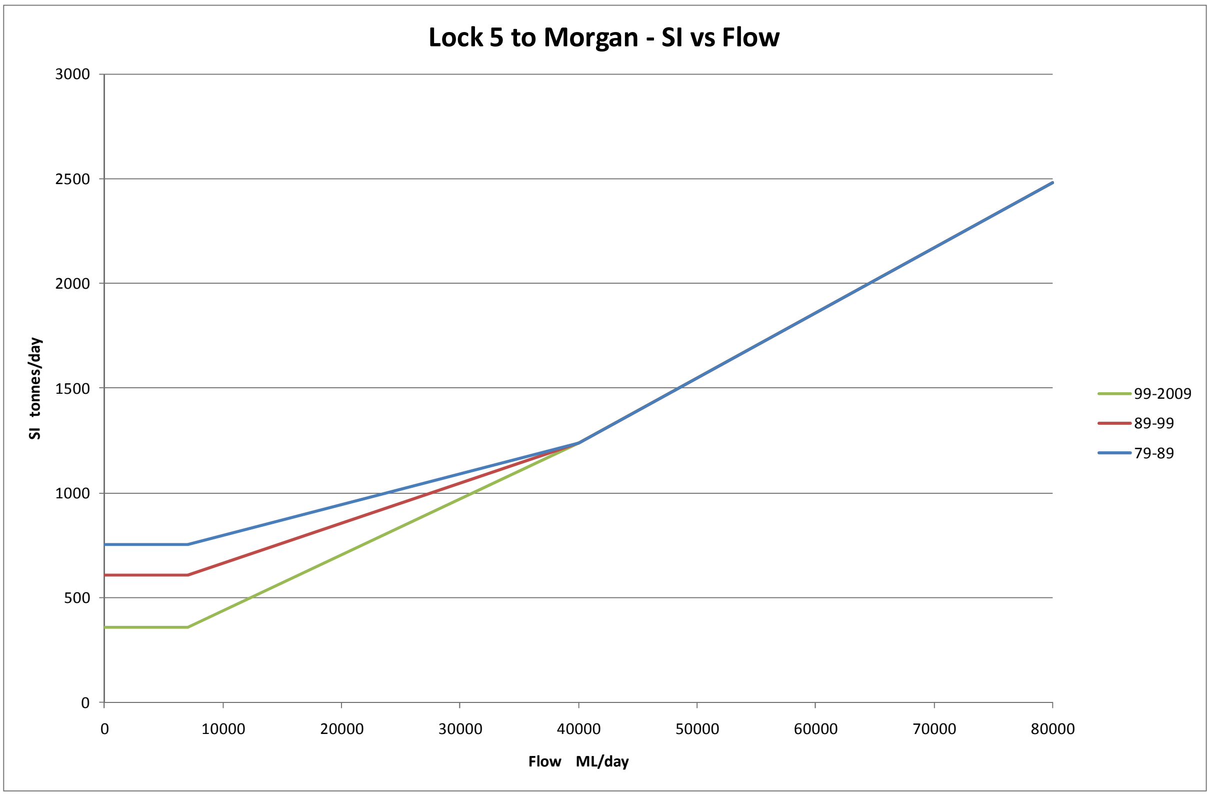


Figure 6.21: Lock 5 to Morgan – salt inflow vs flow relationship

6.4.4 Salt inflow over time – Lock 5 to Morgan

The monthly salt inflow to the Lock 5 to Morgan reach and sub-reaches is shown in Figures 6.22 to 6.25. The time period has been split to enable presentation of the data. The following observations are noted:

- The peak values for salt inflow coincide with the peak flows in all flood events for the period. The size of salt inflow peaks appears to be correlated with the flows. This is consistent with the salt inflow being driven by surface water flows during the flood events.
- The salt inflow between flood events has a significant base load and some form of flood recession.
- There are many peak salt inflow events during floods in this reach. This could be due to flow from drainage basins (e.g. Disher Creek, Berri, Katarapko and Loveday) and the flushing of anabranches (e.g. Pike River, Toolunka Creek) and wetlands (eg Wachtels Lagoon, Hart Lagoon and Ramco Lagoon). A detailed analysis of evaporation basin management records and wetland/anabranch hydraulic characteristics would be required to identify causal factors for the observed salt inflow peaks.
- The high peaks at Lock 3 in 1981 and 1983 reduce downstream indicating incomplete mixing and may be due to the outflow from Lake Bonney which is immediately upstream of Lock 3.

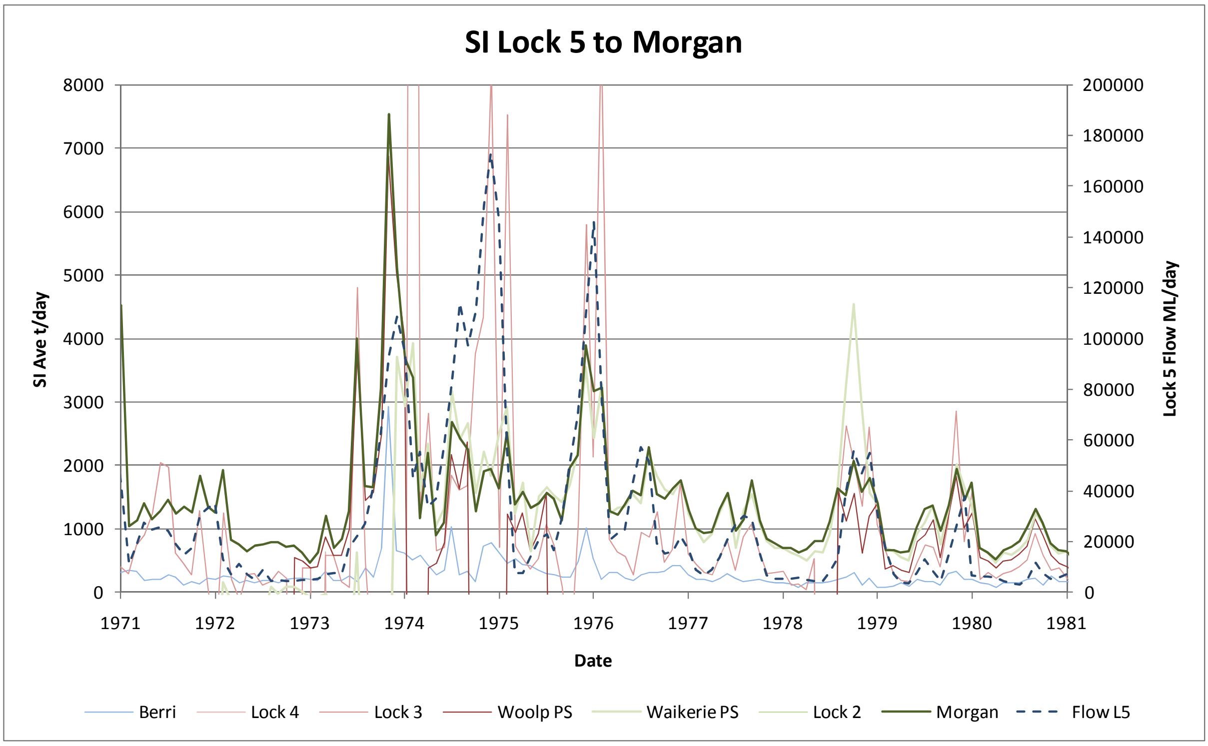


Figure 6.22: Salt inflow 1971 to 1981 – Lock 5 to Morgan

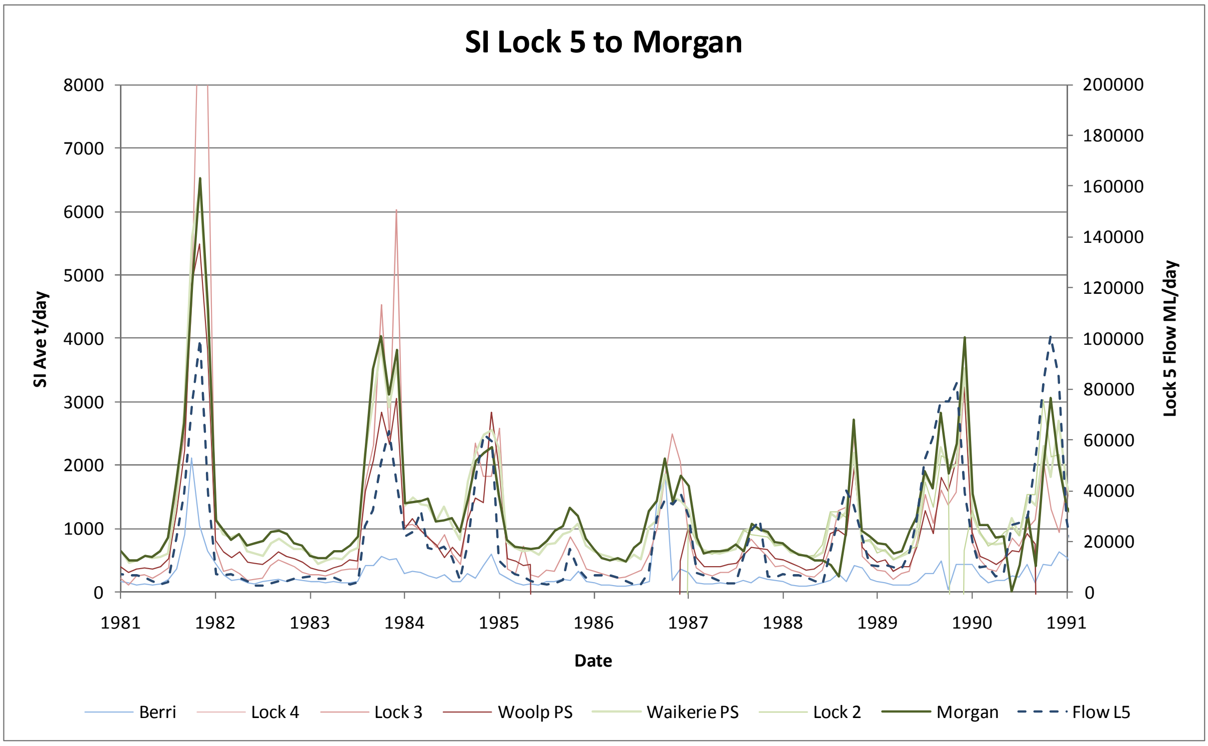


Figure 6.23: Salt inflow 1981 to 1991 – Lock 5 to Morgan

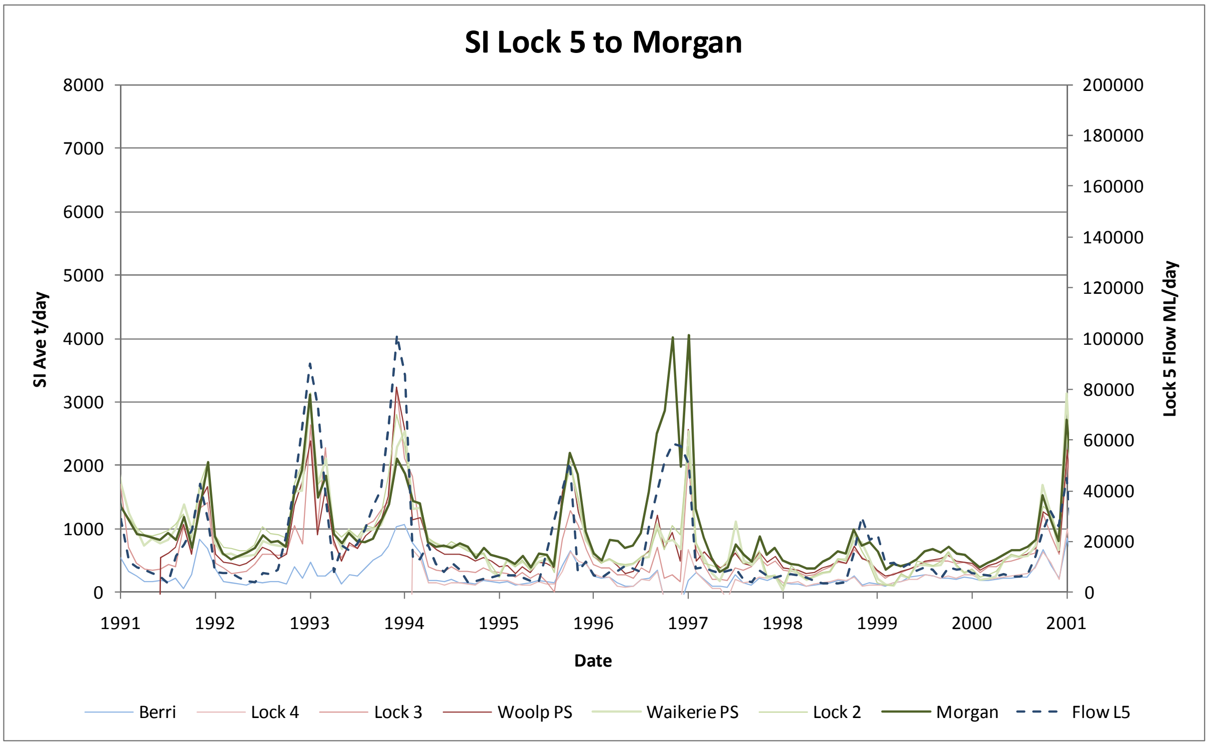


Figure 6.24: Salt inflow 1991 to 2001 – Lock 5 to Morgan

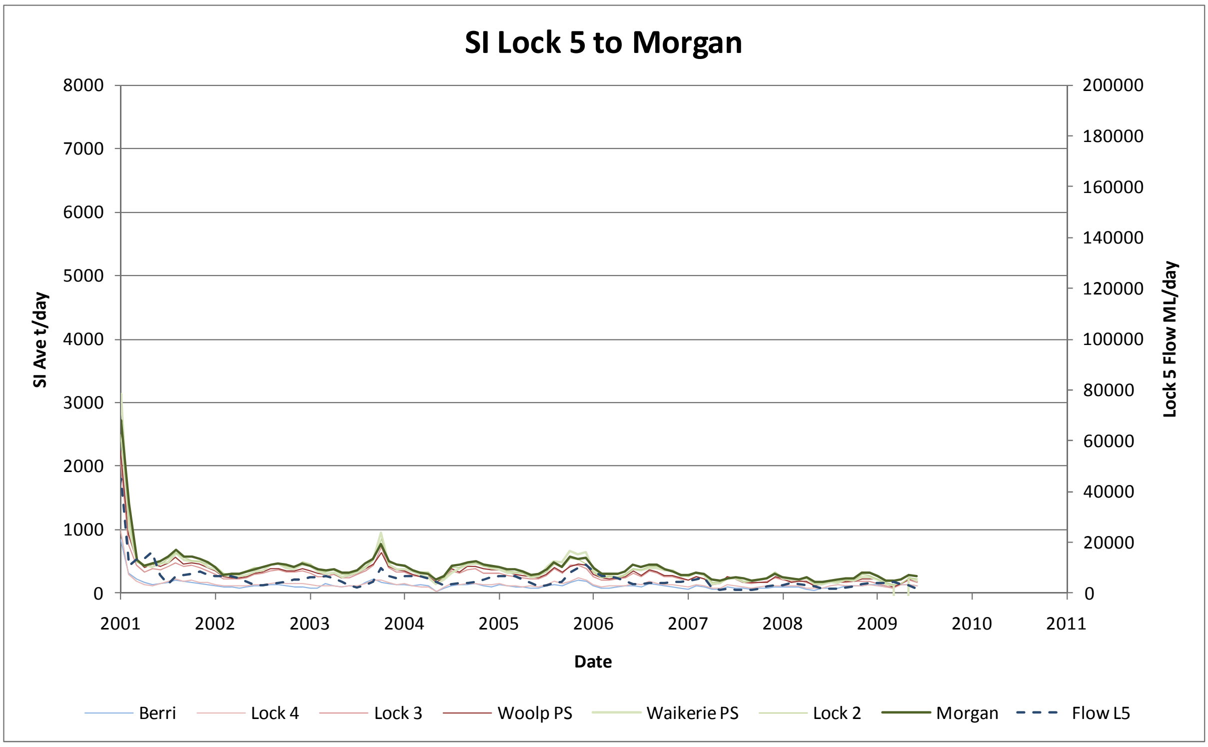


Figure 6.25: Salt inflow 2001 to 2009 – Lock 5 to Morgan

- Base salt inflow is considerably lower in the late 1990s than the 1980 and early 1990s, reflecting the impact of the Woolpunda and Waikerie SISs, which were commissioned in the early 1990s, and other salinity mitigation measures.

The observed salinity data for the period have been analysed and show sustained large increases in salinity between the stations during the large flood events, consistent with the high salt inflow during the floods.

There are also short salinity spikes indicating threshold events such as discharge from a disposal basin or commence-to-flow through a wetland/anabranch system.

6.4.5 Salt stored in the floodplain

In the Lock 5 to Morgan reach, the daily average salt inflow during floods is some three to four times that at flows <7,000 ML/d. This suggests that floods are an important mechanism for the overall export of salt from the floodplain. The low flow regime during Period 4 (1999 to 2009) has resulted in significantly less export of salt from the floodplain via the river than would have occurred had there been flows similar to the wetter sequences of previous decades. In order to make some assessment of the possible impact of future floods it is important to quantify what mass of additional salt has, in effect, been stored in the floodplain during Period 4, due to the lack of flooding. Where and how it has been stored and how it will be released are also key factors in assessing the river salinity impact.

An assessment of the additional salt stored in the Lock 5 to Morgan reach during the low flow Period 4 must take into account the significant decline in the base load due to SIS installation. The average daily salt inflow for flood and transition flow ranges is significantly higher than the base flows, as detailed in Table 6.4. The total tonnage of salt exported during each period and that exported assuming the low flow range salt inflow had been present for the whole period are shown in Table 6.5. It is conjectured that the variation of salt inflow between the periods and variation between "Base Load" and "All Flows" could indicate the following:

- The base load has decreased in a pattern consistent with the installation of SIS from 1990 onwards and other improvements in irrigation drainage management. The quantum of the decrease in base load from the period 1970-89 to 1999-2009 equates to some 145,000 tonnes per year decrease which is equivalent to 398 tonnes per day. The benefits of Waikerie and Woolpunda SIS according to the MDBA BIGMODis 280 tonnes per day.
- The ratio of Total/Base salt inflow appears to be influenced by the amount of flooding during the period (refer to Section 6.1.3), with the highest flow period (1970-79) having the largest percentage value. The period 1989-99 was the period with the second highest flood flows and has the second highest percentage. The period 1979 to 1989 had less flooding with floods not occurring in four of the 10 years, and it therefore has a lower percentage value. The period 1999-2009 included an extended period of drought and only one flood event and has the lowest percentage value. If it is argued that the ratio of Total/Base load could be in the order of 180% during a wet sequence of years then the reduction in salt inflow to the river during the period 1999-2009, due to the low flows is in the order of 730,000, calculated as follows:
    - (180%-124%)*1,300,000 = 730,000.
- It could also be argued that additional salt inflow due to flooding is not impacted by the base level of salt inflow but only influenced by the amount of flooding. In the two periods 1979-89 and1989-99 the difference between base load and total salt inflow was 1.61 and 1.73 megatonnes respectively. If additional salt inflow of this level could have also occurred during 1999-2009 but didn't due to lack of flooding, the reduction in salt inflow to the river during the period 1999-2009 is in the order of 1,390,000 tonnes, calculated as follows:
    - 1,700,000 – 310,000 = 1,390,000.

The actual amount of additional salt stored in the floodplain due to lack of flooding in the period 1999-2009 is expected to lie in the range 730,000 to 1,390,000 tonnes, with the authors considering a figure at the lower end more likely.

Table 6.5: Lock 5 to Morgan – total salt inflows

Period	Salt inflow Base load	Total salt inflow All flows	Total/ Base load	Total minus base load
	Megatonnes /Period	Megatonnes /Decade	Ratio %	Megatonnes
1970-79	2.56	5.21	203%	2.65
1979-89	2.75	4.36	159%	1.61
1989-99	2.22	3.95	178%	1.73
1999-2009	1.30	1.61	124%	0.31

A conservative (low), coarse assessment of the total mass of salt stored in the Lock 5 to Morgan floodplain has been calculated using the following parameters:

- a floodplain area of 509 km^2 from GIS information
- a Monoman aquifer thickness of 10 m which is considered a likely minimum thickness
- aquifer porosity of 0.15
- average floodplain groundwater salinity of 22,000 mg/L.

Based on these parameters the mass of salt stored in the floodplain between Lock 5 and Morgan is in the order of 16,000,000 tonnes (16 megatonnes). The range of additional salt stored during Period 4 discussed above (730,000 to 1,390,000 tonnes), represents an increase in the order of 5% to 9%.

Given that the estimate of the total mass of salt is most likely low, and the additional stored salt is more likely at the lower end of the 730,000 to 1390,000 range, it is considered that the percentage increase would be at the lower end of the 5% to 9% . However, more extensive data gathering and analysis would be required to provide a more robust estimation.

6.5 Other reaches - Euston to Murray Bridge

Analyses of other reaches, similar to that done for the high risk reaches, would assist detailed understanding of key processes in those reaches and help complete the overall picture. It is recommended that this work be undertaken in a subsequent project.

Part 4 – Floodplain Salt Conceptual Model

7 Floodplain Salt Conceptual Model

A draft Floodplain Salt Conceptual Model and its constituent elements is illustrated in Figure 7.1.

The conceptual model seeks to provide a comprehensive and definitive assembly of all of the inputs, pathways, processes, salt stores and destinations for salt in the floodplain as they are currently understood. There are regional, floodplain and river elements within the conceptual model.

The colour themes in Figure 7.1, which are carried through in Figures 7.2 and 7.3, provide detail of the sub-elements of each element. For instance, regional inputs is one of the regional elements within the Floodplain Salt Conceptual Model (Figure 7.1). Figure 7.2 illustrates that there are three sub-elements of the regional inputs eement: tributaries and upstream inflow, groundwater and irrigation+rainfall.

Figures 7.2 and 7.3 illustrate the potential interactions between the elements and highlight the inferred major interactions that occur in the Lock 5 to Morgan reach during the early inter-flood period. Each reach of the river and each part of the flood cycle, will have its own version of Figures 7.2 and 7.3.

