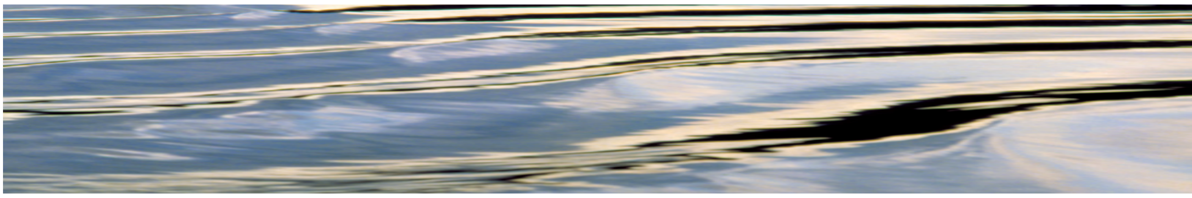
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

A REVIEW OF SALT MOBILISATION AND MANAGEMENT IN IRRIGATED AREAS OF THE MURRAY-DARLING BASIN

TECHNICAL REPORT
Report **05/1**
March 2005

Ruth Duncan / Matthew Bethune / Evan Christen / John Hornbuckle



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CSIRO

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A Review of Salt Mobilisation and Management in Irrigated Areas of the Murray-Darling Basin

Bibliography

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1. Water salinization - Control - Murray River Watershed (N. S.W.-S.Aust.). 2. Water salinization - Control – Darling River Watershed (Qld. and N.S.W.). 3. Drainage – Murray River Watershed (N.S.W.-S. Aust.). 4. Drainage – Darling River Watershed (Qld. and N.S.W.). 5. Murray River Watershed (N.S.W.-S.Aust.) - Environmental aspects. 6. Darling River Watershed (Qld. and N.S.W.) – Environmental aspects. I. Duncan, Ruth, 1981- . II. Cooperative Research Centre for Catchment Hydrology. (Series: Report (Cooperative Research Centre for Catchment Hydrology); 05/1).

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A Review of Salt Mobilisation and Management in Irrigated Areas of the Murray-Darling Basin

Ruth Duncan[1], Matthew Bethune[1], Evan Christen[2], John Hornbuckle[2]

[1] Department of Primary Industries, Victoria
[2] CSIRO Land and Water, Canberra, ACT

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Preface

Surface and sub-surface drainage schemes are vital components for managing waterlogging and salinisation in irrigation areas of Australia. These drainage schemes can contribute large amounts of salts, nutrients, and sediments into natural watercourses and have led to a decline in water quality in rivers and reduced health in some riverine ecosystems in the Murray-Darling Basin.

This document is part of the Cooperative Research Centre (CRC) for Catchment Hydrology's Project 2A, *'Reducing the impacts of irrigation and drainage on river water salinity.'* This project focuses on predicting and managing the impacts of irrigation and drainage on river water salinity. The major salt mobilisation processes affecting irrigation drainage salinity are identified and applied in the development of modelling tools for use specifically in irrigation areas. These modelling tools help managers develop scenarios to reduce the impacts of irrigation drainage on river water salinity. This report is the first step in this process, and provides a summary of the dominant salt mobilisation processes from irrigation areas.

Peter Wallbrink, Program Leader
Land-use Impacts on Rivers
CRC for Catchment Hydrology

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Executive Summary

The objective of this report is to review previous studies of salt mobilisation processes and management strategies in irrigation areas. Improved understanding will facilitate the identification of effective options for reducing the impact of drainage from irrigation areas on river water salinity. Although nutrients, sediments and pesticides are also major water quality issues associated with drainage from irrigation areas, they are not covered in this report.

Changed land use and irrigation has increased recharge to the groundwater system. Increased recharge has contributed to the formation of shallow watertables and is a major cause of salt mobilisation. Once mobilised, salt is transported to surface drainage and river systems through the following processes; salt wash-off, groundwater seepage, engineered sub-surface drainage and channel outfall.