This illustrates a fundamental constraint for this Project – the timing and importance of each component of the Floodplain Salt Conceptual Model varies significantly along the river and with river flow (or river elevation). The river has been subdivided into approximately 30 sub-reaches for this report. As will be discussed later, the river flow regimes can be divided into at least five flow categories and there are some 32 individual sub-elements to be considered in each reach and for each flow range.

This gives a total of nearly 5,000 individual sub-elements to be addressed for a relatively coarse subdivision of the floodplain into reaches. Of course, this number will reduce as reaches with similar characteristics are grouped together and process groups are identified, but the scale of the diversity needs to be appreciated to put this project in context.

This complexity and degree of interaction indicates why an overview of this sort has not been attempted previously and why this report is not a thorough statement of the sum of previous work. The complexity and interactions also make development of a unified predictive numerical model a challenging task.

Chapter 8 describes the regional elements, addressing the regional sources of salt to the floodplain and discusses how and why salt leaves the floodplain. Note that we use the word “floodplain” to mean the entire floodplain landscape: its surface, soils, surface water features and floodplain sediments.

Chapter 9 discusses the fate of salt in the floodplain during inter-flood periods: floodplain salt transport direct to river or to floodplain salt stores.

Chapter 10 discusses the mobilisation of stored floodplain salt. The range of process interactions should be similar in all reaches, however the dominant processes are expected to vary from reach to reach, perhaps widely. Also, the processes vary with timing (e.g. winter vs. summer, flood vs. inter-flood).

Chapter 11 discusses the timing of salt inputs to the river.

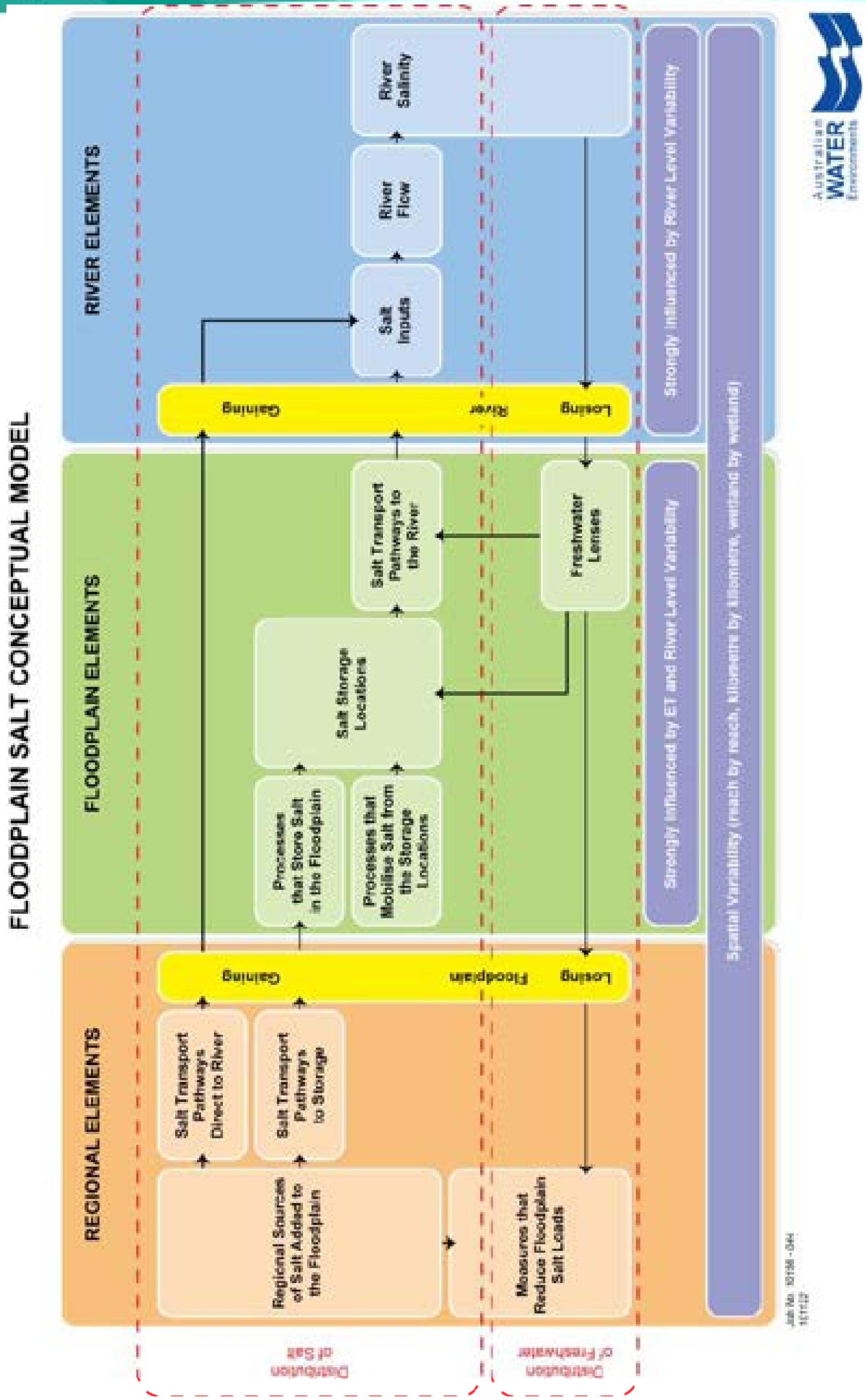
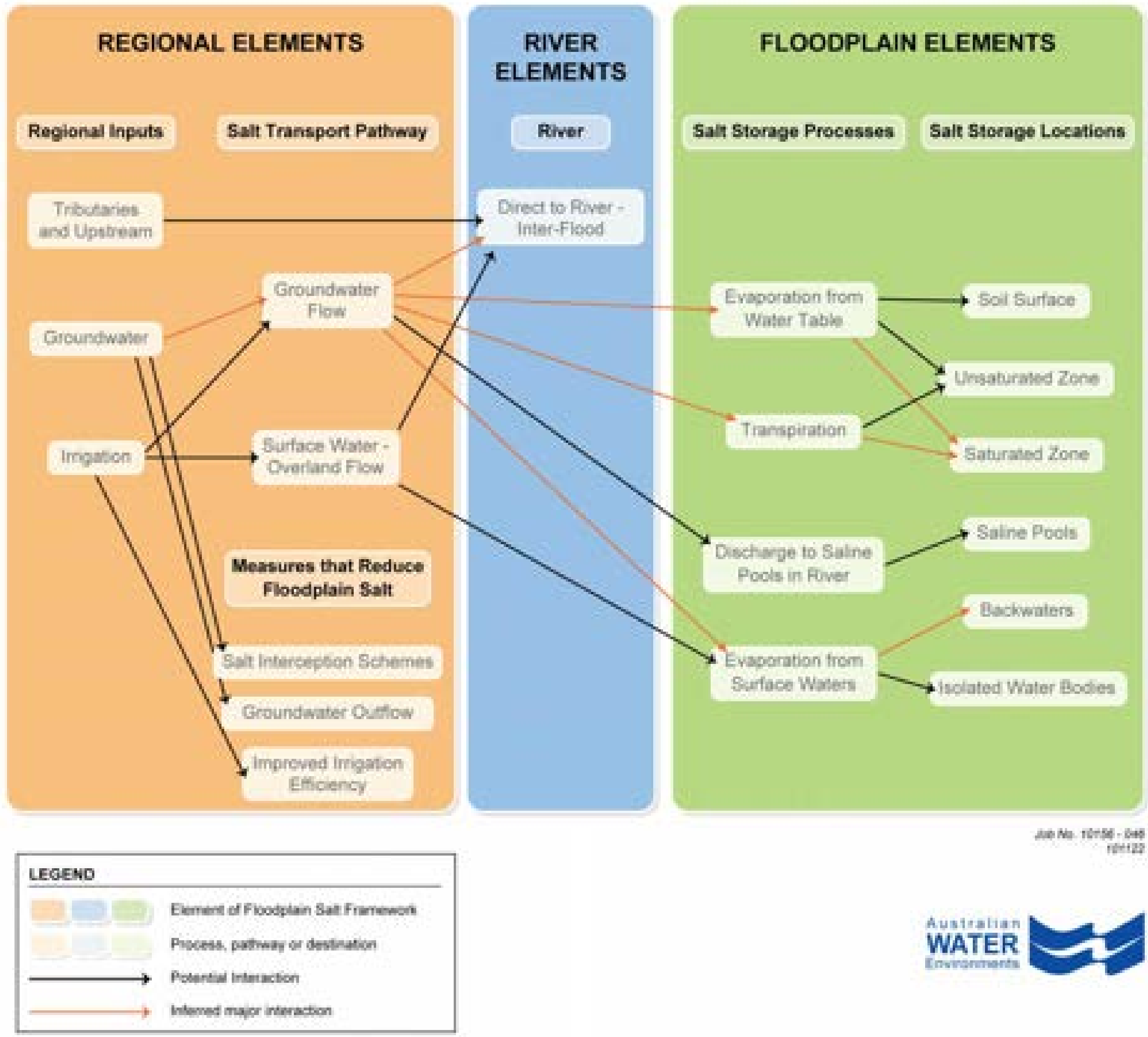
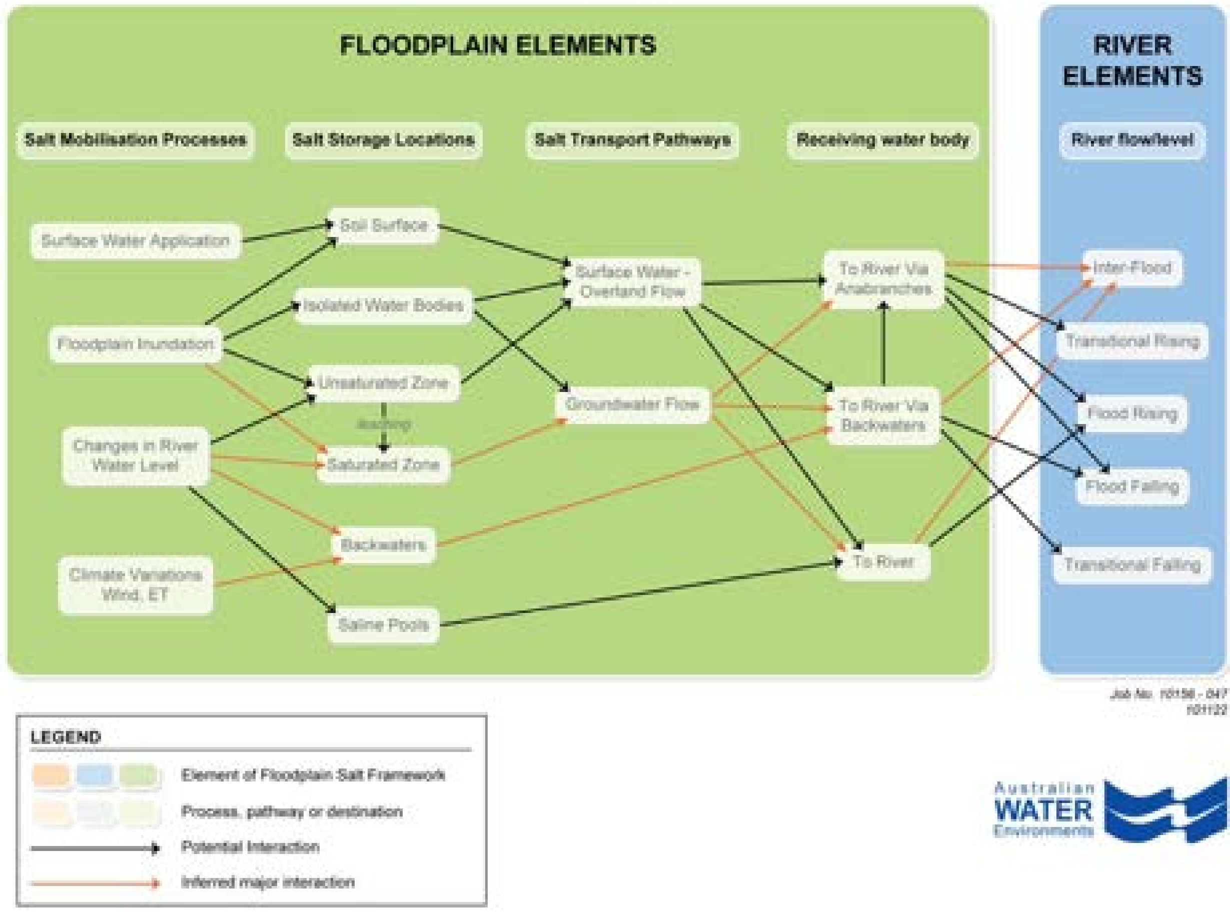


Figure 7.1: The Floodplain Salt Conceptual Model and its constituent elements



Note: Inferred major interactions will vary by reach and for each part of the flood cycle

Figure 7.2: Relationship between regional salt sources and floodplain salt storage locations



Note: Inferred major interactions will vary by reach and for each part of the flood cycle

Figure 7.3: Relationships between floodplain salt storage locations and salt inputs to the river

8 Sources of salt to the floodplain

The main regional sources of salt added to the floodplain and river are regional groundwater fluxes, irrigation and tributaries. A minor source is rainfall, which adds salt to the floodplain directly, as rain includes a small fraction of salt.

The salt from regional sources is transported into the floodplain via groundwater or surface water flows. The regional inputs either discharge direct to the river, or enter or pass through salt stores on the floodplain.

Salt leaves the floodplain via groundwater outflow from the floodplain (losing floodplain conditions) or to the River Murray, with a further amount removed by floodplain salt interception scheme bores.

Management measures which reduce the regional sources of salt to the floodplain include salt interception schemes and irrigation management improvements.

8.1 Regional groundwater flow and impact of irrigation

The regional groundwater heads represent the current head distribution and provide indications of the direction of flow, particularly in relation to the floodplain. The current pattern of groundwater flow into the floodplain is the sum of regional groundwater, rainfall recharge, irrigation drainage fluxes and flux from losing reaches of the river.

The regional groundwater salinity patterns are the culmination of groundwater processes over millennia, modified by irrigation and floodplain management actions over recent decades. Regional groundwater along the Lower River Murray is saline and it is the main source of salt to the floodplain. Appendix Figure A8 illustrates that the gaining floodplain reaches (see Appendix Figure A3 for boundaries) generally contain higher salinity water in the floodplain than in the losing floodplain reaches.

Irrigated areas near the River Murray may increase the regional groundwater flux to the floodplain sediments. Water is applied to the land surface. Evaporation and transpiration reduce the volume of irrigation water leaching past the root zone, and the salinity of recharge is thereby higher than the salinity of irrigation water. The irrigation drainage is of lower salinity than the regional groundwater and tends to form a lower salinity zone on top of the more saline “native” groundwater. The salinity of the groundwater discharge to the river and floodplain is a mix of the regional groundwater and irrigation drainage waters.

Where shallow water tables develop, some of the irrigation drainage may be captured in subsurface drains and transported to floodplain disposal basins or directed inland away from the floodplain to local or regional disposal basins. For example, subsurface drains at Berri discharge to the floodplain Berri Basin. Water from this basin can be pumped to the regional Noora Disposal Basin, or in the past was discharged to the river when river flow exceeded a threshold value. Berri Basin was held below pool level to reduce salt inputs to the river at low flows. Irrigation drainage salt discharging direct to river via major drainage schemes is included in the “Accounted Salt Loads” in BIGMOD where the flux has been measured or calculated.

All other drainage water percolates downward and joins rainfall inputs to eventually become recharge to the regional water table. In irrigation districts, the irrigation recharge builds mounds in the regional water table, increasing groundwater gradients and groundwater fluxes toward and away from the floodplain on either side of a groundwater mound in the regional aquifer. The flux away from the floodplain may return to the floodplain over long time frames (e.g. 10s to 100s of years), or may migrate under regional gradients away from the floodplain and not reach the floodplain for 100s to tens of thousands of years (Collingham & Forward 2005).

Examination of Appendix Figure A8 suggests that the reaches with most risk of adding salt to the river are the gaining floodplain reaches that are not protected by SIS and still exhibit low resistivity NanoTEM signals. Key reaches are Mallee Cliffs to Red Cliffs, between Lock 5 and Berri at Pike (partially under construction), and Loxton to Lock 3.

8.2 Removal of regional salt from the floodplain

Through-flow and losing floodplains continually lose salt from the floodplain through its migration into the regional groundwater system on the down-gradient side of the through-flow or losing floodplain. These discharge processes will tend to counterbalance the salt accumulating processes discussed in later sections.

Salt also leaves the floodplain via the River Murray. The quantification of this under various conditions is the subject of this report.

Salt is also removed from floodplain groundwater via the small number of SIS bores which pump directly from floodplain aquifers. Most SIS bores pump from regional aquifers. Appendix Figure A3 illustrates that SISs have been or are being implemented in gaining floodplain areas. The low resistivity NanoTEM riverbed resistivity locations (Appendix Figure A8) indicate where saline groundwater occurs in the river bed sediments and the risk of salt inflow during inter- flood periods is highest.

8.3 Management measures which reduce salt movement into the floodplain

Salt interception schemes are constructed to capture saline groundwater discharging to the river. The locations of the currently active SISs in the study area are shown in Appendix Figure A4. The saline groundwater is pumped to regional disposal basins, reducing and delaying the salt load to river. The SISs currently prevent over 1200 t/d from reaching the river (MDBA 2009b).

Improved irrigation management practices can reduce the volume of irrigation drainage. This reduces the volume of subsurface drainage discharging to the floodplain and the volume of recharge to the water table. Both activities reduce the salt load to the floodplain.

9 Fate of salt in inter-flood periods

Previous chapters demonstrate that salinity exceedances mostly occur at flows <5,000ML/d – that is, during the inter-flood period. Therefore, the processes that deliver salt to the river during inter-flood periods are important in assessing salinity exceedances.

The Floodplain Salt Conceptual Model (Figure 7.1) discriminates between salt transported “Direct to the River”, and salt that undergoes storage and mobilisation before reaching the river. The processes and pathways of salt transport direct to the river are discussed below, followed by discussion of the salt storage mechanisms and locations.

9.1 Salt transport direct to the river or anabranches

9.1.1 Tributary inputs and upstream inputs

Salt from upstream and tributary inputs (e.g. Darling River and Darling Anabranch) is transported direct to the river. Inspection of the Morgan salinity hydrograph (Figure 4.1) shows that the salinity target at Morgan is exceeded most often during low river flows, so tributary inputs have not been the driver of the timing of salinity exceedances at Morgan, although the salt introduced in the tributary inflows may contribute to the exceedances. The rate of salt inputs from surface waters may change from day to day and may have significant local effects on river salinity, however the river salinity impacts from these sources do not appear to be a major or even a modest contributor to the timing of salinity exceedances at Morgan.

Analysis of the record to identify and analyse the effects of individual tributary inflows has not been undertaken in this study due to scope and time constraints. Additional work in this area would be useful to demonstrate the effects of inputs from tributaries and hence calculate the relative risk ranking for the tributaries (e.g. Darling, Murrumbidgee, Edwards/Wakool, Barr Creek, Loddon, etc).

9.1.2 Anabranches

Major anabranches which circumvent a Lock have a head differential available to drive significant flows, even at times of very low flows in the river. Flow through some of these anabranches is considerable; the Chowilla anabranch often has a flow greater than the main river channel. Anabranches with upstream and downstream openings in the same weir pool may have low through-flow rates.

Some evaporative losses will occur from the anabranches, however the rate will not be substantially different to the rate of evaporation from the river itself.

An anabranch can be a focus of regional or local groundwater discharge where the anabranch circumvents a Lock and intrudes into the regional groundwater flow field (e.g. Chowilla Creek, Lindsay River). The section of the anabranch upstream of the Lock is most at risk from groundwater inflows because the anabranch has lower water levels than the upstream pool in the river. This provides a preferential zone for groundwater discharge. This effect has been observed for instance in the Chowilla anabranch in the Murtho model (AWE 2010c).

Salt loads may come from groundwater inputs, and the salinity may increase due to evaporative concentration. Anabranches will tend to flush on the rising limb of a flood.

9.1.3 Groundwater flow direct to river

Figure 7.2 illustrates that groundwater flow is thought to be the dominant transport process delivering salt direct to the river or its connected surface waters.

The patterns of groundwater discharge to the river are strongly influenced by whether the floodplain is gaining, through-flow or losing. Salt transport direct to the river from groundwater tends to occur where regional groundwater gradients are strongest, where the floodplain is narrow, and where the floodplain groundwater salinity is high. Appendix Figure A8 combines the regional flow directions and salinity data. It indicates the relative risk from direct salt input from groundwater to the river.

Salt interception schemes tend to be located where in-stream salinity data from Run of River and in-stream continuous salinity stations indicate that the direct groundwater salt inputs add approximately two or more tonnes of salt per day per kilometre of river. The in-stream NanoTEM data (Figures 3.3 and A8) illustrate the areas where the in-river salt loads are currently anticipated to exceed 2 t/d/km:

- The Sunraysia reach, from Colignan to Merbein, contains SIS that currently intercept saline groundwater and there remain small lengths of river where salt loads >2 t/ d/km are implicated from the low (<3 ohm-m) riverbed resistivity results.
- Similarly, the South Australian Riverland region, from Lock 6 to Morgan, contains SIS and remnant low riverbed resistivity reaches indicating saline inflows.
- Note that the Murtho and Pike SIS are being constructed in the Lock 6 to Lock 5, and Lock 5 to Berri reaches currently. These are expected to reduce the length of low resistivity in these reaches over the coming years.

Note that in these figures, where SISs have been constructed the NanoTEM shows the present lower groundwater salt input into the river.

In both the Sunraysia reach and the SA Riverland, the areas identified as high risk occur where the regional data indicate gaining floodplain conditions occur (Appendix Figure A3).

The groundwater flow direction and flux rate can change over short distances. For instance, where NanoTEM triple runs have been conducted to measure the resistivity near each bank and in the middle of the river, the results indicate that the river can be gaining on one side and losing on the other. At Bookpurnong and elsewhere, the river close to the irrigation area is gaining and the bends further away are losing. These trends are confirmed from riverbed sediment coring data (Tan *et al*. 2006; Berens *et al* 2007) and Run of River and Close-Spaced EC survey results (Barry Porter, SA Water, pers. comm.).

The magnitude of the groundwater salt loads discharging direct to the river will change with river stage.

Tributary and surface water inputs, and even direct groundwater inputs, may have significant local effects on in-river salinity. These local effects have not been investigated due to project constraints. Evapotranspiration from the floodplain produces an annual cycle of groundwater levels that are generally observed to be lowest prior to winter and peak after winter (e.g. see floodplain hydrographs for the Murtho and Chowilla reaches in AWE 2010c). The lower groundwater levels would reduce groundwater gradients to the river and resultant salt inflows during summer – conversely the direct groundwater inflows in winter can be expected to be larger than the summer inflows in inter-flood gaining river reaches.

9.2 Salt transport to floodplain storages

Some of the salt entering the floodplain does not discharge directly to the river. The high net evaporation rate in the Lower River Murray region causes salt to be stored in the floodplain. The salt may be stored on the soil surface, in the unsaturated zone, in the saturated zone, in backwaters, and in disconnected surface water bodies (Figure 7.2). A transitory salt storage process and location occurs where direct groundwater discharge leads to the formation of saline pools of groundwater in deep holes in the river.

9.2.1 Evaporative salt storage processes and rates

Regional groundwater can be diminished in volume in transit through the floodplain by evaporation through the soil, transpiration by vegetation where the floodplain aquifer salinity is low (e.g. near losing river reaches) and evaporation from open water.

These losses reduce the flux available for discharge to the river. The water will be lost to the atmosphere from the unsaturated zone and from surface water bodies while the salt remains within the landscape.

The impact of evapotranspiration on floodplain processes depends on whether the floodplain is a gaining, through-flow or losing type. In gaining floodplain reaches, gaining stream conditions will occur where groundwater inputs and recharge are greater than the evapotranspiration losses, and losing stream conditions will occur where groundwater inputs and recharge are less than the evapotranspiration losses. In through-flow floodplains the river will tend to be losing as a result of the regional gradient and evapotranspiration losses, unless a floodplain storage held above river level is causing within-floodplain local flow systems, creating flux from the ponded storage to the river. In losing floodplains, the river will also be losing. Evapotranspiration may increase the rate of loss.

Gaining floodplains are anticipated to concentrate salt more than the through-flow or losing floodplains because the other floodplain types have a component of regional groundwater flux advecting the salt out of the river valley and into the down-gradient regional groundwater system.

The potential evapotranspiration rate of the study area is between 1500 and 2500mm (BOM 2001). The actual evapotranspiration rates required to account for the estimated net groundwater losses from the floodplain through evapotranspiration processes is surprisingly small – calculations using groundwater model data at Murtho (AWE 2010c) and Chowilla (Yan *et al*. 2005) indicate that losses need only be 10 to 25 mm/annum. Vegetation transpiration rates from groundwater have been estimated at 1.0 to 2.0 mm/d for redgum and 0.1 to 0.3 mm/d for blackbox (Jolly 2004). The rate of evaporation from surface waters is expected to be toward the upper limit of the range because the water bodies are a small part of the landscape.

9.2.2 Salt storage locations and mass

9.2.2.1 Indicative size of salt stores

For illustration purposes, the following simple calculations are presented. The estimates are based on the Murtho solute transport model input data and output data (AWE 2010c).The values should be viewed as unverified estimates only, however they do serve to illustrate the relative orders of magnitude of salt in each of the stores. The unsaturated zone salt storage calculations are particularly uncertain, as effective porosity is used in calculations. Use of total porosity will increase the salt mass by perhaps a factor of ten.

The estimates of salt store in the Murtho floodplain, between Lock 6 and Lock 5 are:

- Saturated zone salt mass of 12.8 million tonnes of salt, assuming modelled floodplain thickness and salinity (approximately 30,000 mg/L) and a porosity of 15%, area of 31,500 ha This equates to 406 t/ha.
- Unsaturated zone salt mass of 0.9 million tonnes of salt, assuming an effective porosity of the Coonambidgal silty clays of 5%, volume calculations of the unsaturated zone calculated using the model input of LiDAR based surface elevations per cell and modelled depth to watertable, and assuming the unsaturated zone salinity equals the underlying saturated zone salinity. This equates to 28 t/ha, which is within the range of the 43.2±19.1 t/ha calculated from Chowilla floodplain soils by Jolly (1994).
- Backwater salt mass of 0.0014 million tonnes of salt, using backwater and anabranch area and bed elevation data, and assuming a salinity of 1000 mg/L based on measured backwater salinity data (SKM 2004).

These preliminary calculations indicate the largest mass of salt is stored within the saturated zone. It seems likely that the total mass of salt stored in the floodplain may correlate with the Floodplain Classification (Figure 2.1) i.e. a higher salt mass stored in the gaining floodplains than in the through-flow and losing floodplains.

9.2.2.2 Soil surface

Salt may be stored on the soil surface, however, surface salt (e.g. salt efflorescence) is not common on the floodplain. Salt efflorescence would be derived from evaporation processes (not evapotranspiration) from shallow water tables. Surface soils can be "fluffy" (indicative of soil structures modified by crystal growth) and taste saline, however in our experience this is the exception rather than the norm.

9.2.2.3 Unsaturated zone

Jolly (2004) discusses salt accumulation in the unsaturated zone, however empirical evidence of salt mass increasing during drought or decreasing after floods does not appear to be available. The WINDS and WAVES models (Overton *et al* 1997; Slavich *et al* 1996; Overton & Jolly 2004) are able to replicate current estimates of salt mass in the unsaturated zone, although the need to assume boundary condition values for unknown boundary conditions, and the wide range of input parameters and parameter values, suggest that the model outcomes may not be unique.

Sensitivity analysis of the current models, replicated measurements pre- and post-flood and pre- and post-drought, and consideration of alternate salt storage and release mechanisms in the unsaturated zone is suggested. Weisbrod and Dragilla (2006) provide interesting alternate insights into alternate potential salt storage and release processes. (Chapter 2)

The various AEM surveys have undertaken assessments of the quantum of salt stored in the unsaturated zone. These results may provide additional insight into the distribution of salt and the pattern of salt storage indicated by that data should be examined for correlations with regional groundwater and floodplain processes.

9.2.2.4 Saturated zone

Floodplain salinities are variable reflecting the highly variable nature of key influencing factors; evapotranspiration, overbank flow recharge, groundwater fluxes and the complex variability of the hydrogeological properties of the floodplain sediments. The volume and residence times of both saturated and unsaturated zone salt stores are also key factors influencing salinity. The residence time in the saturated and unsaturated zones is influenced by over bank flooding and the resultant recharge to the floodplain aquifers and by bank storage from the river and anabranches. The ratio of evapotranspiration to groundwater flow plus recharge will influence the degree of concentration of salt in the unsaturated zone. Additional work to correlate the AEM data with point source salinity data will improve confidence in the AEM dataset and hence increase its usefulness as an analysis and diagnostic tool.

9.2.2.5 Backwaters and anabranches

The salt mass in backwaters is sourced from evaporative concentration of river water (particularly in summer) and sometimes from groundwater inputs. The Gurra Gurra (aka Salt Creek) system opposite Berri reaches salinities up to 7,500 EC (AWE 2001) and Lake Bonney at Barmera reached 12,800 EC in 2008 (PB & AWE 2010). Evaporative concentration accounts for 35% to 70% of the salt increase in the Gurra Gurra system (AWE 2001; REM 2002).

Figure 9.1 combines the data presented in Figure 3.5 and Table 3.5, and shows the incremental area inundated for specific flow bands per reach, and the area inundated by specific types of surface water bodies per reach. Each colour band indicates the area inundated by a given flow range (positive values) or by surface water types (negative values). The surface water areas are shown as negative values to assist in graphical presentation of the data. The Lock 5 to Morgan reach has been identified as having a high risk of salt inputs (Chapter 6) and Figure 9.1 illustrates that this reach also has a large area of backwaters. The mass of salt stored in backwaters, the timing and rate of storage, and the management of these salt stores has not been systematically examined in this reach to our knowledge. Individual wetland water balances have been conducted (e.g. Gurra Gurra (AWE 2001) Lake Bonney (PPK 1999), Ramco Lagoon (AWE 2000)) but that work has not been compiled or reviewed to identify a consistent methodology for assessment. Groundwater models have not routinely included the connected backwaters, and solute transport modelling of the groundwaters and surface waters has not been undertaken except for parts of the Murtho area.

As will be discussed in Section 10.3, the backwaters are implicated as the source of considerable salt inputs. In addition, it seems likely that interconnected surface-groundwater modelling of flux and solute transport would provide useful insights into the wetland areas at high risk from groundwater accumulation, particularly in the Lock 5 to Morgan reaches.

9.2.2.6 Disconnected surface waters

Disconnected water bodies are another storage site for salt. They include floodplain disposal basins (e.g. Disher Creek) or wetlands or swamps that are filled during floodplain inundation but do not drain fully on the flood recession (e.g. Hattah Lakes, Coombool Swamp – Chowilla). These bodies will empty in response to evaporation and seepage. Residual pools in disconnected backwaters at Bookpurnong (current authors) and opposite Bottle Bend (John Cooke, Vic Dept. Sust. Envir., pers. comm.. 2009) have been observed to contain crystallised salt. At all of these locations, groundwater inputs were the dominant salt source.

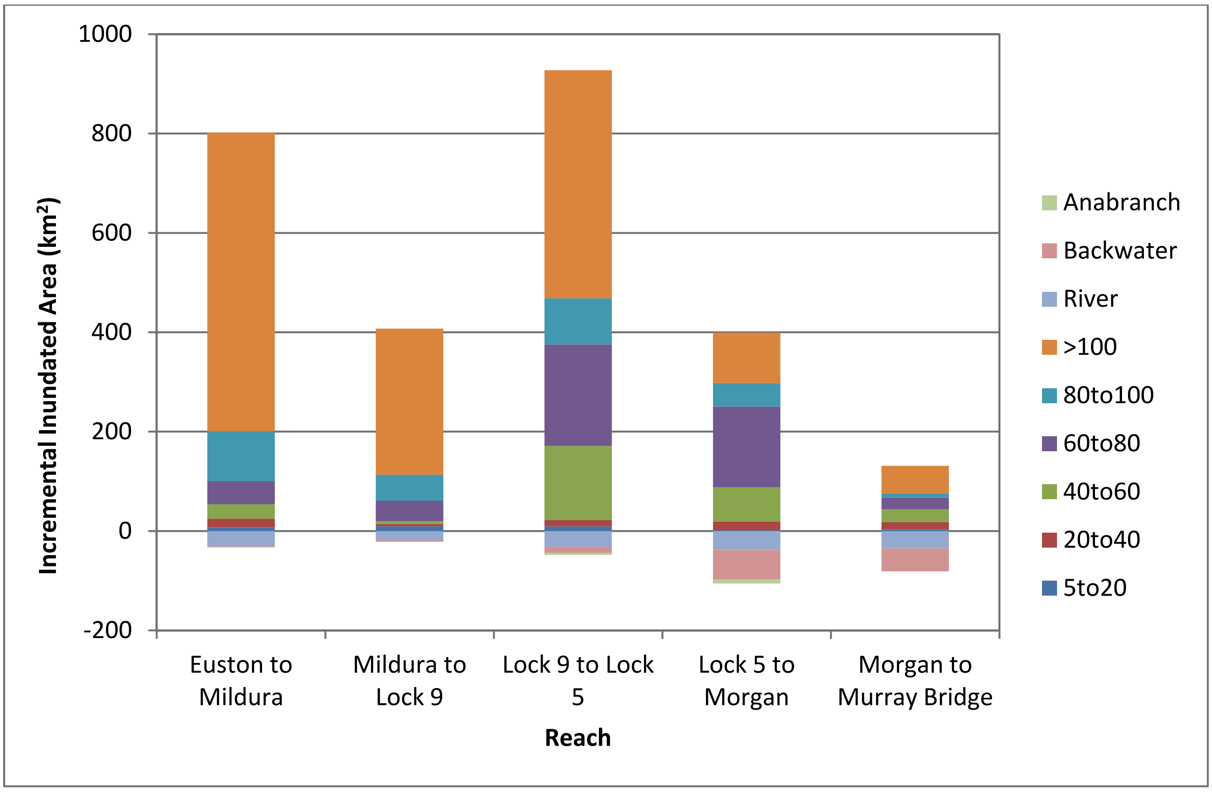


Figure 9.1: Major reaches - incremental inundated area by major reach for key flow ranges with surface water bodies

9.2.2.7 Saline pools

Finally, saline pools within the river or anabranches may store salt. Saline groundwater discharge to the river or an anabranch will preferentially be attracted to the deepest parts of the river because the density difference between saline groundwater and river water (Telfer 1989). This process has been noted at Woolpunda (Telfer 1989), in the Wimmera River (Anderson & Morison 1989), in the Lindsay-Wallpolla anabranch (Dudding 1992), and in the Edward–Wakool system (Green 2001). The salt mass is thought to be small compared to the total salt mass stored in the floodplain, however high flow events can generate significant local salinity spikes downstream of the source (Dudding 1992; Green 2001).

10 Mobilisation of stored floodplain salt

We now consider the mobilisation of stored floodplain salt in the Floodplain Salt Conceptual Model (Figure 7.1).

The processes, sources, pathways and receiving waters relating to floodplain salt mobilisation are illustrated in Figure 7.3, and are discussed below. Figure 7.3 illustrates, for the processes and pathways identified to date in the study area, those thought to be dominant in the Lock 5 to Morgan reach during the early part of an inter-flood period.

Salt mobilisation processes discussed in this Chapter include: floodplain surface water application by rainfall or irrigation, floodplain inundation by overbank flows, changes in water level in the river and connected water bodies, changes in wind direction, and strength and changes in evapotranspiration rates.

These processes variously mobilise salt from the salt stores discussed in Chapter 9. The salt mobilised from the salt stores is transported to the connected surface waters via surface water or groundwater. The timing and rate of discharge is influenced by the antecedent and current river flow or stage. The anticipated timing of the activation of processes is illustrated in Figure 11.1.

10.1 Surface salt

Salt can be mobilised from the soil surface when rainfall or floodplain inundation occurs. Salt can also be entrained with eroded soils. Irrigation can theoretically mobilise surface salt into surface waters but it would be a poor irrigation practice that resulted in surface salt in the irrigation area, so this is not considered further. Irrigation mobilisation of salt in the unsaturated zone and the saturated zone is discussed in later sections.

Any salt derived from surface salt wash-off during floodplain inundation will occur either on the rising limb of floods as the first overbank flows return to the river, or on the recession as the floodwaters recede. These inputs mostly occur during times of high river flows, so we expect that the salt inputs do not have a significant impact on in-river salinity.

The quantum of salt exported from surface wash-off has been calculated at between 80 and 360 t/d during floods across Lindsey Island (Dudding 1992). Other workers have assumed the rate of export from soils is assumed to be low (Jolly 2004, AWE & URS 2007). Additional work may be required in this area. Separating the surface salt loads during a flood or at the very end of the flood recession from the inputs from backwaters and groundwater may be difficult.

10.2 Isolated surface water bodies

Salt in isolated water bodies will tend to be mobilised by surface waters only during floods. By definition, the isolated water bodies are disconnected from the surface water system during inter-flood periods, therefore salt inputs from these sources will not be transported in surface waters during the inter-flood period. Salt inputs from isolated surface water bodies to the river do not appear to pose a risk to salinity exceedance targets at Morgan because the inputs occur during floods.

Isolated water bodies also mobilise salt via their impact on groundwater levels following flood recessions. For example, leakage from the isolated Coombool Swamp is discussed in Section 6.3.3.

10.3 Backwaters

Salt in backwaters can be mobilised by four processes: large changes in river level during floods, small changes in river level during inter-flood periods, Evapotranspiration variations and changes in wind direction.

10.3.1 River level changes during floods

The water level in a backwater will tend to follow the river stage at the connection point. For backwaters with good connection to the river, the major proportion of the backwater drainage and salt load input to the river should occur within the flood recession and should persist for only a short period after the river level has stabilised.

Some backwaters are not well connected to the river (e.g. Lake Bonney is a large water body with a narrow connection to the river). Basic hydraulic principles suggest that the backwater water level may lag the river level by a few hours to a few days when the connection to the river is constricted. To our knowledge, the lag times for backwaters has not been calculated.

Backwaters can have an upstream inlet that allows floodwaters to enter the backwater once flows exceed the "commence-to-flow" threshold (e.g. Salt Creek at Bookpurnong). At this point the through-flow of floodwaters will tend to mobilise the salt through and out of the erstwhile backwater, delivering the stored salt into the flood flows. This process adds to total salt export but given the salt loads are introduced into high river flows, the salinity impacts are small.

The analysis of BIGMOD outputs in the preceding sections shows repeated evidence of salt recessions lasting less than 15 days in the Lock 5 to Morgan reach (Figure 6.15). In the 15 day period, some 2,000 to 10,000 tonnes of salt is added to the river per day. The Lock 5 to Morgan reach contains the largest area of backwaters in the study area and this short duration, high salt load recession can be conceptualised as being caused by these backwaters draining into the river on the flood recession. A simple calculation[1] suggests that the salinity of the backwaters needs only be 2,300 mg/L higher than the river water salinity to generate this salt load. This suggests that the mechanism is plausible.

However, additional work is required to test the assumptions and better quantify the process. A survey of backwater depth and salinity is required if the above calculations are to be checked and backwater hydrodynamic modelling may also be required to evaluate the rate and timing of discharge from backwaters on flood recession. The backwater sill cross-sectional area will also affect the rate of discharge from the backwater.

It is possible that some unknown groundwater discharge process is contributing to this short duration high salt input response. However, groundwater models of the Murtho area show groundwater responses peak on flood recession and asymptote toward pre-flood salt loads over many months (AWE 2010c), not the 15 days clearly evidenced in the unaccounted salt load data (Figure 6.15). This unknown process could possibly be related to hydraulic loading effects – a rapid reduction in river stage will reduce the weight of water on the floodplain and the groundwater system may discharge rapidly but for a short time via a pressure release process.

Further work is warranted given the magnitude of the salt load, although it is noted that even with additional data it may still prove difficult to discriminate between the inputs from backwaters and groundwater.

10.3.2 Small changes in river level during inter-flood periods

In the inter-flood periods and particularly during flows less than 5,000 ML/d, small declines in river level associated with small changes in flow can be conceptualised as dragging salt into the river from the backwaters (or from groundwater, which is discussed later). This effect has been noted in the Run of River surveys in 2004 (Barry Porter, Dept for Water, pers. comm.), where a small change in flow in the July run caused significant anomalous salt loads in the Woolpunda to Waikerie reach. The survey was repeated in the

[1] The area of backwaters in this reach is approximately 35 km^2 (excluding Lake Bonney because it is an accounted salt inflow) and assuming a pre-flood average water depth in the backwaters of 0.75m gives a total backwater volume of 26.25 GL. Assuming that the average salinity increase over the 15 days is 4,000 t/d (i.e. 60,000 t over the 15 days), then the salinity of the backwaters (i.e. mass of salt added to the River divided by the volume of the backwaters) has to average 2,286 mg/L more than the River water. This calculation does not take into account the loss of salt from the backwaters during the flood when they convert to anabranches, which means that the pre-flood backwater salinity would need to be higher than the calculation indicates.

following months when the river stage was held stable during the survey. The results from the second survey were lower than from the first.

Seasonal changes in river flow will have small effects on river stage and some cyclic salt input patterns may result.

Additional work is required to identify the sources and processes controlling the discharge of salt during small changes in river level during inter-flood periods. The records from individual continuous EC recording stations can be used to isolate the relative contributions of salt from backwaters in the inter-flood periods at a reach scale. This work will help identify the reaches where backwaters pose a significant salinity risk.

10.3.3 Evapotranspiration variations

Salt in backwaters and wetlands can also be mobilised by changes in groundwater levels driven by evapotranspiration.

The analysis of BIGMOD unaccounted salt loads (Section 6.4.2), and the analysis of Ramco Lagoon in AWE (2000) suggests that evapotranspiration variations can have a strong effect on in-river salt loads during inter-flood periods. In the Lock 5 to Morgan reach, rhythmic salt load input fluctuations of between 200 and 400 tonnes per day are observed, consistent with summer accumulation and winter discharge of salt from the backwaters. The annual variation would be expected to be more pronounced in the upstream reach (Lock 5 to Lock 3) because it has a significantly higher area of wetlands than the downstream reach. (i.e. the Lock 5 to Lock 3 reach has 61.6 km^2 of wetland compared to 10.2 km^2 in the Lock 3 to Morgan reach).

These variations, given they can occur in inter-flood periods, can have a significant impact on the winter salinity peaks when flows are low in winter.

While an evaporative driver of salt input processes has been demonstrated at Ramco Lagoon, it is noted that the rhythmic salt inflow patterns discussed in this section could also be attributed to changes in stage due to seasonal variations in river flow.

10.4 Wind

At any given water level in a backwater, wind effects will influence the interaction between the river and the backwater. For instance, it is conceivable that persistent south-westerly winds will facilitate surface water and salt export from the lagoons upstream of Lock 3, where the outlets are on the north-eastern side of the backwaters. This effect has not been quantified, but is assumed to occur on occasion. The process may have little impact on inter-flood salinity at Morgan, although impacts immediately downstream of the backwater mouth may be significant.

10.5 Saline pools

Saline pools in deep holes in the river can be partially or completely scoured under more turbulent higher flows. This process has been noted at Woolpunda (Telfer 1989), in the Wimmera River (Anderson & Morison 1989), in the Lindsay-Wallpolla anabranch (Dudding 1992), and in the Edward– Wakool system (Green 2001). The salt mass mobilised is thought to be small compared to the total salt mass stored in the floodplain, however high flow events can generate significant local salinity spikes downstream of the source (Dudding 1992; Green 2001).

10.6 Unsaturated zone

Mobilisation of salt from the unsaturated zone has not been the subject of any significant field investigation. In fact, it is not clear that there is significant accumulation or release of salt from the unsaturated zone in response to climatic variations. One interesting observation is that the soil salt mass in storage appears to be correlated with the underlying groundwater salinity (Jolly 2004).

Weisbrod and Dragila (2006) have conducted a range of experiments in fractured chalks and have found that the rates of salt transport vertically, and the rates of evaporation from the unsaturated zones, are both enhanced in the presence of fractures in the unsaturated zone. The implications of this work should be examined in the context of the River Murray Floodplains.

Models such as ENSYM estimate salt movement in the root zone but it is not clear to us whether these results have been field tested. Such models require parameters which may be difficult to estimate on a wide scale. A verified range of salt accumulation and release conceptualisations will be a valuable contribution to understanding and quantifying salt processes in the floodplain. It may also provide inputs to the management of vegetation.