Major findings of the report are:

- There are few good quality, long-term data sets available for assessing salt mobilisation from irrigation regions.
- Most calculations of salt mobilisation were conducted during the development and implementation of land and water management plans. Calculations were typically based on short periods of limited data and the accuracy of findings is difficult to assess. Interpretation of these calculations should consider the prevailing climatic conditions during the study.
- Salt mobilisation is highly variable between irrigation areas in the Murray-Darling Basin. The dominant process is affected by hydrogeological, management and climatic conditions.
- Salt mobilisation of up to 10 t/ha/year is recorded from irrigation areas.
- The volume of water from channel outfall and irrigation runoff entering the surface drains results in low salinity in most drains during the irrigation season. Higher drain salinity occurs during winter when diluting flows are less, the higher salinity levels being attributable to groundwater seepage, discharge from sub-surface drainage systems and rainfall induced surface wash-off.
- Sub-surface drainage can mobilise large amounts of salt from relatively small areas. There is potential to achieve reductions in salt loads from irrigation areas by changing management and design of sub-surface drainage systems by ensuring systems specifically provide the leaching requirement of irrigated crops.
- Groundwater seepage contributes large amounts of salt to drainage systems in areas with shallow saline watertables and deep drains.
- Large reductions in salt load have occurred from many of the irrigation areas in the Murray-Darling Basin over the last 10-20 years. These reductions are associated with a combination of management and climatic influences.
- The prevailing climatic conditions have a large impact on the magnitude, pathways for and management of salt mobilisation. Short-term studies may not capture the magnitude or pathways of salt mobilisation under the range of current climatic conditions in the Murray-Darling Basin. Management strategies need to be developed that manage salt mobilisation and export under the full range of climatic conditions.
- Considerable potential exists to divert a greater proportion of irrigation drainage flows from river systems for irrigation. Particularly, in the Murrumbidgee Irrigation Area and Shepparton Irrigation Area, where drainage water generally has a low to medium salinity (<3 dS/m) and would be suitable for irrigating salt tolerant crops.
- Retaining additional salt within irrigation regions should not have a substantial impact on regional groundwater quality or root zone salinity over the next 100 years. However, localised environmental or productivity losses could occur in some areas as a result of increased salt storage.
- The cost of diverting additional irrigation drainage water needs to be assessed against the benefits of improved water salinity in the river system. The costs and benefits associated with managing other water quality issues (nutrients, turbidity and pesticides) should be included into this analysis.

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1. Introduction

Irrigation provides the foundation for reliable agricultural production and regional economic security (Hillel 2000; Tanji 1990). There are 2.5 million hectares of irrigated land in Australia, corresponding to 1% of the agricultural land. The irrigation industry in Australia has diverse cropping and management systems. The irrigation industry contributes an estimated 26% ($28.3 billion) of the total gross value of agricultural production at the farm gate (Environment Australia 2001; McLennan 2000). Value adding of these primary products provides an estimated four-fold increase in economic value, making irrigation fundamental for the economic and social well-being of rural communities and Australia as a whole.

Eighty per cent of Australia's irrigated agriculture occurs within the Murray-Darling Basin (MDB) (Figure 1). Large storage reservoirs have been constructed to support the irrigation industry as rainfall in the MDB is highly variable both spatially and temporally (McMahon 1982; Finlayson 1988). This has resulted in the major rivers within the MDB becoming highly regulated. Currently about 70% of natural flows in the river system are diverted for consumptive use, with irrigation being the major water user. The changed flow regimes have affected the