It seems unlikely that salt will be transported laterally through the unsaturated zone. Salt mobilisation is more likely to occur once it is brought to the soil surface, or leached downward into the groundwater. Rates and mechanisms for salt transport from the unsaturated to the saturated zone need to be developed and quantified.

10.7 Saturated zone salt mobilisation

The saturated zone is the largest store of salt in the Murtho floodplain, and it is relatively mobile.

This section discusses the groundwater-river interactions as simply as possible – however the direction (into or out of the river) and flux rate will change in any one square metre of riverbed in response to regional input trends, season (evapotranspiration and rainfall) and river stage.

The timing and shape of the flux components illustrated in Figure 10.1 are based on detailed modelling of the Murtho floodplain (Lock 6 to Lock 5) during the benchmark sequence of floods (AWE 2010c). In inter-flood periods, groundwater flux to the river occurs (by definition) in gaining reaches of the river – this flux is the direct groundwater discharge to the river. In losing reaches of the river, losses from the river to bank storage occur. Following flood recession, flux returns to river are the summation of three processes:

- release of suppressed direct groundwater discharge inflows (i.e. “backed up” regional flux)
- floodplain inundation promoting recharge to groundwater and groundwater discharge to River
- displacement of bank storage back into the river (i.e. flux from the river moving into groundwater and back again).

The emplacement and displacement of bank storage is discussed later in this Chapter, along with the continuous bank storage outflows illustrated in Figure 10.1 and a more general discussion of freshwater lenses. Direct discharge to the river in inter-flood periods is discussed in Section 9.1.

The Murtho groundwater model results illustrated in Figure 10.1 indicate that at Murtho, with a wide floodplain, the groundwater recession lasts for around 12 months.

Figure 10.1 illustrates the direction and magnitude of groundwater fluxes during an inter-flood and flood sequence. The upper figure shows both modelled discharge to the river from the aquifer and the modelled recharge to the aquifer from the river over time. The lower figure shows the actual and modelled river levels. The Murtho model example demonstrates that both gaining and losing stream fluxes occur within a given reach at the same time. The relative proportions of gaining and losing stream components will vary along the river in broad correlation with the balance between gaining and losing reaches of floodplain. For example, in losing floodplain reaches the direct groundwater discharge to river component in Figure 10.1 can be expected to be zero.

At present it is not possible to unpack the contributions of the three processes to the total salt loads from field data alone, although it can be modelled.

The salinity of the three groundwater recession flux components is likely to vary systematically:

- the suppressed direct discharge will be largely saline
- the bank storage release will be largely fresh but will also be partially mixed with saline groundwater
- the floodplain inundation returns will vary spatially according to the near-river salinity distribution and the volume of salt stored on the surface and in the unsaturated zone.

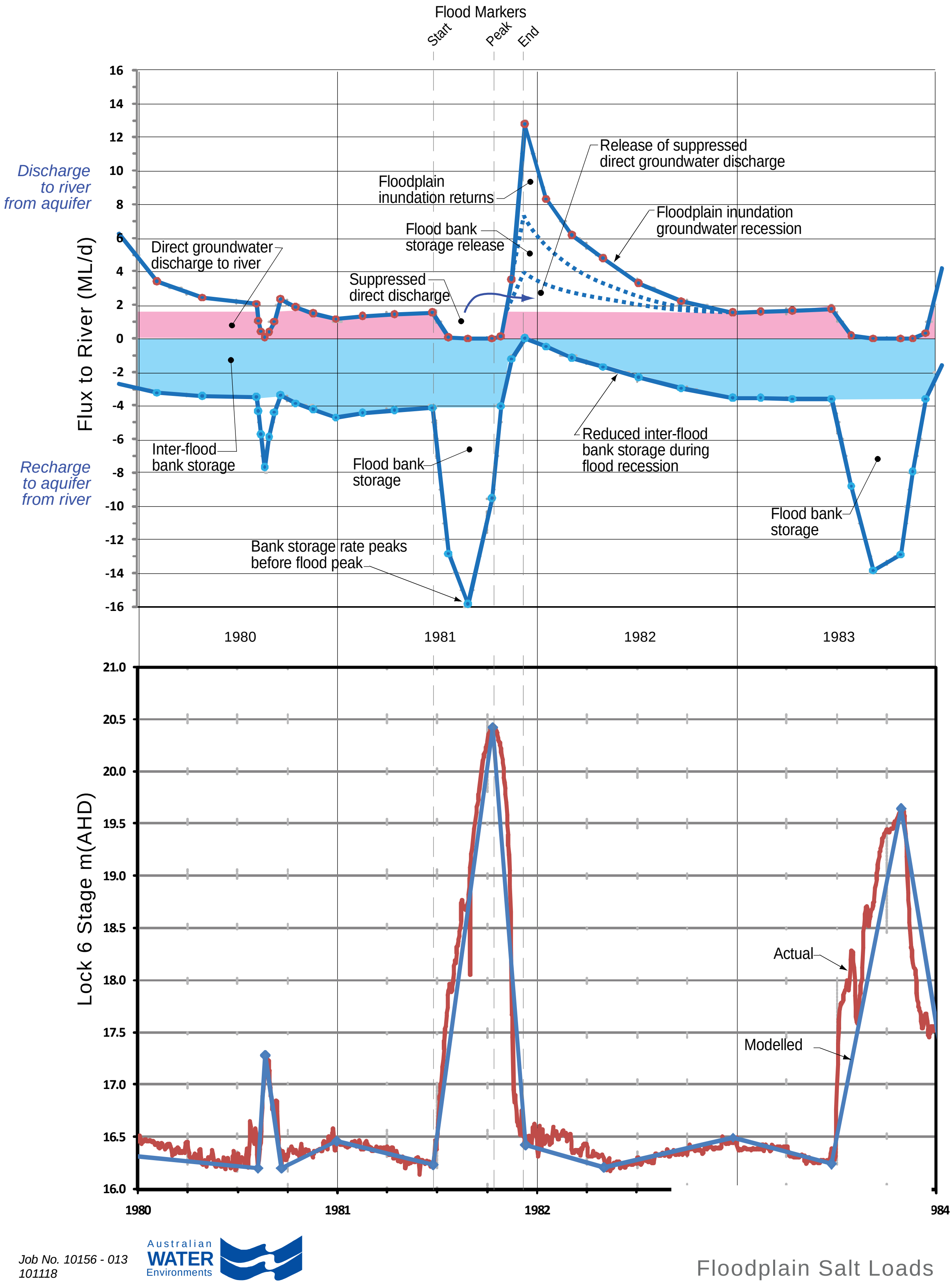


Figure 10.1: Modelled groundwater inflows and outflows during the 1982 Flood illustrating key components of saturated zone salt mobilisation

10.7.1 Suppression and release of direct groundwater discharge during floods

The Murtho model results (Figure 10.1) present the sum of all groundwater fluxes to and from the river in the Lock 6 to Lock 5 reach. The model results show that there is flux to and from the river at the same time, although the flux to and from the river is not happening at the same location — rather, some reaches of the river are gaining and some reaches are losing water. The reaches gaining water are those close to the regional direct groundwater inflow to the floodplain and the reaches that are losing water are generally distant from the floodplain edge. The losing reaches are caused by evaporation from the floodplain, which depresses the groundwater head in the floodplain to below river level.

This section discusses the flux to river (the red component in Figure 10.1). These fluxes affect river salt loads and salinity. The losses from the river to the floodplain are discussed in Section 10.6.3 - the losses do not have a direct effect on river salinity but do have an indirect effect.

10.7.1.1 Suppression

The model results illustrate that direct groundwater discharge to the river and connected surface water bodies is suppressed as river levels rise, because the rise in river stage will reduce the gradient from the aquifer to the river and hence reduce the flux to river. The suppressed discharge causes rises in groundwater levels in the highland aquifer (e.g. Woolpunda) and the floodplain.

AWE (2009) demonstrates, using numerical simulation of a typical strip through the Qualco floodplain that heads in the floodplain respond to inputs through the river bank recharge from floodplain inundation and from regional groundwater inputs. The relative contributions from these three sources are dependent on the regional flux, the river-aquifer head difference, the riverbed/bank conductance and the floodplain vertical hydraulic conductivity.

In the model results presented in Figure 10.1, the direct discharge to river is fully suppressed during the flood. However, where groundwater gradients are strong (e.g. downstream of Lock 4 at Bookpurnong) and if changes in river level are relatively minor the suppression can be conceptualised as being less than complete or maybe even minor because of the steepness of the groundwater hydraulic gradient.

10.7.1.2 Release

The Murtho model results (Figure 10.1) show that the regional discharge recommences during the falling limb of the flood, as the head in the river falls and the gradients, and hence flux, toward the river increase.

The groundwater flux to the river following the flood has been compartmentalised in Figure 10.1 to illustrate a notional arrangement – however the reality is that a range of factors contribute to the accumulation of water in the groundwater systems and to the release of the water to the river following the flood. The exact timing of the release of any one component is a rather theoretical consideration, because the flux is driven by gradients and not the source.

The salinity of the released regional discharge water can be conceptualised as approximately the same as the inter-flood direct groundwater discharge salinity although it will be partially mixed with bank storage water. This component of the groundwater recession will contribute to river salt loads and salinity. The impact on salinity will depend on the river flow into which the groundwater is discharging, as well as on the groundwater salinity itself.

The location of the suppressed discharge release will be roughly coincident with the location of the direct groundwater discharge. In these areas, gaining stream conditions prevail and freshwater lens development is expected to be minor or non-existent.

10.7.2 Small changes in river level during inter-flood periods

In the inter-flood periods, and particularly during flows less than 5,000 ML/d, small declines in river level associated with small changes in flow can be conceptualised as mobilising inputs of saline groundwater from the near-river aquifer, from those reaches of the river or anabranches where freshwater lenses do not occur.

This process may also add additional salt to the backwaters, but mixing processes may mitigate the impact on in-river salinity. Porter (DFW, pers. comm.) illustrates this potential effect from examination of individual in-stream salinity records from reaches where backwaters are not common. This effect has not been scrutinised in this study, but warrants analysis using conceptual numerical modelling.

10.7.3 Floodplain inundation groundwater recharge

Overbank flows emplace floodwaters across the floodplain. Overbank flows tend to occur once flows exceed approximately 40,000 ML/d.

10.7.3.1 Rates and distribution of infiltration

The rate of floodplain infiltration will be controlled principally by the vertical hydraulic conductivity of the Coonambidgal Formation (the generally clayey or silty surficial unit in the floodplain).

Work undertaken in the Lindsay–Wallpolla area by BRS included the mapping of soil types using morphological characteristics and obtaining initial estimates of the vertical conductivity properties. Hughes (2005) in mapping soils at Pike and Murtho, assigned relative permeabilities to soil types under a morphological classification similar to the BRS approach. The morphological work consistently suggests that the high level floodplains have the lowest vertical conductivities, with permeability increasing as the terraces get lower in elevation and the age of the terraces gets younger.

It is therefore possible that the high terraces, which represent the oldest and thickest clay sequences, may have vertical permeabilities less than 10^{-3} m/d. The extent to which this low permeability persists across the high terraces is unknown.

Additional work has been undertaken modelling movement of water through the unsaturated zone on the highland at Murtho (AWE 2010b), using HYDRUS, an unsaturated zone model. Those results indicate that perching of water over a clay layer does not occur to any significant extent with a vertical conductivity of 10^{-3} m/d, but significant perching occurs with a vertical conductivity of 10^{-4} m/d. It is recommended that conceptual modelling be undertaken to calculate the relationship between floodplain vertical hydraulic conductivity and leakage rates through the Coonambidgal Formation, for a typical range of depths and durations of inundation. This work can then link with floodplain soils classification and hydraulic property investigations to provide a more informed and empirically based approach to floodplain recharge calculation. Additional work may be required, including chloride mass balance, water table fluctuations, water isotopes, 1D modelling, regional water balance, etc.

Jolly *et al*. (1994), in modelling the Chowilla floodplain, recognised the spatial variability of the floodplain vertical hydraulic conductivity. They concluded, based on calibration to groundwater trends during the flood, that uniform recharge though the whole floodplain was not the primary driver of the observed groundwater trends, and that a remote recharge zone was required to provide an acceptable calibration. Yan *et al*. (2005) in modelling the Chowilla floodplain, applied different recharge rates based on three broad floodplain soil classifications.

Empirical evidence for extensive infiltration of floodwaters through the clayey Coonambidgal Clay has not been collected. To the contrary, paired pre- and post-flood soil salinity profiles at the same site at Chowilla suggests that infiltration did not occur (Akeroyd *et al*. 1998). The HYDRUS modelling results, when applied to the Akeroyd *et al*. (1998) results, suggest that the Akeroyd site may have been in tight clays.

The idea that infiltration of floodwaters from overbank flows is a dominant contributor to rises in floodplain water levels and to the groundwater recession flux will stand review.

10.7.3.2 Interdependency between floodplain infiltration rate and bank storage volume during a flood

A model testing the sensitivity of groundwater recessions to the vertical hydraulic conductivity of the Coonambidgal Clays (i.e. k'v = 10^{-1} to 10^{-3} m/d) for a 1 km wide floodplain at Qualco indicates that the floodplain vertical hydraulic conductivity has little influence on the rate and timing of groundwater inputs to the river following floodplain inundation (AWE 2009). The model outputs also indicate that there is little impact on the rate and timing of the groundwater inputs when a flood is modelled with and without overbank inundation. It is noted that this result may not be scalable to wide floodplains (5 to 10 km wide).

The work above illustrates that the floodplain fills either from vertical infiltration or from recharge laterally (i.e. from regional inputs and from inflows through the bed and bank of the river). The relative proportion of these three components will affect the salinity of the groundwater recession. If water can enter the floodplain easily through inundation infiltration, then the volume entering from the river may be less than if the infiltration is minimal. While both bank storage and floodplain infiltration can be conceptualised as adding fresh water to the aquifer, the floodplain infiltration water has a longer average flow path length back to the river than does the bank storage water. In addition, the infiltrating water may also mobilise salts from the unsaturated zone to the aquifer.

As discussed in the next Section (10.6.4.3) the width to depth ratio of the lens and of the river are similar, so that if fresh water occurs at the edge of the river it is also likely to underlie the river. Therefore the bank storage fresh water seems likely to be added around the river, and will need to be displaced before the regional saline groundwater can reach the river.

Figure 10.1 illustrates that the release of suppressed direct groundwater discharge will form part of the flux to river in the post-flood period. The remaining flux is sourced from a combination of floodplain inundation returns and bank storage release, not from inundation infiltration alone. The relative proportions of these two latter processes will depend on the vertical hydraulic conductivity range of the Coonambidgal Formation.

The flux and salinity of the groundwater entering the river during the flood recession will vary reach by reach and kilometre by kilometre, and can be anticipated to be correlated with the salt flux from direct groundwater discharge during inter-flood periods and the hydraulic properties of the Coonambidgal Formation.

10.7.3.3 Summary

The contribution of floodplain inundation to the groundwater recession appears to be more uncertain than is sometimes assumed. Empirical evidence and modelling results suggest that infiltration through broad swathes of the Coonambidgal Formation is not always a dominant process causing an increase in the floodplain water level during a flood.

The conceptual model for floodplain inundation and the effect on groundwater levels and groundwater recessions needs to be more nuanced, to recognise and account for the diversity of physical parameters and the interplay of processes that are outlined herein.

10.7.4 Bank storage and release

The salinity of the groundwater surrounding the river channel and the connected floodplain water bodies is sensitive to whether the river is a gaining or losing stream.

Losing streams will develop a fresh water lens around the water body and any groundwater returns to the river are likely to be relatively fresh. In contrast, gaining streams have no protective freshwater lens and these reaches of river will provide entry points for saline groundwater on flood recessions and in periods between floods.

The AEM data (Appendix Figure A6) illustrate that freshwater lenses tend to be more prevalent and larger in the losing to through-flow floodplains than in the gaining floodplains.

10.7.4.1 Bank storage

Bank storage can occur almost continually or only rarely, depending on the strength of the losing or gaining river fluxes. It is therefore easiest to define bank storage in terms of two end-members, noting that these definitions modify the “bank recharge” definition of Jolly (2004):

- inter-flood bank storage — losses through the river-bed and bank where losing river conditions dominate during inter-flood periods
- flood bank storage — losses through the river-bed and banks where losing river conditions are caused by increases in river level.

The occurrence of inter-flood bank storage is associated with:

- areas where the regional groundwater inputs to the floodplain are less strong (i.e. through-flow or losing floodplains) and where direct discharge of groundwater to river does not occur
- times when evapotranspiration rates are greater than the regional groundwater + rainfall input rates.

Bank storage processes generate freshwater lenses in the aquifer adjacent the river.

Figure 10.1 shows the modelled rate of inter-flood bank storage in the Lock 6 to Lock 5 reach of the river. During the flood, flood bank storage occurs and the rate of storage is significantly higher than during the inter-flood period. The rate of flood bank storage peaks before the peak of the flood – the reason for this must be that the flood peak does not represent the peak gradient from the river to the aquifer. Rather the peak gradient occurs before the flood peak because water levels in the aquifer build up during the flood and at some stage before the flood peak the rate of rise of the groundwater will exceed the rate of rise of the river level. In the modelled example, the rate of bank storage at the peak of the flood is similar to the rate of bank storage during the inter-flood period. The rate of input during the flood is around three times the inter-flood rate.

10.7.4.2 Bank storage release

As the river stage falls, the bank storage water can be released back to the river. The rate and magnitude of bank storage release will be influenced by at least the permeability of the river bed sediments, the permeability of the adjacent aquifer, and the duration and magnitude of the flood event.

Figure 10.1 shows that in the immediate post-flood period, the modelled bank storage processes reduce to effectively zero at the end of the flood, coinciding with the maximum groundwater flux back to the tiver. This means the whole length of the Lock 6 to Lock 5 reach is a gaining stream at the end of the modelled flood – losing stream conditions cease for a short time as the groundwater discharges back to the river at its maximum rate. During the floodplain inundation groundwater recession, the inter-flood losses are reduced below their "normal" level.

The model suggests that in inter-flood losing stream reaches, the flood bank storage adds to the inter-flood freshwater lenses. Some proportion (or none) of this flood bank storage may return to the river during the flood recession. In inter-flood gaining reaches (i.e. where direct discharge to river occurs), the flood bank storage may partly or completely be returned to the river in the flood recession.

The evapotranspiration flux may capture some, or a significant proportion, of the bank storage. In strongly losing rivers and through-flow floodplains, the bank storage may never be released back to the river, but will instead be advected across the floodplain and into the regional groundwater system rather than returning to the river.

The floodplain between Wakool Junction and Hattah Lakes has extensive fresh water lens beneath and adjacent the river. Given the correlations between losing river and losing floodplains and freshwater lens development, it is suggested that close analysis of regional and local groundwater gradients may conclude that the floodplain in this area should be classified as losing rather than through-flow.

10.7.4.3 Freshwater lens – shape, stability and dynamics

In-stream NanoTEM datasets (Telfer *et al*. 2005, 2006, 2007, 2009) appear to provide good discrimination between fresh and saline groundwater in the floodplain. The NanoTEM data extend from Wellington to

Echuca. Airborne Electromagnetic data have been collected from Echuca to Bookpurnong for a range of clients. Hatch *et al*. (2007) has compared the results from the two datasets and from resistivity data over a small reach of river, and found a high degree of correlation between them. The NanoTEM data show that freshwater lenses are ubiquitous upstream of Hattah Lakes, are common between there and Lock 5, and are less common downstream of Lock 5 to Lock 1, then moderately common downstream of Lock 1. This pattern correlates with the AEM data (Fig A13). It is concluded from the AEM data and from fundamental hydraulic principles that the freshwater lenses generated from inter-flood bank storage are likely to be larger and more permanent than the lenses generated solely by flood bank storage – the latter can be conceptualised as persisting for very short times.

Cartwright *et al*. (2010) have evaluated the formation of the extensive freshwater lens in the Robinvale area and conclude that it is largely flood-derived and that drought will therefore be degrading the lens extent. The Robinvale lens occurs in a through-flow or possibly losing floodplain environment.

In contrast, it is considered by the current authors that the inter-flood freshwater lens development in gaining floodplains will be enhanced by drought and degraded by floodplain inundation. This is due to evapotranspiration lowering groundwater leads during droughts, inducing more flow from the river.

The size of freshwater lenses in the floodplains of the Lower River Murray broadly correlates with the gaining/losing floodplain analysis: extensive lenses in losing or weakly through–flow floodplains such as at Robinvale, non-existent to narrow lenses in gaining floodplains where direct discharge to river occurs (e.g. Woolpunda), and lenses of moderate extent in through-flow to weakly gaining floodplains (e.g. Chowilla, Murtho).

Preliminary assessment of the depth (from NanoTEM and AEM data) and width (AEM) at Sunraysia and Murtho shows that the ratio of depth to width of the fresh water lenses are between 1:30 and 1:50. A pumping trial was proposed at Bookpurnong (Telfer & Philp 2005) to test the hypothesis that pumping would draw fresh water into the aquifer in a lenticular fashion due to density effects (i.e. that the fresh water would preferentially invade the aquifer at the top of the aquifer). Berens *et al*. (2009) report on implementation of the trial program. The results shown in Section 2.4.5 demonstrate that the wedge shape occurs even under high pumping rates – the ratio is a little less than 1:50 assuming the graphed data represent half the lens extent. This suggests that the observed height:width ratio is hydrodynamically stable. Table 10.1 illustrates that the freshwater lenses, based on interpretation of the NanoTEM data, are roughly 15 to 18 m deep. The river averages say 3 to 5 m deep, and rarely exceeds 15 m deep (Telfer *et al*. 2006).

Table 10.1: Interpreted depth of freshwater per reach based on NanoTEM 20 ohm-m criteria

Major reach	Description	Mean depth of fresh water lenses (m)
1	Euston to Mildura	16.9
2	Mildura to Lock 9	18.1
3	Lock 9 to Lock 5	18.5
4	Lock 5 to Morgan	17.1
5	Morgan to Murray Bridge	15.8

If the 1:30 to 1:50 dimensions represent the stable shape for a freshwater lens under a linear river in a saline groundwater environment, as the preceding analysis suggests, then this has important implications for river and vegetation management in the Lower River Murray. These dimensions would mean that the lenses encase the river in fresh water, and it seems possible that the river would be largely protected from the ingress of saline water during a groundwater recession. A freshwater lens would provide protection during a period following over bank flows when groundwater returns to the river. The larger the freshwater lens, the more groundwater can be returned before saline groundwater reaches the river. This hypothesis needs a considerable amount of work to confirm or refute it and will be informed by the modelling programs discussed in the Recommendations Chapter.

11 Timing of salt delivery to the river

The indicative timing of salt delivery to the river is indicated in Figure 11.1:

- The upper part of the graph illustrates the flows at Morgan and the salinity at the five key salinity stations in the study area in the period preceding, during and following the 1981 flood.
- The lower part of the figure illustrates the likely timing of salt inputs to the river for each process.

The timing is illustrated for both direct and mobilised salt sources, and for salt mitigation processes. The timing is derived from the preceding analyses of processes and BIGMOD unaccounted salt loads.

The variable thickness horizontal bars illustrate when each process is active during changes in river flow and level – thick bars denote maximum rates of activation for each process, thin bars represent reduced rates and no bar denotes no activation. The bars do not illustrate the relative magnitude of salt delivery between processes.

The activation chart illustrates that there are a range of processes that can deliver salt to the river at any one time.

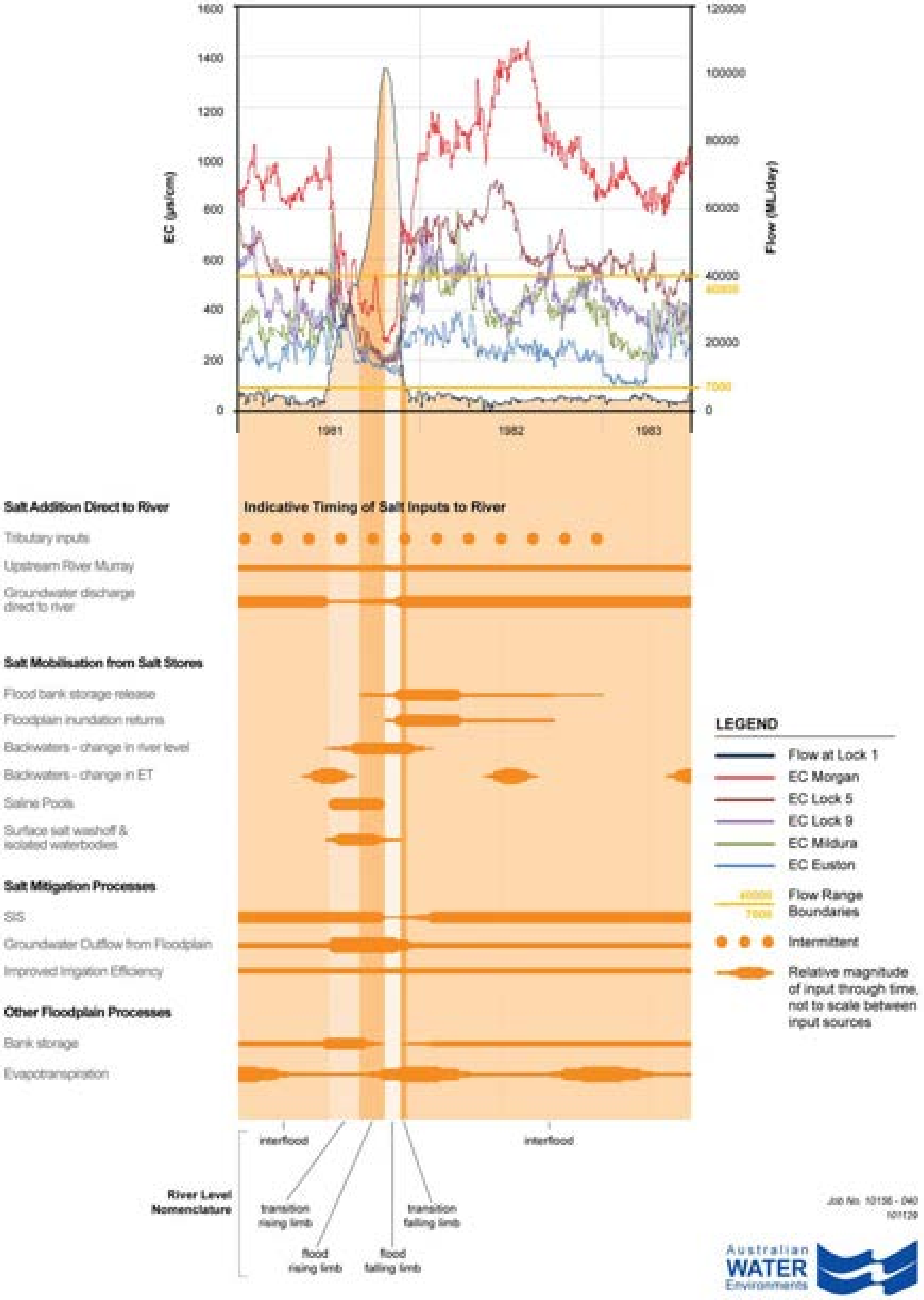


Figure 11.1: Process activation through the flood cycle

Part 5 – Management strategies, conclusions and recommendations

12 Investigation of operational procedures for mitigating salinity exceedances

A range of possible operation procedures are discussed in the sections below. These are presented as ideas that may provide the basis for further investigation. Other operational impacts, river management issues, water sharing arrangements and environmental impacts would need to be fully explored before pursuing any operational changes.

12.1 Dilution flows

It is generally understood that an increase in flow provides additional dilution for incoming salt inflows and thus may result in lower river salinity. However there are many complicating factors when trying to assess the impact of additional flows, for example:

- an increase in flow may increase salt inflow, as is discussed in more detail in Section 12.3
- the temporal and spatial distribution of the salt inflows and flow variations are required to assess the dilution impacts
- management issues about where and how dilution flows could be provided and what other long-term impacts this has on future water availability.

These factors make it difficult, with currently available data and tools, to accurately predict the EC impact of additional flows and are beyond the scope of this project. However the history of EC exceedances at Morgan has been analysed using some simplifying assumptions, with a view to assessing what additional flows may have been required to keep EC at Morgan below the 800 EC threshold. Simplifying assumptions include:

- the change in flow does not impact on the quantum of the salt inflow
- no additional losses through evaporation and seepage with the additional flow
- the fact that the tonnage of salt removed through extractions will decrease due to lower salinity water has been ignored
- operational and management impacts have not been assessed.

Several different options for assessing dilution requirements are described below and the aggregated flow requirements summarised in Table 12.1.

Option 1. As discussed in this report, very few events of over 800 EC at Morgan occur at flows above 5,000 ML/day at Morgan. The first option is to quantify how much additional flow would have been required at Morgan to bring flows to 5,000 ML/day on days when EC exceeds 800 EC. No assessment as to how and where the additional flow comes from is used.

Option 2. The second option is to introduce sufficient flow to dilute Morgan salinity to below 800 EC. When EC exceeds 800 EC at Morgan and flow is below 5,000 ML/day the dilution volume has been computed assuming additional water is provided at Morgan at the corresponding Lake Victoria salinity. No routing of the flow has been done.

Option 3. Similar to Option 2 but recognising there have been salinity mitigation measures since the periods 1970 to 1989 and assuming total decrease in salt inflows, due to SIS construction and other salinity mitigation measures of 400 tonnes/day. Waikerie and Woolpunda SISs are within this reach and account for a decrease in salt inflows of 280 tonnes/day.

Table 12.1: Initial assessment of additional flows

For days when salinity at Morgan >800 EC and < 5000 ML/day average additional flows (GL/year)			
	Option 1	**Option 2**	**Option 3**
Period	To increase flow to 5,000 ML/day	Dilute to 800 EC using Lake Victoria water	Reduce salt load at Morgan by 400 t/day, and dilute to 800 EC using Lake Victoria water
1970 - 79	146 GL/year	123 GL/year	27
1979 - 89	264	192	34
1989 - 99	50	28	Not Applicable
1999 - 2009	0	0	Not Applicable

From Table 12.1 it can be seen that Options 1 and 2 provide similar results for the required additional flows in the first two periods (1970-1979 and 1979-1989). Flows would have been substantial at about 10% of SA's annual allocation. Flows required in the latter two decades are much smaller or even zero.

There are several reasons for the significant decline in the assessed need for dilution flows in the latter two decades, including:

- changed operating rules that have decreased the occurrence of very low flows to South Australia
- significant investment in SIS infrastructure that has reduced the level of salt inflow
- improved irrigation drainage management that has reduced the level of salt inflows
- during 1999-2009, the extended period of drought, reducing salt inflows.

Options 3 demonstrates the significant impact SIS and other salinity mitigation measures would have had, if they were in place during the period 1970 to 1989. The required dilution flows are much reduced and more manageable.

The targeting of dilution flows has some difficulties because when an additional flow is introduced it effectively causes an increase in flow for the entire reach, i.e. it cannot travel as a pulse of higher flow with the high salinity water body. This is effective if salt inflow is uniformly distributed along the reach but not as effective for concentrated salt inflow. The flows can be better targeted if the location of the salt inflow is known. The difficulties with targeting the dilution flows would mean that higher flows than indicated in the table would have been required in practice.

The operational and management issues of how the additional water is provided to Lake Victoria and which allocation the water comes from would need to be discussed/negotiated between the river management bodies.

It may be that some water could be provided by rescheduling the monthly flows under South Australia's annual entitlement (*Water Act (Cwlth 2007)*, Schedule 1, Clause 90) or keeping current additional dilution flows for the times when most needed. Water sharing and storage arrangements between the States are bound by Agreements and these options may require negotiation of the operating rules between the States.

BIGMOD could be used to test a range of dilution flows. BIGMOD can be run in a “current conditions set-up” (i.e. using assumptions relating to current system infrastructure, operating rules, water sharing rules and level of diversions) across the full modelling period. Department for Water has undertaken a number of modelling investigations to determine the flow requirements to ensure that salinity at various locations along the river remains below specific levels.

12.2 Manipulation of Lock 3 weir pool on flood recession

As discussed in the report, there are very large salt loads immediately following a flood in the Lock 5 to Morgan reach. The peak loads occur in the initial 10 to 15 days after the flow drops below 20,000 ML/day. We hypothesise that the main contributors to the high salt loads are the draining of the very large permanent wetland water bodies upstream of Lock 3 (Including Lake Bonney) and bank storage release. The salinity impact of these high salt loads depends on the flow in the river. When river flow is low these high salt loads cause salinity spikes which are observed in the salinity record (refer to salinity spikes in Lock 5 to Morgan reach following floods of 1996 and 2000 as shown in Figure 4.1 and Appendix Figures A9 and A10).

The salinity impact of these events could be reduced significantly by manipulating pool levels to have these high salt loads discharge into the river when there is still a flow high enough to dilute them. Lock 3 weir will provide the most benefits as the majority of permanent wetlands are upstream of Lock 3 and this reach shows the high salt inflow immediately post flood.

A possible mechanism for managing these high salt export occurrences is as follows. At a flow of 40,000 ML/day, the downstream level at Lock 3 is some 950 mm below the upper pool level. The upper pool level could be reduced by say 0.5 m for flows between 40,000 and say 10,000 ML/day. The lower river levels would ensure backwaters discharge into significant flows. When flow drops below the lower threshold flow, the pool could be brought back to normal pool level, with the rise in level immediately stopping the saline discharge from backwaters and bank storage release. The volume required to fill the pool back up to level is in the order of 17,000 ML which at 10,000 ML/day flow could be done over several days without adverse flow impacts. Levels under the revised operation are shown in Figure 12.1.

The strategy would have the dual benefits of discharging highly saline water when there is still enough flow to dilute it and more salt would be discharged from the wetlands leaving a fresher water body for the post flood period.

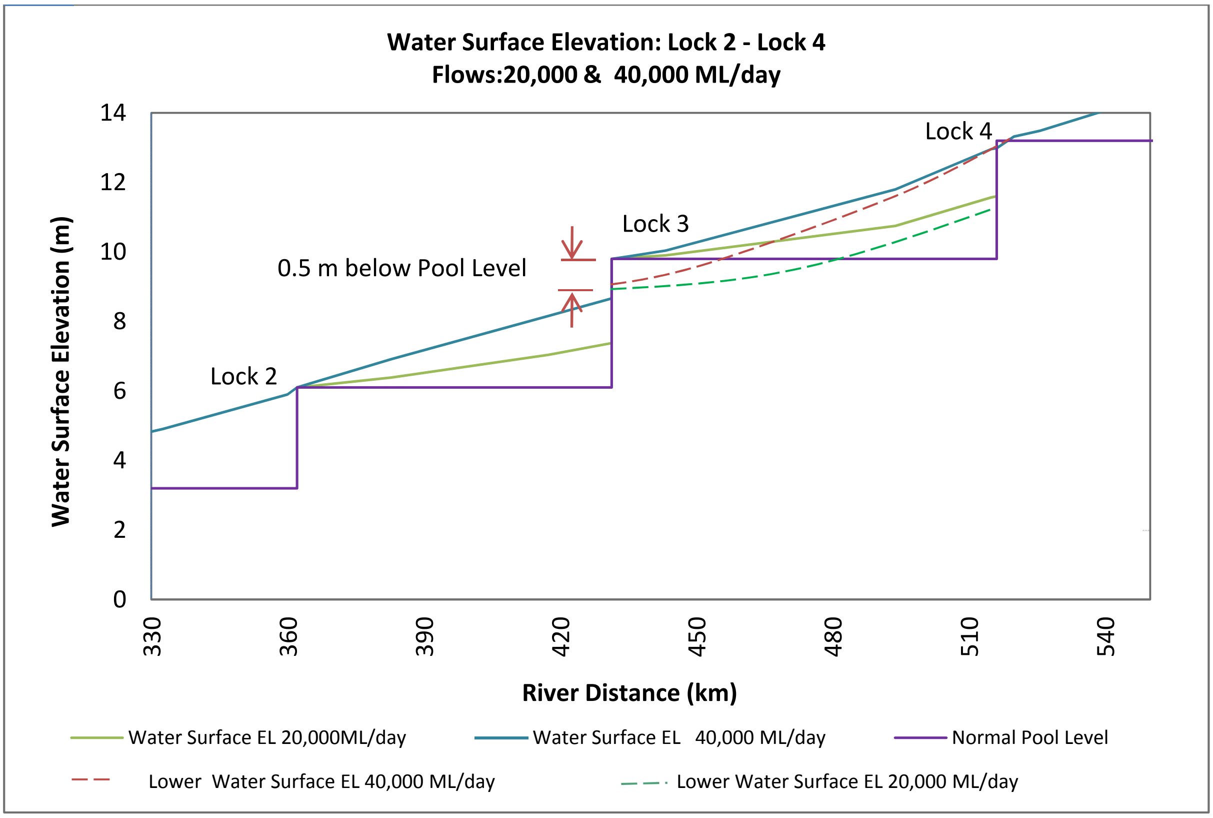


Figure 12.1: Lock 3 weir pool - Manipulation of levels during flood recession

Further investigation would be required to determine the most appropriate threshold flows and levels prior to implementation. The impact on other river operations, users and the environmental impacts would also need to be assessed.

Flood recessions can be very steep and difficult to manage operationally and may reduce the window of opportunity for this strategy.

It is considered that the Lock 3 weir pool manipulation would be the best location to pursue further investigation and a possible trial.

12.3 Pulsing of flows

Analysis of BIGMOD salt inflow has demonstrated that, in specific reaches (e.g. Lock 5 to Morgan), an increase in flow, with associated increase in water levels, increases salt loads to the river. BIGMOD model estimates of salt inflow for the Lock 5 to Morgan reach for an event when flow increased to 17,000 ML/day in 1980 are shown in Figure 12.2. Salt inflow increased substantially during the period of higher flow, both on the rising and falling limb. Similar patterns are observed in other periods of flow increase in years when there are no floods. During these occurrences, whilst the salt inflow does increase, the additional flow is sufficient to result in a lower salinity. The processes that are causing the increase in salt load at higher flows are not fully understood and more analysis into the cause would be required before developing an operational strategy.

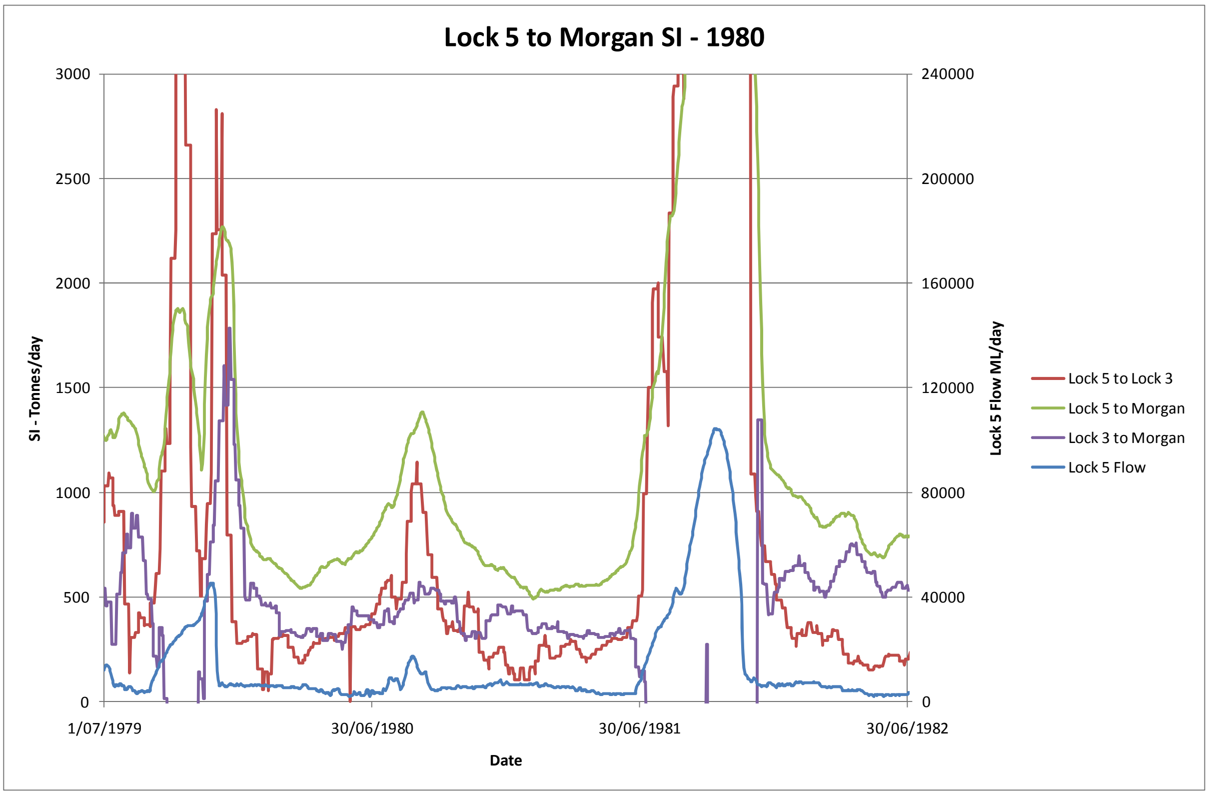


Figure 12.2: Lock 5 to Lock 3 SI during minor flow increase

Under normal river operation strategy, flow is kept relatively constant during each monthly period. It may be possible, at times of lower salinity, to introduce more flow/level variability to enable the export of additional salt and thus maintain lower salinity levels in wetland water bodies.

This strategy is likely to be most effective in the Lock 5 to Lock 3 reach where there are a large number of wetlands "activated" by the increase in flow and water level.

A proposal to introduce pulsed flows would need to be investigated in more detail to determine operational ability to provide periods of higher flow, likely impacts and possible benefits.

12.4 Salt interception schemes

The SISs are major investments that have a major role in determining River Murray salinity. Their impact on salinity is through the reduction of unaccounted salt inflow to the river. Historically, the design of SIS has generally ignored floodplain process as these processes were poorly understood. The operation of SIS during floods varies, with some being turned off during high flow events (e.g. Mildura, Mallee Cliffs), others being decommissioned due to borefields being on the floodplain (parts of Waikerie and Bookpurnong) and others operating unchanged (e.g. Woolpunda).

With the new understanding of processes and location of floodplain salt storage and mobilisation gained during this project it is likely that the operation of some SIS assets may be able to be modified to enhance benefits to the river. This may be through the targeted building of freshwater lenses at critical locations which may in-turn reduce peak salt loads and enhance environmental benefits. It is suggested that a set of aims be established and in light of the greater understanding of floodplain process, that operation of the SIS be reviewed.

12.4.1 Salt inflow to Lake Victoria

The BIGMOD assessment of accounted salt loads into and out of Lake Victoria indicates that over the 39 year study period 1,057,000 more tonnes of salt flowed from Lake Victoria into the river than flowed from the river into Lake Victoria. This represents an average salt load of 74 tonnes per day which is most likely the result of saline groundwater inflows to Lake Victoria. The salt inflow has remained relatively consistent over the study period. The impact of this significant salt load has been estimated, using the 2005 MDBA Ready Reckoner values, at an average 15 EC impact at Morgan and an associated cost impact of $2.55 m/year. It is recommended that this salt inflow be investigated and possible salinity mitigation options be developed to reduce salinity.

13 Previous assumptions and current ideas

Table 13.1 illustrates some of the paradigm shifts that have occurred through this project.

Table 13.1 What do we think we know now?