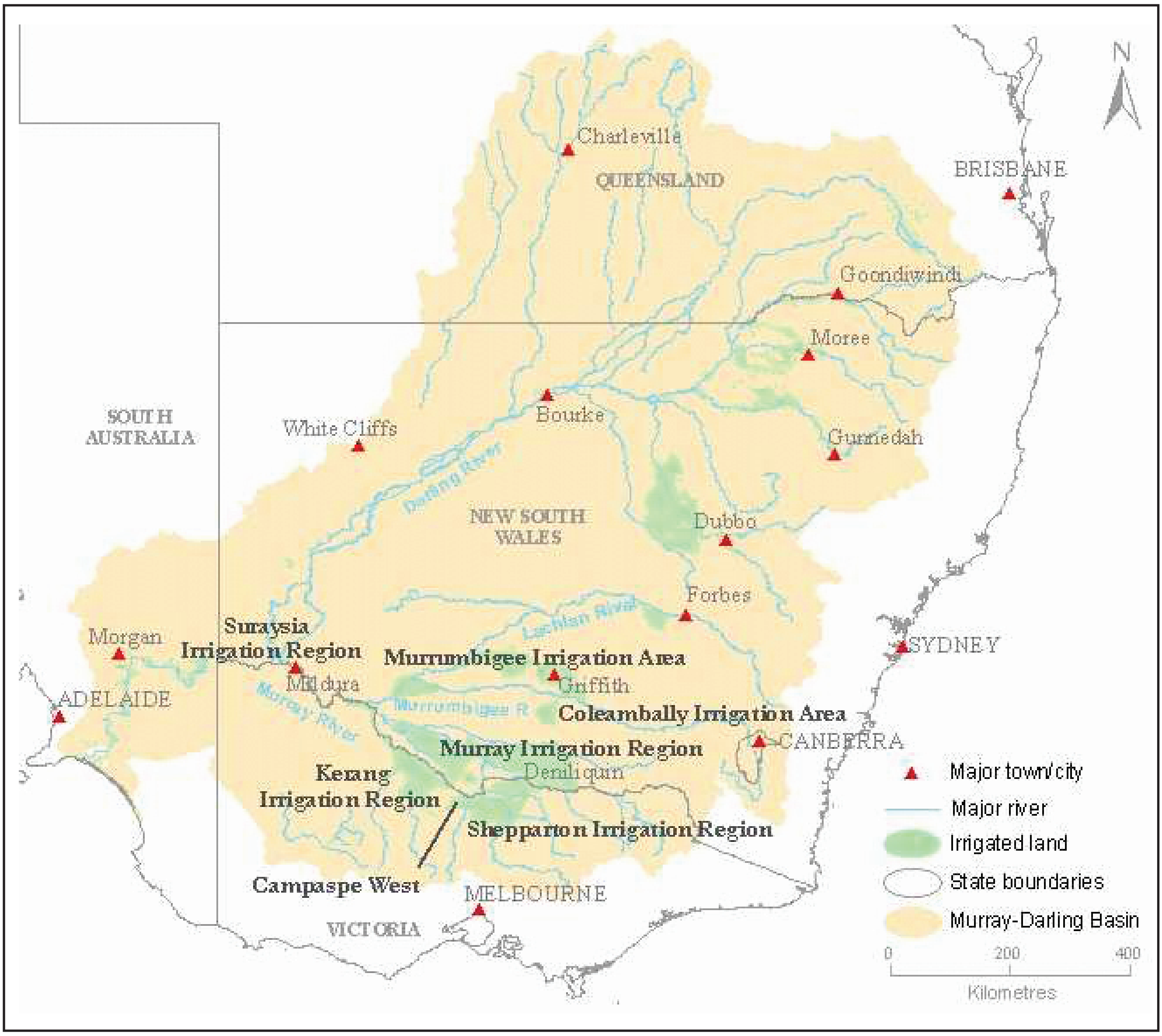


Figure 1. Location of Major Irrigation Areas in the Murray-Darling Basin (MDB). Adapted from data obtained from the Murray-Darling Basin Commission.

health of river ecosystems. Low river flows are threatening the health of some wetlands, including ten wetlands listed under the Ramsar convention (Crabb 1997a). The mouth of the Murray River (outlet of the MDB to the Southern Ocean) closed in 1981 for the first time in recorded history (Eastburn 1990). Since this time there has been considerable press coverage and community concern over the health of the river system.

River salinity trends in tributaries of the MDB are rising (Walker *et al.,* 1998; Williamson *et al.,* 1997). In the late 1980s, river salinity was identified as approaching undrinkable levels and potentially jeopardising the sustainability of irrigation in the lower reaches of the Murray River (MDBMC 1989; MDBMC 1999). There is considerable environmental and social pressure to reduce water salinity in rivers (Crabb 1997a; Blackmore *et al.,* 1999).

A range of government policies has been developed to combat rising salinity trends in the MDB. The Murray-Darling Basin Commission (MDBC) has established that each State is responsible for any actions significantly affecting river salinity to regulate impacts of irrigation areas on water quality (MDBMC 1989). States have been allocated a set Salt Disposal Entitlement to the river system each year. This has become a major factor in managing salt mobilised by irrigation drainage. Effective management of mobilised salt within the irrigation areas is necessary to enable productive agriculture and adherence to Salt Disposal Entitlement guidelines.

This document reviews studies of salt mobilisation processes and their management in irrigated areas with a view towards identifying options to reduce the impact of drainage return flows on river water quality.

2. Salt Mobilisation Processes In Irrigation Areas

Changed land use and irrigation has increased recharge to the groundwater system. This increased recharge has contributed to the formation of shallow watertables and is a major cause of salt mobilisation in the soil profile. Once mobilised, salt is transported to surface drainage and river systems through the following processes:

1. Salt wash-off;
2. Sub-surface drainage (engineering);
3. Groundwater seepage;
4. Channel outfall.

2.1 Salt Wash-off

Conceptually, two sources of salt contribute to salt loads in surface runoff in irrigation areas. The first source consists of salt applied in irrigation water and rainfall. Salinity of water diverted from rivers for irrigation is typically between 0.1 and 1.0 dS/m, increasing with distance downstream. Salt supplied by irrigation water also increases with groundwater or farm reuse. The second source consists of salt pickup from the soil. Salt pickup occurs in overland flow associated with both irrigation and rainfall. The magnitude of salt pickup increases as soil salinity increases, and is affected by irrigation supply volume, irrigation salinity, irrigation timing and soil type (Gilfedder *et al.,* 2000b; Rhoades *et al.,* 1997). Salt pickup should not be large in areas where leaching maintains soil salinity at levels suitable for agricultural production. Conversely, salt pickup will be large in discharge areas (Gilfedder *et al.,* 2000b) where soil salinity is high as a result of a shallow watertable and restricted leaching. Capillary rise of groundwater further concentrates salt in the surface soils in discharge areas (van Hoorn and van Alphen 1994). In some areas, watertables are high enough to intersect the soil surface and discharge directly to the surface (Mudgway *et al.,* 1997). Both these discharge scenarios result in elevated salt concentrations near the soil surface and contribute to high salt loads in surface runoff.

A number of mathematical approaches have been adopted to describe the salt wash-off process. A common approach is to assume that the soil has a shallow surface-mixing layer, and the concentration of salts in runoff is proportional to the soil salt concentration in this mixing layer. A refinement of this approach is to model the salt mass balance of the surface water body and the surface soil layer. Salt transport between these two compartments (Rp, kg/day) is a function of soil salinity in the mixing layer (EC_{soil}) and a constant (f) of proportionality (Equation 1) (Havis *et al.,* 1992; Connell *et al.,* 2003). This approach implies that there will be limited salt pickup during irrigation in areas with high leaching rates, as surface soil salinity will be low and of a similar magnitude to the irrigation water salinity. Transport of salt between soil and overland flow has also been described using Ficks law of diffusion (Equation 2). The diffusion coefficient (D) in Equation 2 would typically be found through a calibration process. Ficks law indicates that salt will only move from the soil into surface water if soil salinity is greater than salinity in the overland flow. Thus, salt pickup would still occur in rainfall runoff due to the low salt levels in rainfall.

$$R_p = EC_{soil} . f \tag{1}$$

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}(D\frac{\partial c}{\partial x}) \tag{2}$$

The mixing layer concept was found to provide the best description of salt pickup in a recent salt export study in the MDB (Connell *et al.,* 2003). In this approach, salt pickup is simply described as a constant proportion of the salt store in the mixing layer, where the mixing layer was assumed to be the upper 5 cm of the soil profile. The salt store in the mixing layer changes over time as a result of leaching, infiltration and salt pickup. This approach has been applied to catchment scale studies of salt loads in irrigation and rainfall runoff (Connell *et al.,* 2003; Sinclair Knight Merz 2003b; Nathan and Mudgway 1997).

2.2 Engineering Based Sub-Surface Drainage

Shallow watertables are now prevalent in all the major irrigation areas of the MDB. Sub-surface drainage is required to manage waterlogging and soil salinity. The two main forms of sub-surface drainage are horizontal drains and vertical tube well or spear point systems (Figure 2). Horizontal pipe drains are often used for high value perennial horticulture and pumping from tube wells or spear point systems to control salinity in lower value perennial pastures (Christen *et al.,* 2001).

Horizontal drains aim to remove excess soil water in a timely manner to prevent damage to crops arising from waterlogging and soil salinity (Ritzema 1994). The sub-surface drains are typically installed between 1.2 and 2.5 m depth and 20 to 80 m apart. Horizontal drains offer greater control over watertable conditions and the amount of groundwater extracted (Ritzema 1994) than vertical drains. However, shallow tube well or spearpoint systems can have considerably lower installation costs on a per hectare basis (Salinity Pilot Advisory Council 1989; Christen and Hornbuckle 2002).

Both forms of sub-surface drainage can generate large volumes of variable quality groundwater (Table 1). The amount of salt mobilised through sub-surface drainage is a function of the salinity of drainage water and the volume.