	What did we think we knew?	What do we think we know now?
1	Groundwater recession salt loads from floodplain inundation are a major driver of total salt to river.	Groundwater recession salt loads from floodplain inundation are the main source of salt load between Lock 6 and Lock 5, and are also a significant source of salt between Lock 5 and Lock 3. However the highest salt loads enter the river during floods, in the Lock 5 to Morgan reach. Groundwater recession salt loads from floodplain inundation are a relatively small contributor to the overall level of salt inflow.
2	Groundwater recession salt loads from floodplain inundation are a major driver of Morgan salinity exceedances.	The timing of salinity exceedances is associated with flows <5,000 ML/d, whether they occur soon after a flood when groundwater recession salt inputs can be significant, or many months after the flood when groundwater recession salt loads are only a minor contributor to the overall salt load. At these later times, the salt load may be derived from any one or a combination of: floodplain inundation groundwater returns; “direct” groundwater discharge from regional aquifers to the river, changes in river level drawing salt from backwaters; or changes in river level causing groundwater inflows. The 1974 extreme flood is the possible exception, where groundwater recession salt inputs from Chowilla contributed directly to the major salinity exceedance at Morgan.
3	Drought is causing salt accumulation in the floodplain.	Yes, drought is causing salt accumulation. In the Lock 6 to Morgan reaches, which is where most of the salt reaching the river comes from. The quantum of additional salt stored in the floodplain since 2000 due to the drought is probably less than 10% of the estimated pre-drought floodplain salt mass.
4	The salt accumulated during the drought will release in or after the next flood, with significant impacts at Morgan.	Post-flood salinity is not correlated with the time elapsed between floods. Based on the analysis of salt patterns over the last 30 years, this study concludes that the 2000 to 2009 drought is unlikely to significantly increase the post-flood salt inputs to the river compared to a no-drought scenario. The post-flood salinity regime and the peak salinity levels will however be affected by flood magnitude and the management of the flood recession.
5	Salt storage occurs in the unsaturated zone.	Probably, but there is not much (possibly no) empirical evidence that the salt mass stored in the unsaturated zone changes significantly during a drought or following a flood. Salt mass can be anticipated to increase when management or other changes induce increased rates of evaporation from the soil (e.g. increases in groundwater level). An additional but scantly considered salt storage location is the floodplain groundwater. Salt transport mechanisms between the unsaturated and saturated zones have not been conceptualised

		or quantified in any detail.
6	The low salinity at Morgan since 2000 (the "salinity holiday") is due to the drought causing floodplain salt storage and corresponding low salt exports.	Low salinities at Morgan since 2000 appear to be primarily due to SIS implementation. Irrigation efficiency improvements, and low salinity inputs from Hume Dam since 2000, are also considered to have had an impact. The role of drought-induced salt storage is thought to be of less importance in contributing to the "salinity holiday".
7	MSM_Bigmod is a useful modelling tool, but doesn't explain floodplain processes.	MSM_Bigmod is not only a useful modelling tool - the accounted and unaccounted salt load datasets from the model are valuable and underutilised, and analysis of this dataset has significantly informed this study. This study has analysed the MSM_Bigmod unaccounted salt loads, which when combined with spatial and process information has provided new insights into floodplain salt delivery processes. MSM_Bigmod provides the logical starting platform for developing enumeration of a floodplain conceptual model.
8	Floodplain processes are difficult to quantify.	Still true but the Floodplain Salt Conceptual Model developed in this study should provide a framework for assembly of knowledge and data, by breaking the complex problem into constituent parts.
9	Relative salt and salinity risk from reach to reach is unknown.	The relative risk is better quantified now, however additional data mining is required before we can confidently develop a predictive model of salinity inputs from the floodplains of the River Murray
10	Swan Hill is a good River Murray salinity baseline station.	Swan Hill is a poor River Murray salinity baseline station. Swan Hill is adversely influenced by salt inputs from Victoria, and the river is possibly poorly mixed at the measuring site. The river salinity is further affected by dilution from inflows downstream of Swan Hill by the Murrumbidgee, Edwards, and Wakool rivers. Euston is a much more representative site.

14 Conclusions

We are still at the beginning of understanding salinity processes in the River Murray system despite the ongoing research efforts. The size of the region, the number of different hydrogeological and hydrological regions, the medium and small-scale heterogeneity, the number of processes, our present incomplete conceptualisation of many of those processes, and a lack of data makes a comprehensive overview of floodplain salinity challenging.

14.1 Report aims and project constraints

- **This project "*involves the integration of existing knowledge and the development of a conceptual model to improve the understanding of the flood-recession salt mobilisation in preparation for managing the impacts of high river salinities that are inevitable in the future." (Project Brief)***
- We focus on the reaches from Euston to Morgan, and on salinity exceedances at Morgan. Salinity impacts below Morgan, where river water is extracted for urban water supply, are outside the scope of this study. Local salinity peaks and mitigation strategies for these local peaks have not been assessed in this study due to budget constraints and should be addressed in further work.

14.2 Floodplain reach characteristics

- Regional datasets have been assessed and condensed into useable figures to inform this and other analysis efforts. The assessment and incorporation of local datasets is beyond scope, but will improve the regional analysis when budget allows.
- **The reaches with most risk of adding salt to the river are the gaining floodplain reaches that are not protected by SIS and still exhibit low resistivity NanoTEM signals. Key reaches are Mallee Cliffs to Red Cliffs, Between Lock 5 and Berri at Pike (part under construction), and Loxton to Lock 3.**
- **The Lock 5 to Morgan reach has the largest area of connected surface water bodies and sits within a gaining floodplain with saline groundwater.**

14.3 BIGMOD analysis

- **MSM_Bigmod data, when combined with spatial and process information, has provided new insights into floodplain salt delivery processes and their relative importance. An analysis of BIGMOD unaccounted salt loads helps inform which floodplain processes are important under different conditions over broad reaches. The unaccounted salt load data are an undervalued and underutilised data set that has significantly informed this study.**
- Salinity exceedances at Morgan occur mainly in inter-flood periods. More specifically, 85% of exceedances occur when flow at Morgan is less than 5,000 ML/d. Most of the remaining exceedances at Morgan occur immediately after the flow increases above 5,000 ML/d – the high salinity water generated during the low flow period is moved past Morgan in higher flows.
- Approximately 60% of the total salt load added to the river downstream of Euston is sourced from the Lock 5 to Morgan reach. In the Lock 5 to Morgan reach, 75% of the salt is exported in flows >7,000 ML/d.
- Floodplain inundation groundwater recession salt inputs are high following the flood recession and decline for more than 300 days. The most pronounced example in the study reach occurs in the Lock 6 to Renmark reach, which includes the Murtho-Chowilla area, where salt inputs decline from 500 t/d to 150 t/d over 300 days. The remaining reaches between Lock 9 and Lock 5 do not appear to have this salt input process, however it does appear to occur in the Lock 5 to Lock 3 reach.
- The pattern of unaccounted salt inputs in the Lock 5 to Morgan reach is very different from that observed in the Lock 9 to Lock 5 reach. In Lock 5 to Morgan, the unaccounted salt input is an order

of magnitude greater, salt export occurs throughout the flood and major salt inputs greater than 5,000 t/d occur in the fortnight following the flow falling below 20,000 ML/d.

- This major salt input occurring in the fortnight following the flow falling below 20,000 ML/d occurs in the reach with major connected water bodies but not in the reach with only minor connected water bodies. This suggests that the unaccounted salt input is largely derived from surface water features rather than from groundwater inputs. The timing, rate and processes controlling groundwater discharge to backwaters and other surface water bodies on the floodplain are poorly understood and quantified, however salt release from these connected water bodies is thought to be a major salt release mechanism in the Lower Murray Floodplain salt balance.
- The rate of salt addition to the river during high flows between Lock 5 and Morgan can be around 10 times higher than the salt load added during low flows. For example, the BIGMOD unaccounted salt loads added to the river in the Lock 5 to Morgan reach is up to 5,000 t/d during flows above 7,000 ML/d and is closer to 500 t/d during inter-flood periods at flows below 7,000 ML/d.
- When evaluating salt inputs, Euston provides a better reference point against which to compare increases in salinity and assess salt loads than Swan Hill and is used as the reference point for this study.
- **Implementation of salt interception schemes has significantly reduced the occurrence of salinity exceedances in the last two decades. For example, if the Woolpunda and Waikerie SISs had not been built, exceedances above 800 EC at Morgan would have increased from 0% to 39% of the record for the last decade.**
- The drought in the last decade is estimated to have increased the salt mass in the floodplain by less than 10% over the decade.
- The MSM_Bigmod unaccounted and accounted salt load data have not been fully interrogated in this study due to budget constraints.

14.4 Floodplain conceptual model

- A large number of workers in a wide range of disciplines have contributed valuable work on aspects of floodplain salt. The previous work has addressed agronomic, river management, in-river salinity and vegetation health aspects of the salinity problem. Information from these previous studies and available datasets have been summarised and synthesised to develop a conceptual model of floodplain salinity impacts.
- Despite the significant amount of work undertaken on the River Murray floodplains in relation to salt and vegetation management over the last three decades, a conceptual model encompassing the range of processes and salt delivery pathways had not been developed. Floodplain processes are sometimes incompletely conceptualised, and are usually poorly quantified. We confirm that River Murray floodplain processes vary in importance from reach to reach and the impact of the processes varies through time, particularly in response to river stage.
- **The Floodplain Salt Conceptual Model consists of the following elements.** Salt loads to the river are sourced from upstream tributaries, baseline inflow from groundwater, floodplain inundation groundwater recessions that last from 6 months to 18 months following a flood, and inputs from backwaters and anabranches particularly in the Lock 5 to Morgan reach. Salt can be stored within the floodplain landscape on the soil surface, in the unsaturated zone, in the saturated zone and in isolated surface water bodies. Mobilisation of salt from these temporary stores adds salt to the river via a number of pathways, including within-bank changes of river level and overbank flows inundating the floodplain. Salt leaves the floodplain landscape via the river and in groundwater discharge into the regional aquifer system (i.e. losing floodplain conditions).
- **The Floodplain Salt Conceptual Model developed in this study is likely to assist with improving the current understanding of the sources of salt, the storage locations in the floodplain landscape, the mobilisation processes, the transport pathways to the river and the river salinity impacts. Owing to the complexity of the region and its processes, and the incomplete conceptualisation of some key processes, some details of the conceptual model are considered provisional. The aim of the model is also to provide a framework for future investigation, quantification and documentation.**
- During the inter-flood period, a range of processes add salt to the river. The “direct to river” groundwater inputs from the regional groundwater system and groundwater inflows resulting from floodplain inundation appear to be the major sources of salt in the interflow period. It seems likely that additional salt mobilised by small changes in river level at the flows <5,000 ML/d may be significant at some locations (e.g. especially in the Lock 5 to Morgan reach) and at some times. The small changes in river level are thought to mobilise:
    - low to moderate salinity water from backwaters, particularly in the Lock 5 to Morgan reach, because the low river level facilitates drainage of saline water from the backwaters into the river
    - inputs of saline groundwater direct to the river.
- **The Floodplain and River Classification Matrix provides a good indicator of the risk of salt accession to the river. The risk of salt inputs to the river from regional groundwater systems increases from virtually no risk for a losing stream in a losing floodplain, to high risk for gaining streams in gaining floodplains. Salt interception schemes are all implemented in gaining floodplains with gaining streams, and the remaining high risk areas also fall within this category.**
- The exact location of additional floodplain salt storage due to the drought is unknown. However, given the major driver of salt storage is evapotranspiration, which is thought to occur throughout the floodplain, it can be reasonably hypothesised that the salt storage is also distributed across the

floodplain rather than preferentially close to the river. It is difficult to conceptualise a model whereby the additional stored salt would be preferentially mobilised by the next flood.

- The processes controlling release of water and salt from the backwaters and anabranches, both during the inter-flood period and during and immediately following floods, particularly in the Lock 5 to Morgan reach, need additional attention. This study suggests that backwater and anabranch interactions with the river are a significant and perhaps locally major component of the salt delivery processes and pathways.

14.5 Predicting salt loads and salinity

- **Based on the analysis of salt patterns over the last 30 years, this study concludes that the 2000 to 2009 drought is unlikely to significantly increase the post-flood salt inputs to the river. The post-flood salinity regime and the peak salinity levels will however be affected by flood magnitude and the management of the flood recession.**
- Development of a predictive numerical model is premature given the current analysis is incomplete and there are important datasets that need to be assembled and analysed before a robust enumeration can be developed.
- The most obvious approach to future enumeration of the conceptual model is in conjunction with the MSM_Bigmod model via calibration of the unaccounted salt against a wide range of constraints (e.g. outputs from groundwater models, in-stream salinity and derived salt load data, development of a backwater model).

14.6 Management strategies

- Three indicative operational procedures which might reduce River Murray salinity have been conceptualised but need additional work: dilution flows, the manipulation of the Lock 3 weir during a flood recession and pulsing of flows. The procedures were evaluated solely in terms of their impact on salinity exceedances at Morgan and there is a need to also assess management and operational issues prior to implementation.
- The SISs are major investments that have a significant effect on River Murray salinity. Historically, the design of SIS has focussed in intercepting the direct discharge of groundwater to the river. With the new understanding of floodplain salt processes and mobilisation pathways gained during this project, it is likely that the operation of some SIS assets may be able to be modified to enhance benefits to the river or the floodplain environment. For example, this may be through the targeted building of freshwater lenses at critical locations which may in-turn reduce peak salt loads and enhance environmental benefits.
- Investigate the opportunity to reduce Lake Victoria salinity levels trough SIS implementation and evaluate the benefits of this proposed action.

14.7 Knowledge and data gaps

- Further work is required to more fully assess the available literature and compile a more thorough and complete literature review, to facilitate efficient and effective progress in understanding floodplain salt.
- Local salinity peaks and mitigation strategies for these local peaks have not been assessed in this study due to budget constraints and should be addressed in further work.
- Numerous data gaps and knowledge gaps occur. The key knowledge gaps include:
    - How the broadscale salinity impacts estimated in this report from MSM_Bigmod data relate to the small-scale features and transient effects which impact water quality for critical

human needs, irrigation and environmental assets. Floodplain processes will vary reach by reach, kilometre by kilometre and wetland by wetland.

- The timing, rate and processes controlling groundwater discharge to backwaters and other surface water bodies on the floodplain are poorly understood and quantified, however salt release from these connected water bodies is thought to be a major mechanism in the Lower Murray Floodplain salt balance.
- The processes controlling release of water and salt from the backwaters and anabranches, particularly in the Lock 5 to Morgan reach, need additional attention. Data are required to quantify the sources and rates of salt mobilisation at the subreach and at individual water body scale.
- The role of the unsaturated zone and the saturated zone in storing salt during a drought and salt mobilisation from the unsaturated zone. The unsaturated zone is often cited as the salt storage location during inter-flood periods, however salt storage and release mechanisms in the floodplain unsaturated zone appear to be incompletely conceptualised and sparsely quantified.
- Recharge rates through the Coonambidgal Clays, and distribution of rates across the floodplain during inundation and also in inter-flood periods, are almost completely unquantified.
- Recharge rates to groundwater in irrigated regions adjacent to the floodplain and within the floodplain.
- Emplacement mechanisms and rates, size, shape, persistence and stability of freshwater lenses, and the degree of protection they afford the river to groundwater recession salt inputs.
- Floodplain evapotranspiration rates, which are known to vary according to soil type, vegetation type, groundwater salinity and climate, but for which there is no agreed method of estimating on the regional scale.

- **Large new data collection programs are not warranted at this time - analysis of the available data is expected to extract a large amount of information and improve the conceptualisation and understanding of floodplain salt loads at relatively minor cost.**

14.8 Review against proposed project outputs

- Current findings on biophysical processes in the Lower River Murray floodplain, including surface-groundwater hydrology, have been collated.
- Key geographic areas and features that drive and are impacted by floodplain salt mobilisation, have been reported.
- A conceptual model has been developed that can demonstrably assist in understanding floodplain salt mobilisation and evaluation of mitigation strategies under current and future water management regimes
- Potential river operational strategies have been presented.
- A ‘road map’ for future investigations, which will improve planning and prioritisation for the MDBA, has been proposed.

15 Recommendations

15.1 Floodplain conceptual model

Item	Action
15.1.1	MDBA adopt the Floodplain Salt Conceptual Model as the best current approach for communicating and developing programs for improving the understanding of all aspects of salt in the Lower River Murray floodplains.
15.1.2	Commonwealth and State Jurisdictions adopt the Floodplain Salt Conceptual Model for communicating and developing programs for improving the understanding of all aspects of salt in the Lower River Murray floodplains.
15.1.3	Key future programs and reports addressing salinity or salt issues be asked to comment on and add additional detail to the conceptual model — including environmental watering projects where the salinity impacts or salt mobilisation is considered.

15.2 Compiling and interpreting available data

Item **Action**

15.2.1 Fully assess the available literature and compile a more thorough and complete literature review, to facilitate efficient and effective progress in understanding floodplain salt.

15.2.2 Evaluate the source of salinity peaks at Swan Hill and if incomplete mixing at the location of the recorder is confirmed as the source of the salinity peaks, identify a better mixed site and relocate the station to that site.

15.2.3 Complete the analysis of the BIGMOD unaccounted salt loads and publish the results in a report that includes the analysis presented in this study, including:

- extending the post-flood salt input analysis to all reaches to identify the patterns of input and hence inform understanding of the input processes
- assessing the cause(s) of negative salt loads in the Lock 11 to Lock 9 reach and applying corrective measures to facilitate discrimination of timing and causes of salt inputs in the Euston to Lock 11, and Lock 11 to Lock 9 reaches, and to assess the key sub-reaches and processes in the Mildura-Mallee Cliffs region
- identify the salt loads and timing from the Red Cliffs to Mallee Cliffs reach of the river
- assess the reach upstream of Lock 6 to assess the impact of Lindsay and Rufus rivers.

15.2.4 Assemble and document the continuous in-stream salinity data collected in SA, Victoria and NSW. Annotate the records with the best available interpretation of the trends evident in the data. Publish the data in an Atlas format to facilitate its dissemination and use by the wide range of workers interested in in-stream salinity and the effects of actions on that salinity.

15.2.5 Compile the available information on backwaters in the Lock 5 to Morgan reach, including hypsographic data, salinity data, commence-to-flow data, locations and elevations of inlets and outlets, etc. Document the data in an Atlas format and digitally. Report on the mass of salt stored in backwaters, the timing and rate of storage, and the management of these salt stores to the extent the data allow. Using the In-stream Salinity Atlas, isolate the relative contributions of salt from backwaters in the inter-flood periods at a reach scale.

15.2.6 Develop a consolidated map of floodplain salinity distribution using AEM data, point data and existing mapped distributions, to provide a baseline for future analysis.

15.2.7 The annual variation in Run of River surveys, even when taken at similar flows, has been one source of doubt on the reliability of the Run of River results. This project has provided new insight into the salt inflow variability (Refer to Section 6.4.2) and it is recommended that the Run of River data be reviewed in the light of this new knowledge to assess possible correlations in the pattern of variability.

15.3 Conceptualising and enumerating high priority elements of the Floodplain Salt Conceptual Model

Item	Action
15.3.1	Assess modelling strategies to examine and quantify groundwater-backwater-river interactions during inter-flood and flood periods.
15.3.2	Following collation of backwater information, examine the potential range and magnitude of groundwater-backwater-river interactions in the Lock 5 to Morgan reach using simple groundwater models initially, and calibrate to the observed (if any) salinity records in the backwaters. Extend analysis to river-backwater interactions using appropriate tools.
15.3.3	The Lock 5 to Morgan reach is a major source of salt and of floodplain inundation groundwater returns. Develop and implement a simulation model of the Lock 5 to Lock 3 reach using the approaches newly developed and implemented for the Murtho (Lock 6 to Lock 5) model, which includes floodplain inundation and solute transport.
15.3.4	Develop a MODFLOW model of the Sunraysia area with floods and solute transport to quantify the impact of flooding on salt loads to river, both to inform the SIS refurbishment at Mildura-Merbein but also to evaluate the Red Cliffs to Mallee Cliffs flood salt loads.
15.3.5	Undertake a detailed literature review and develop conceptual model(s) of surface/unsaturated/saturated zone salt storage and release. This work

should address both in-river salinity and vegetation health aspects of the problem, with the aim of unifying the discussions of floodplain management and in-river salinity. At present there seems to be a divide between the two – groundwater processes are common to and vital in the assessment of both programs. The process assessment will need to improve our ability to:

- predict the timing, distribution and fate of salt which is of major importance in modelled groundwater impacts on river salinity
- calculate and model evapotranspiration
- predict the effects of changes in salt stores on vegetation health.

15.3.6 It is recommended that modelling be undertaken to calculate the relationship between floodplain vertical hydraulic conductivity and leakage rates through the Coonambidgal Formation, for a typical range of depths and durations of inundation. This work can then link with floodplain soils classification and hydraulic property investigations to provide a more informed and empirically based approach to floodplain recharge calculation.

15.3.7 Freshwater lenses are an important but poorly understood component of the floodplain salt and water balance. Work is required to better define the distribution, shape, stability and key influences on fresh water lens development. Additional work is recommended to evaluate the sensitivity of freshwater lens formation to its dependant variables (e.g. riverbed and aquifer permeability, salinity contrast, rate of change in head) for parameter ranges that occur in the Lower River Murray. The modelling work could also assess the sensitivity of lens formation and stability of the lens in the different floodplain classes (gaining, through-flow and losing). This work will inform managers about the degree of protection afforded the river by the lenses, and the extent to which floodplain inundation groundwater recessions perturb the lenses and allow preferential return of saline groundwater to the river.

15.4 Management and monitoring

Item **Action**

15.4.1 Further develop the three indicative operational procedures which might reduce River Murray salinity: dilution flows, the manipulation of the Lock 3 weir during a flood recession and pulsing of flows. Local environmental impacts, management and operational constraints, water sharing arrangements, engineering feasibility and other issues will need to be evaluated.

15.4.2 With the new understanding of processes and location of floodplain salt storage and mobilisation gained during this project, review the operation of SISs to assess which may be able to be modified to enhance benefits to the river.

15.4.3 Implement a salinity sampling program in backwaters in the Lock 5 to Morgan reach to facilitate calibration of groundwater—backwater models, aiming to identify rates of change and hence rates of input of groundwater and to identify from where the winter backwater salt loads are being sourced.

15.4.4 Implement a groundwater monitoring program around Coombool Swamp in Chowilla to identify if it is a driver of the major floodplain inundation groundwater recession at flows >75,000 ML/d. Undertake groundwater flow and possibly solute transport modelling to test the validity of the hypothesis. If proven correct, additional work to assess the likely sites where this process occurs elsewhere would prove a valuable input to the prioritisation and siting of environmental water activities. It may also provide opportunities for very targeted but very cost effective salt interception options.

15.4.5 Develop a monitoring strategy for high flows to test the hypotheses proposed or documented herein – however analysis of the current in-river salinity record is an essential prerequisite.

15.4.6 Undertake an AEM survey of the Pike to Morgan reach of the river, to provide a complete coverage to facilitate interpretation of the salt loads from this reach.

15.5 Predicting river salinity

Item	Action
15.5.1	BIGMOD should be modified to try to account for more of the unaccounted salt load processes. Also, the accounted salt loads should be evaluated.
15.5.2	Use BIGMOD unaccounted salt loads as the basis for a predictive model.

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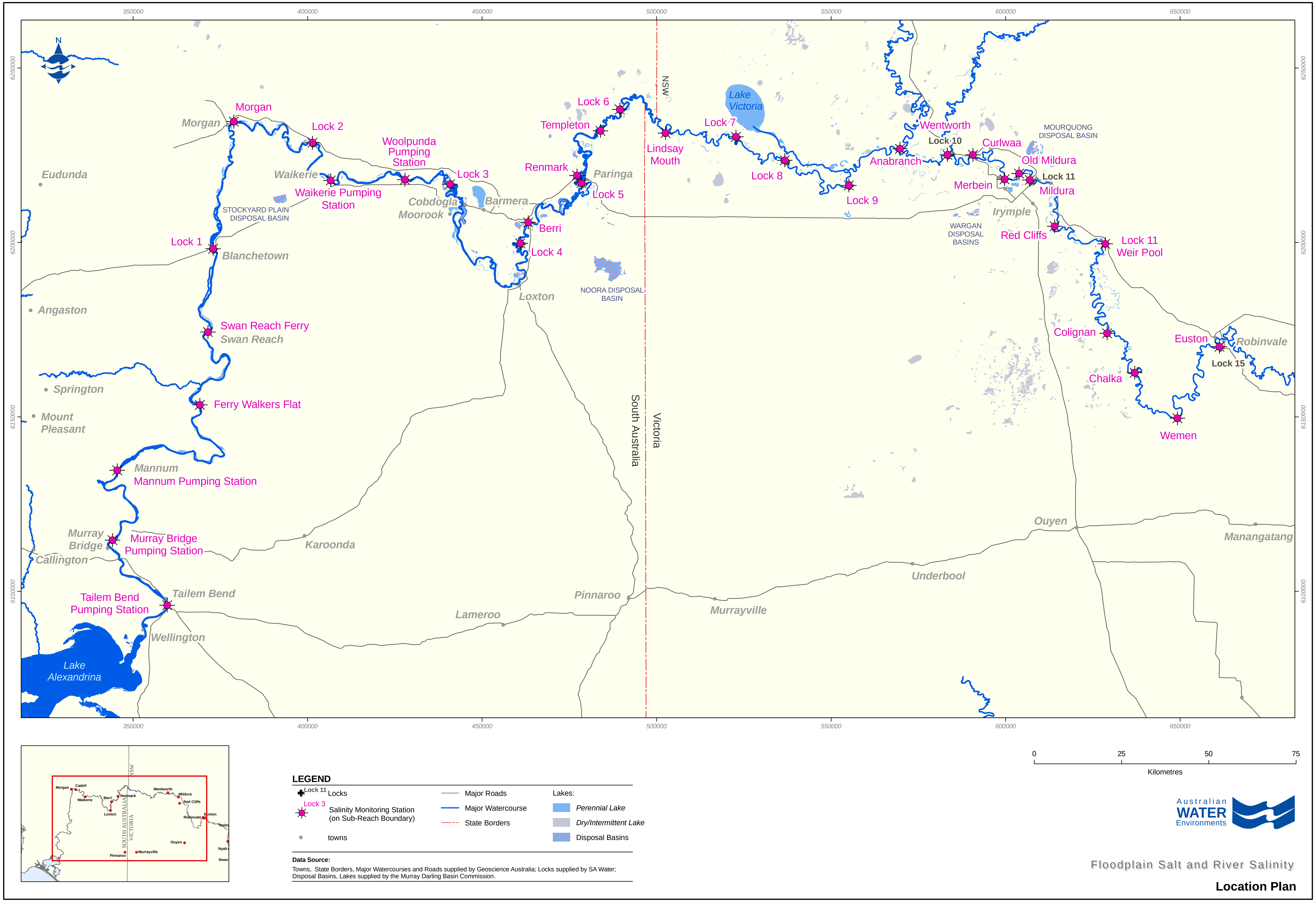
17 Appendixes

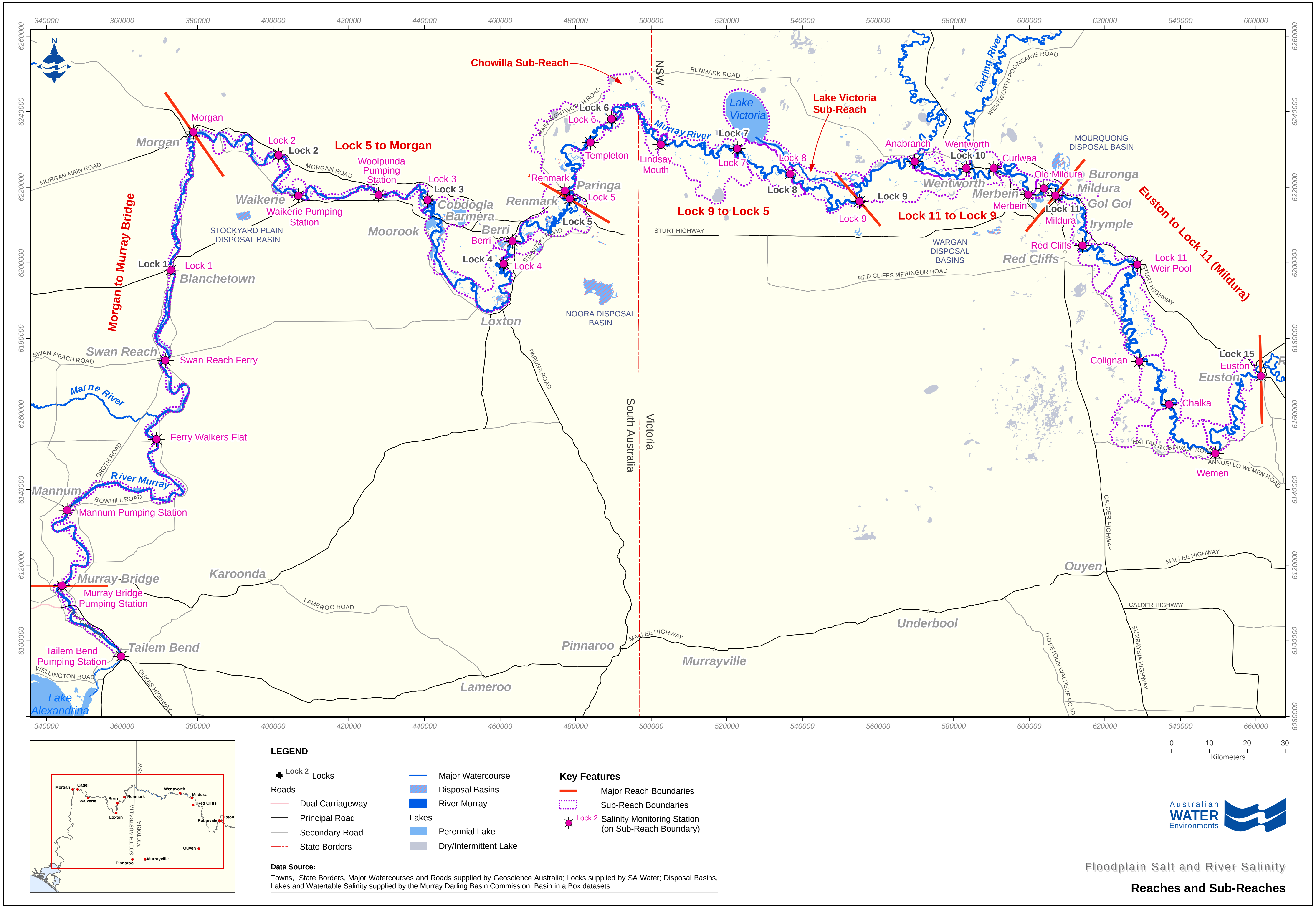


Floodplain Salt and River Salinity

Location Plan

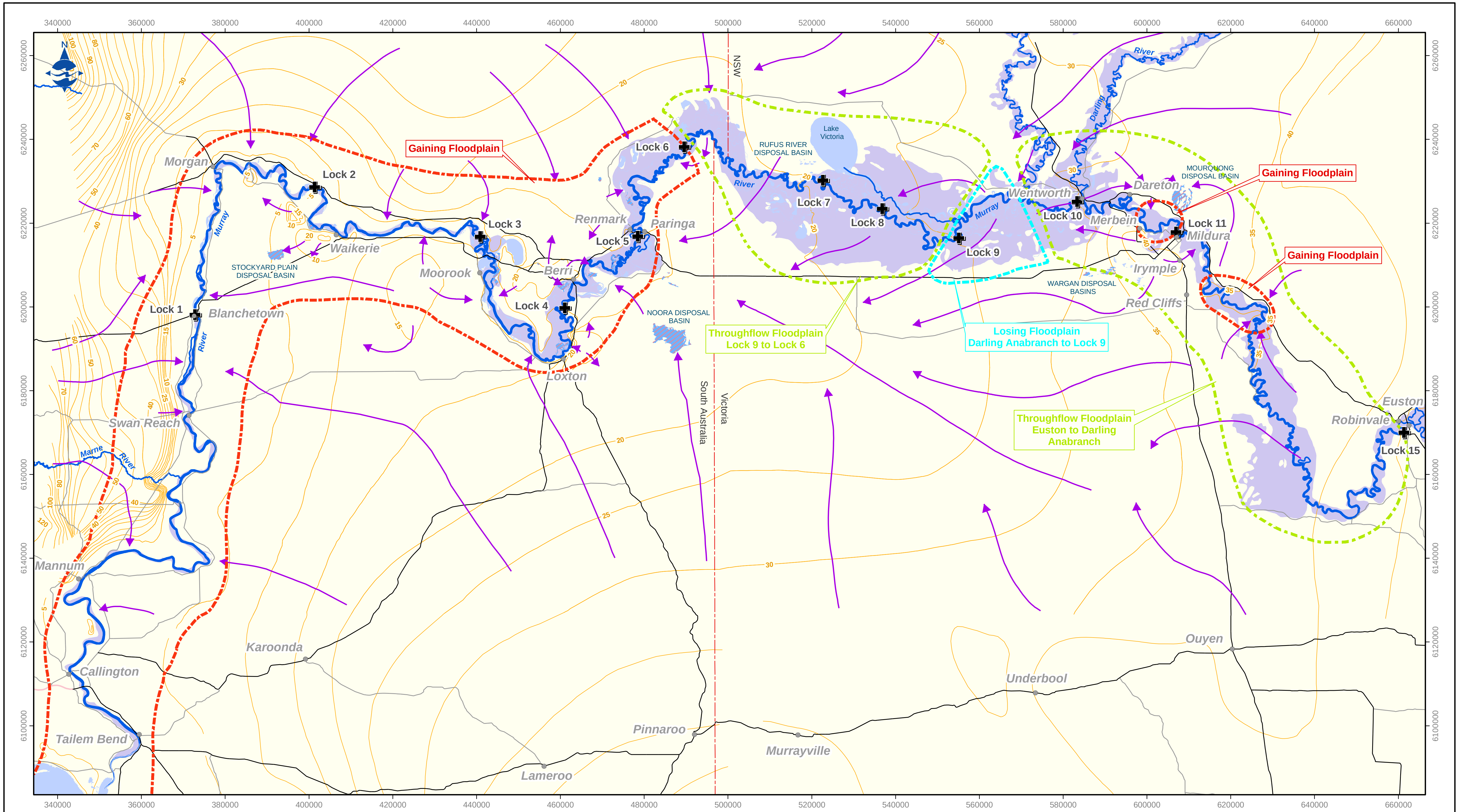
Job No. 10156 - 050
101122

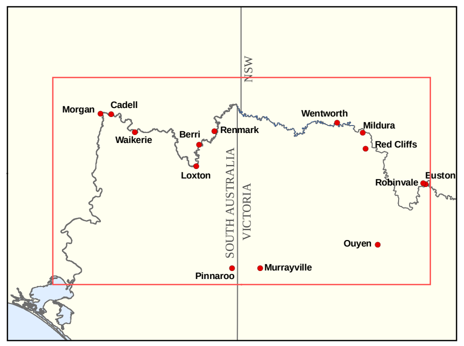
FIGURE A1



Job No. 10156 - 029
100706

FIGURE A2





0 10 20 30
Kilometres

LEGEND

- Locks
- Roads:
  - *Dual Carriageway*
  - *Principal Road*
  - *Secondary Road*
- State Borders
- Major Watercourse
- Direction of Groundwater Flow
- 1997 Groundwater Elevation (mAHD)
- Disposal Basins
- River Murray
- River Murray
- Wetlands
- Wetlands
- River Murray Trench

Floodplain Classification:
- *Gaining Floodplain (High Risk)*
- *Throughflow Floodplain (Moderate Risk)*
- *Losing Floodplain (Low Risk)*

Data Source:
Towns, Major Watercourse, Roads and State Boundaries supplied by Geoscience Australia; Lock supplied by SA Water; Disposal Basins, Wetlands, River Murray Trench (Coonambidgal Formation) supplied by the MUrray Darling Basin Commission: Basin in a Box data.

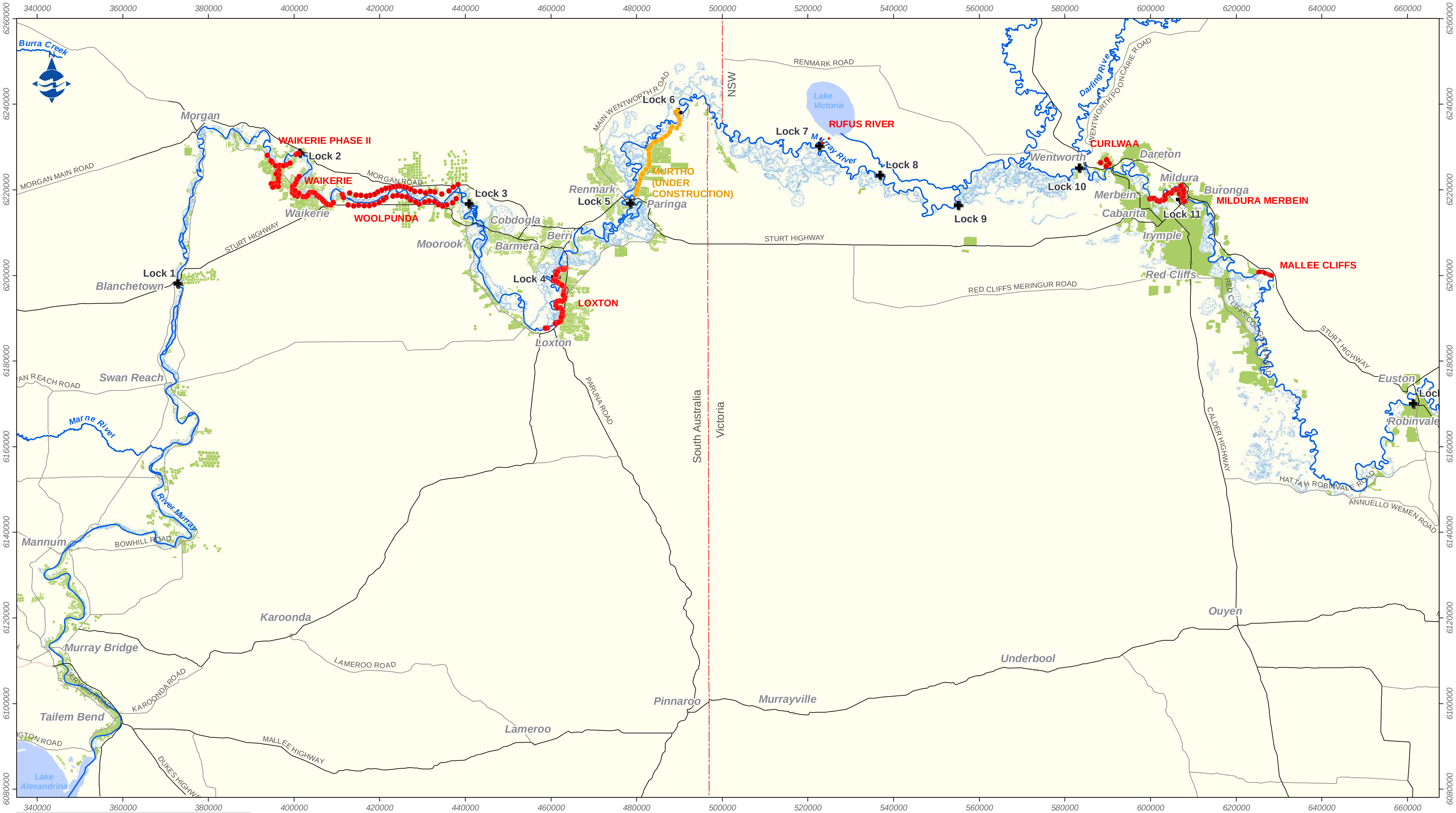
Australian WATER Environments

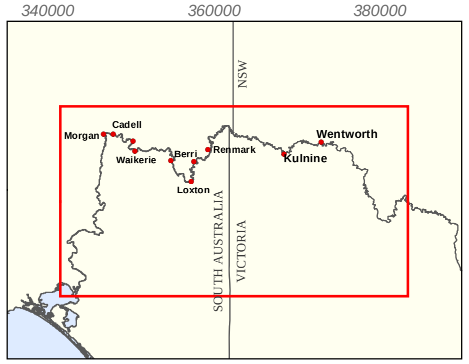
Floodplain Salt and River Salinity

Gaining and Losing Floodplain
Groundwater Elevation
Water Table Aquifers

Job No. 10156 - 025
100624

FIGURE A3





LEGEND

- Locks
- SIS Production Bores
- SIS Production Bores (Under Construction)

Well Point Bores

- Existing Pumping Line
- State Borders
- Major Watercourse

Roads

- Dual Carriageway
- Principal Road
- Secondary Road

- Irrigated Crops
- River Murray
- Wetlands

0 20 40

Kilometres

Data Source:

Towns, Roads, State Borders supplied by Geoscience Australia; Locks supplied by SA Water; Wetlands supplied by Dept of Urban Planning and Transport (DTUPA); Irrigated Crops supplied by the relevant Irrigation Trust excluding Euston area which was supplied by AWE and obtained from satellite imagery supplied by the Murray Darling Basin Commission.

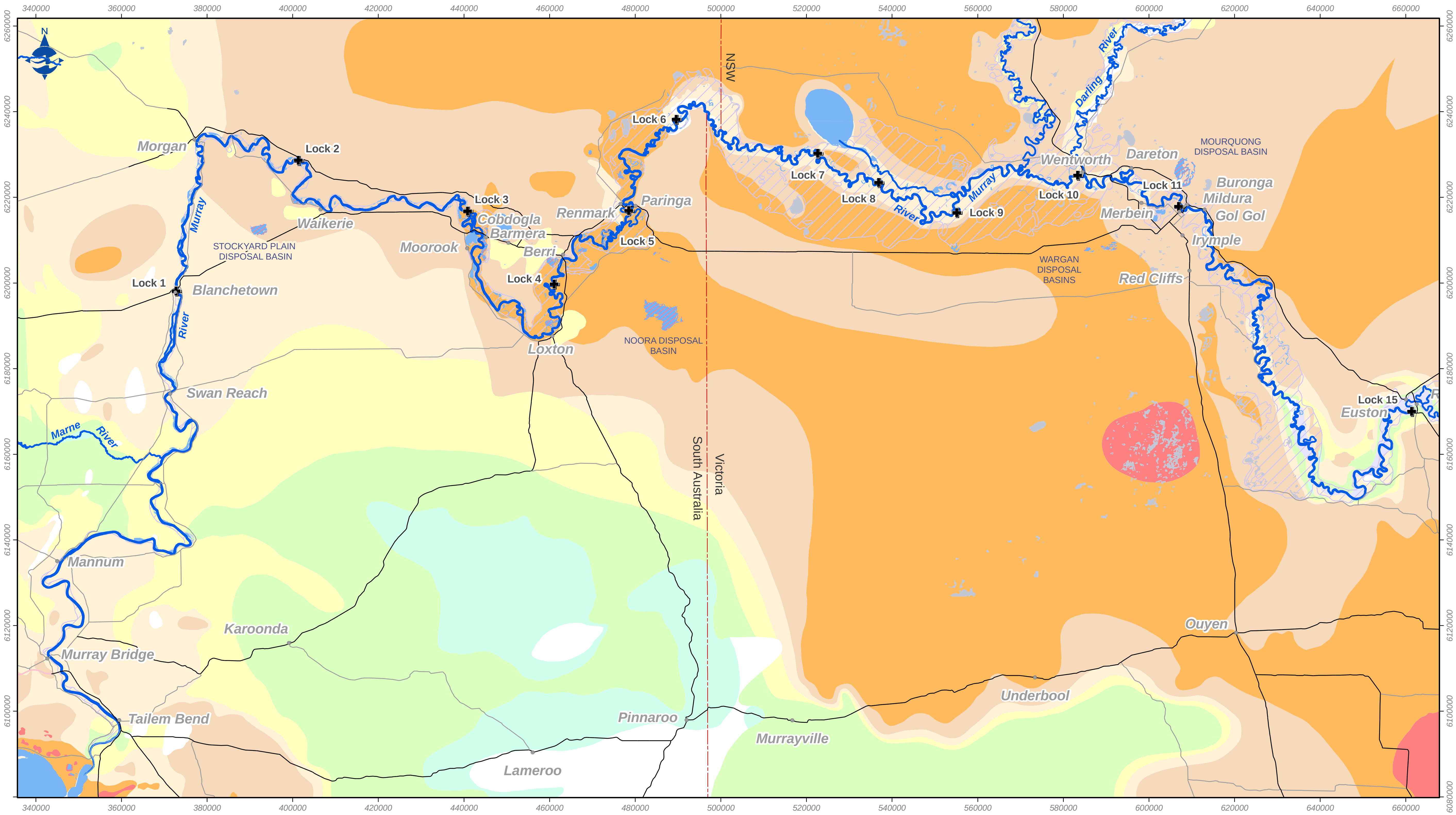
Australian WATER Environments

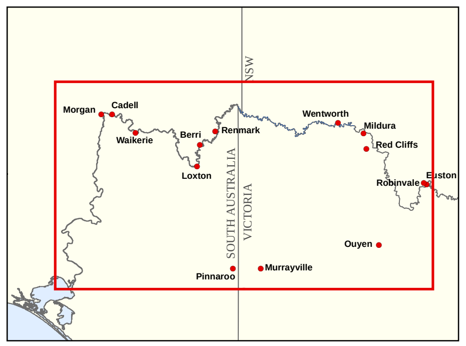
Floodplain Salt and River Salinity

SIS Bores and Irrigation Areas

Job No. 10156 - 027
100608

FIGURE A4





LEGEND

- Locks
- State Borders
- Major Watercourse

Roads:

- *Dual Carriageway*
- *Principal Road*
- *Secondary Road*

- Disposal Basins
- River Murray

Lakes:

- *Perennial Lake*
- *Dry/Intermittent Lake*
- River Murray Trench

Groundwater Salinity (mg/L):

- *> 100000 mg/L*
- *35000 - 100000 mg/L*
- *14000 - 35000 mg/L*
- *7000 - 14000 mg/L*
- *3000 - 7000 mg/L*
- *1500 - 3000 mg/L*
- *1000 - 1500 mg/L*
- *500 - 1000 mg/L*
- *< 500 mg/L*

0 10 20 30
Kilometers

Data Source:

Towns, State Borders, Major Watercourses and Roads supplied by Geoscience Australia; Locks supplied by SA Water; Disposal Basins, Lakes and Watertable Salinity supplied by the Murray Darling Basin Commission: Basin in a Box datasets.

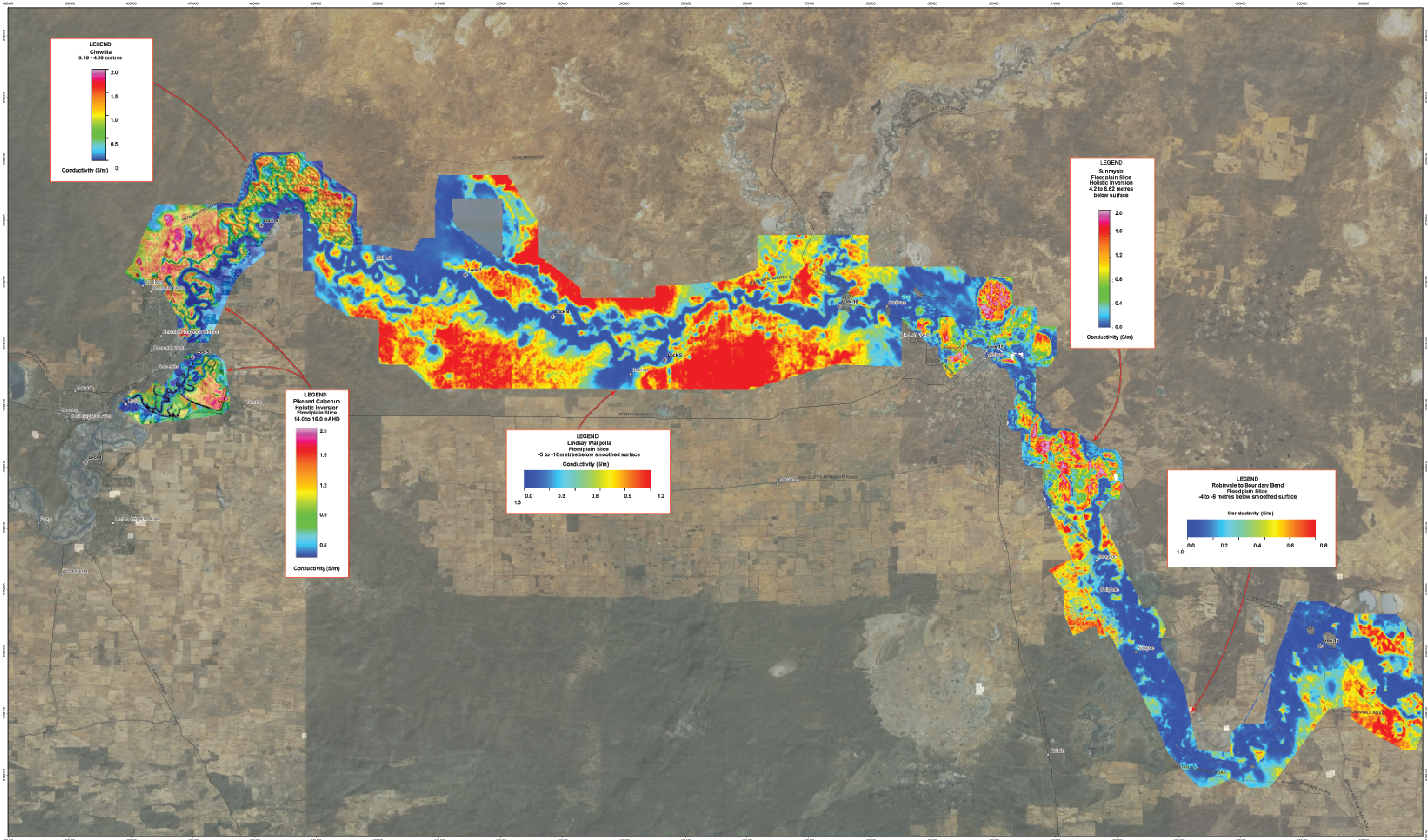
Australian WATER Environments

Floodplain Salt and River Salinity

Regional Groundwater Salinity

Job No. 10156 - 026
100624

FIGURE A5



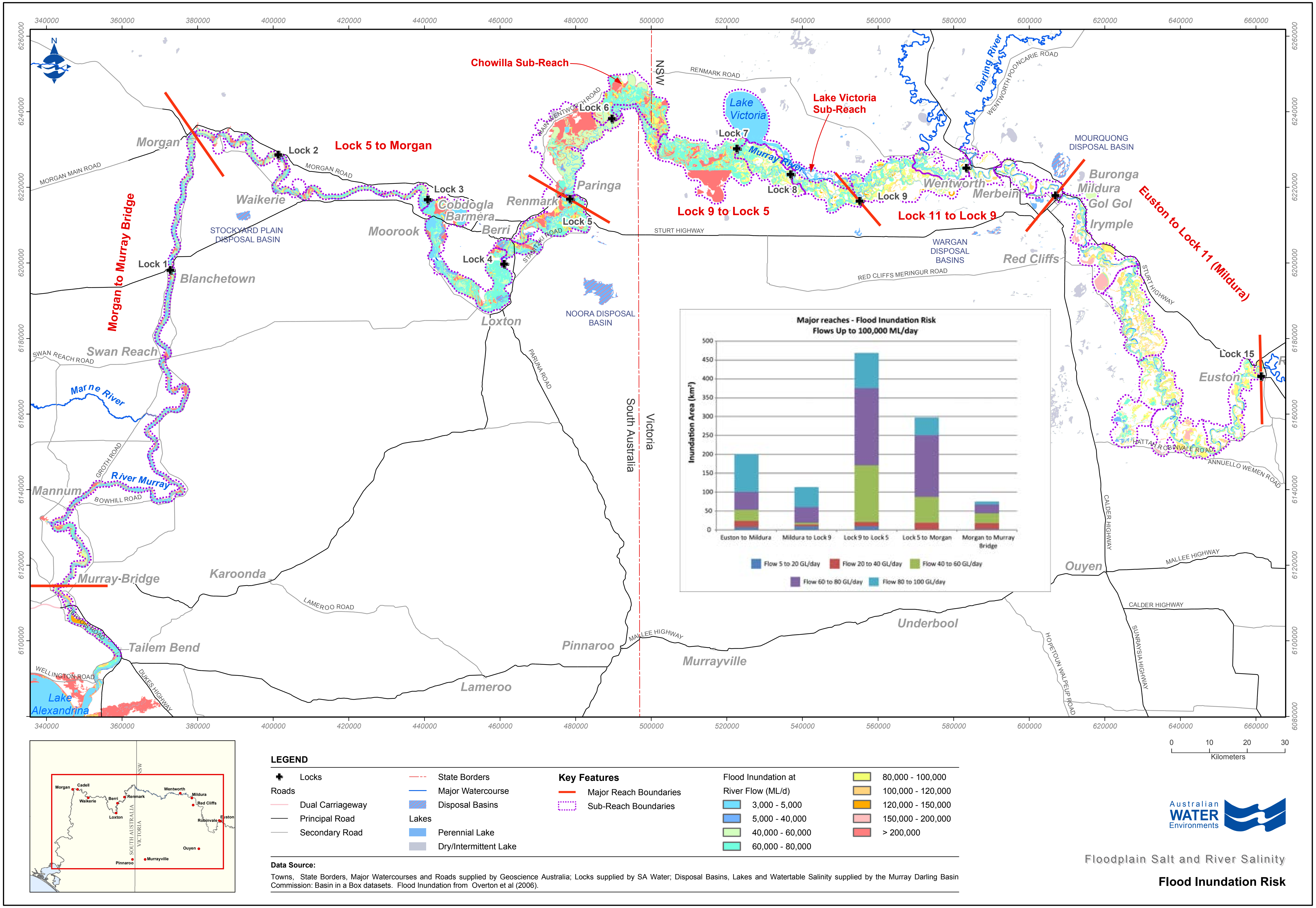
Australian WATER Environments

Floodplain Salt and River Salinity

AEM Compilation

Job No. 10156 - 082
110113

FIGURE A6



Job No. 10156 - 030
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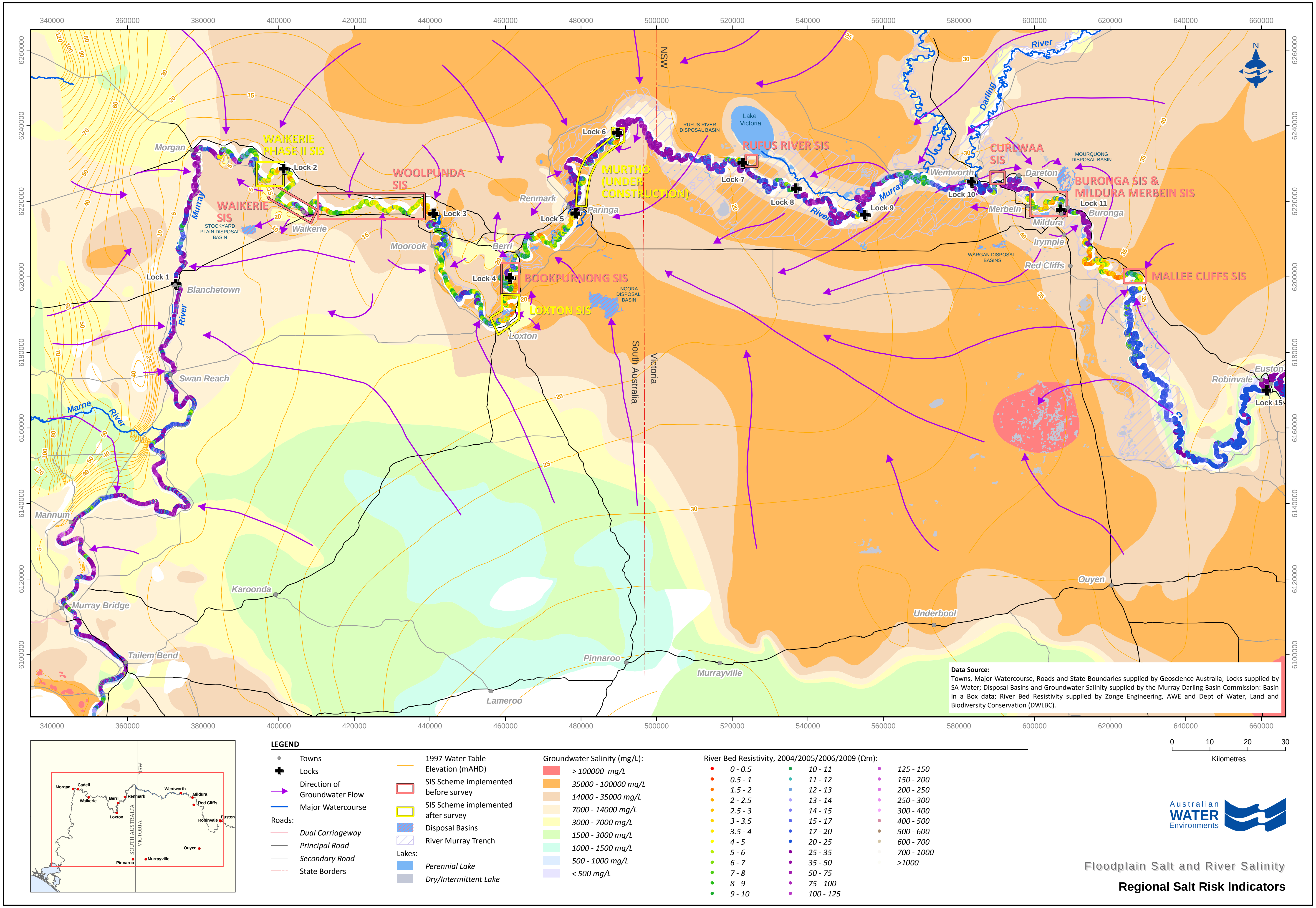
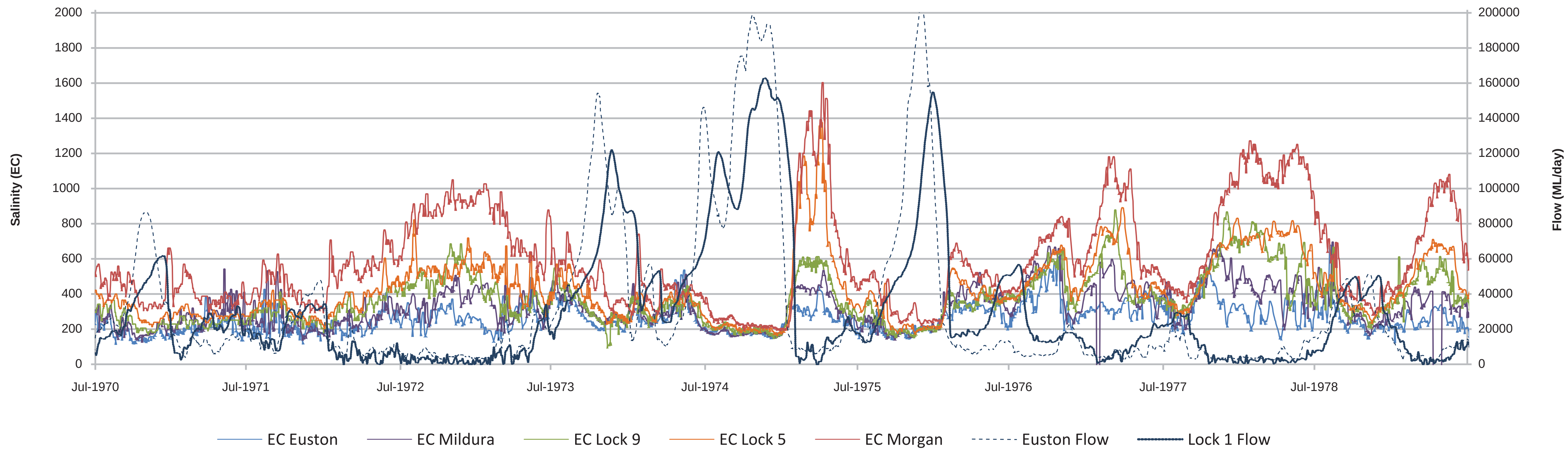
FIGURE A7



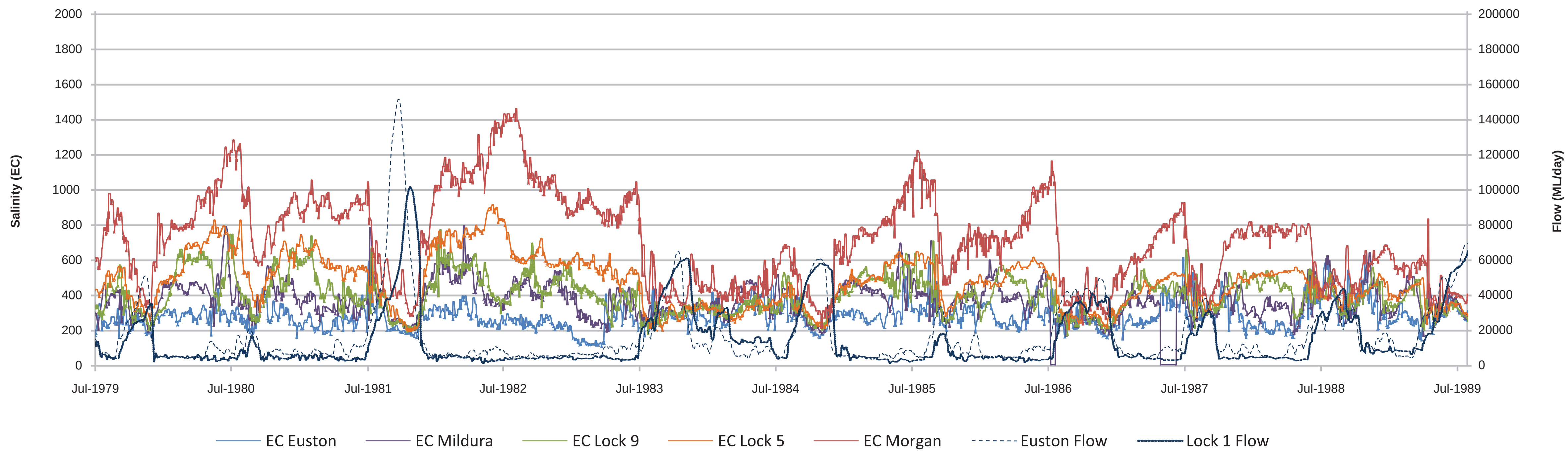
Job No. 10156 - 045
110105

FIGURE A8

Major Reach Flow and Salinity 1970-1979



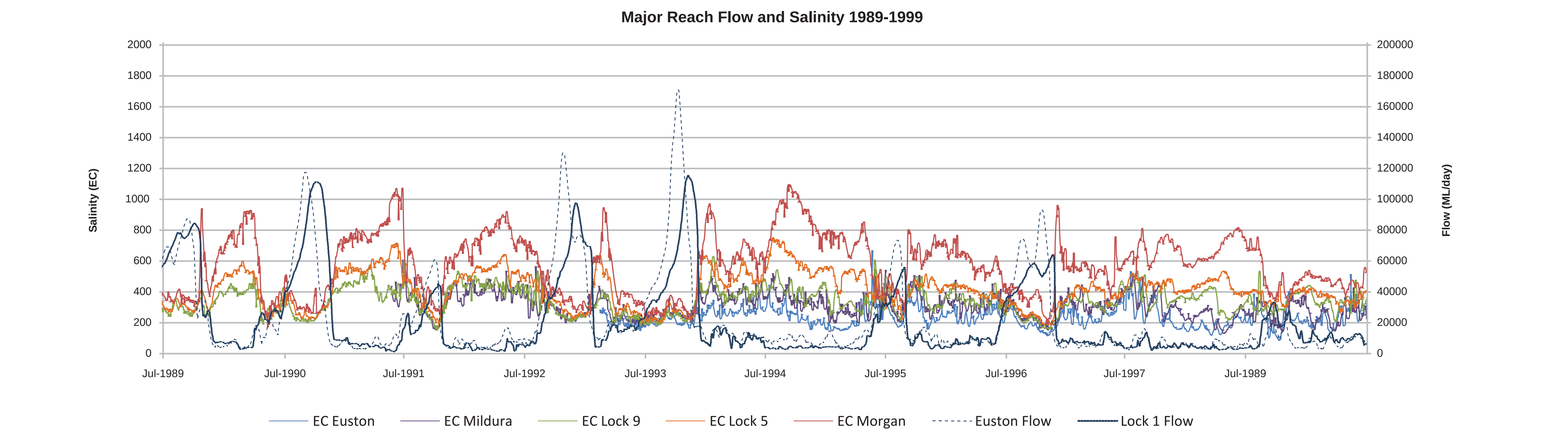
Major Reach Flow and Salinity 1979-1989

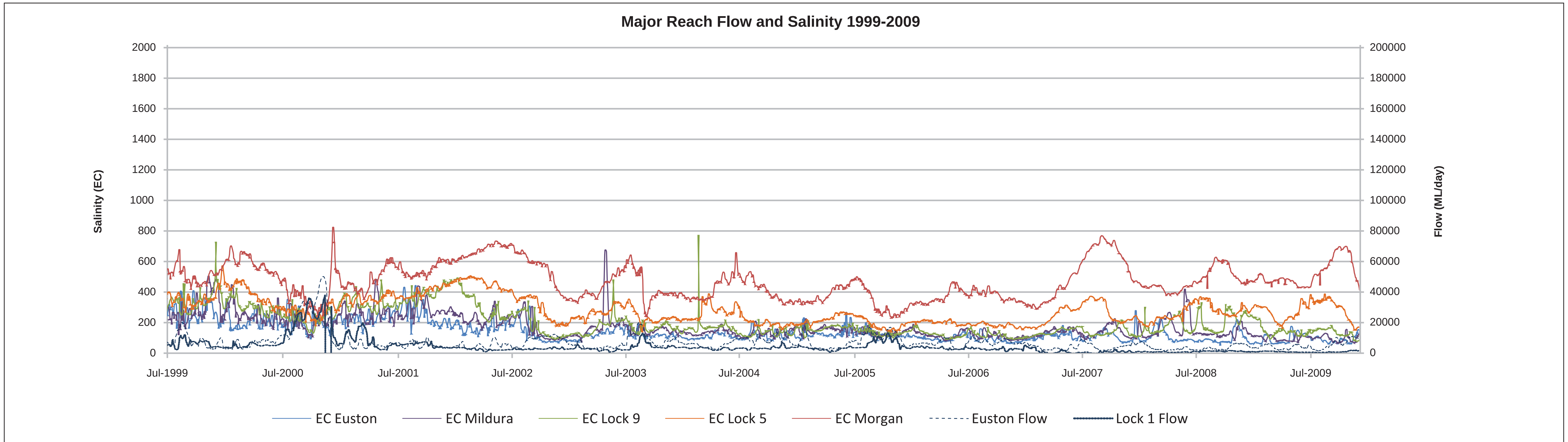


Australian WATER Environments

Floodplain Salt and River Salinity

Major Reach Flow and Salinity (Sheet 1 of 2)





Australian WATER Environments

Floodplain Salt and River Salinity

Major Reach Flow and Salinity (Sheet 2 of 2)

Australian Government

MURRAY–DARLING
BASIN AUTHORITY