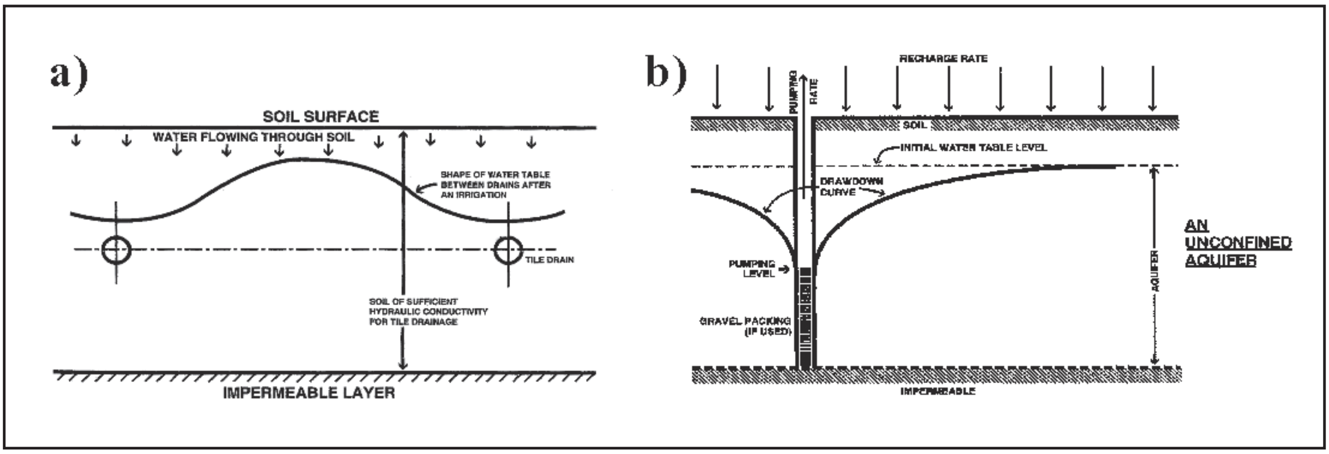


Figure 2. An Example of a (a) Horizontal Tile Drainage System and (b) a Tube Well Drainage System.

Table 1. Representative Groundwater, Irrigation Water and Sub-surface Drainage Salinity from Different Irrigation Areas.

Region	Groundwater (dS/m)	Irrigation Water (dS/m)	Sub-surface Drainage (dS/m)
Kerang	30 - 50	<0.4	Horizontal 20 - 50
Mid Murray	0.5 - 66	0.06	Vertical Public 23 Vertical Private 0.5 - 3
Murrumbidgee/Coleambally	1 - 20	0.05 - 0.15	Horizontal 2 - 12 Vertical 5 - 20
Riverland	1.6 - 3.9	0.3 - 0.8	Horizontal 1.6 - 47
Shepparton	1 - 10	0.05 - 0.15	Vertical Private up to 3.5 Vertical Public up to 10
Sunraysia	2 - 4	0.3 - 0.6	Horizontal 2 - 5

In the Shepparton Irrigation Region (SIR), about 1.5 t/ha/yr of salt is mobilised by spear point systems at a typical sub-surface drainage rate of 1 ML/ha/y and groundwater salinity of 2.5 dS/m. Design and operation of the sub-surface drainage system has a big impact on the volume of groundwater pumped and therefore the amount of salt mobilised (Table 2).

The volume of sub-surface drainage required to manage salinity and waterlogging can be either calculated or assumed using local knowledge. Ideally for salinity control, the amount of sub-surface drainage should be limited to the leaching requirement of the irrigated crop. The depth of groundwater extracted by the sub-surface drainage scheme (G) can be assumed to equal the sum of non-leaching recharge (NLR) and net deep drainage (D, deep percolation less capillary rise) (Equation 3). Capillary rise and evapotranspiration from the watertable can reduce D and the required sub-surface drainage rate. NLR does not contribute to rootzone leaching and includes channel seepage, drainage fluxes bypassing the rootzone and inflows/outflows of regional groundwater into the pumped aquifer (Prendergast *et al.,* 1994a).

$$G = D + NLR \qquad (3)$$

The amount of NLR will vary considerably between irrigation regions as a result of irrigation infrastructure and the underlying hydrogeology. For the SIR, a total NLR of 20 mm/year was estimated, with both channel seepage (McMahon 1984; Webster 1984) and bypass fluxes (Prendergast *et al.,* 1994a; Prendergast 1995) contributing around 10 mm/year. The amount of deep drainage (D) will depend on a range of factors, including soil type, irrigation management, irrigation water quality and hydrogeology (Bethune 2004).

2.3 Groundwater Seepage

High watertables can result in direct groundwater discharge to surface water features such as depressions, open drains, streams and creeks. This can lead to considerable salt export when discharge areas are connected to surface drainage systems. Accessions under irrigation can create large areas with high watertables and increase the gradient, seepage and salt transport between the groundwater and river (or drainage) system. Large gradients between groundwater and river systems naturally occur in areas with incised rivers, such as along reaches of the Lower Murray. The seepage of groundwater into the Lower Murray has been the focus of a number of investigations. Historically, the seepage of groundwater into rivers and irrigation drains in the upper reaches of the Murray-Darling River system has not been considered significant, except where drains or river channels are deep.

Direct groundwater seepage into watercourses can mobilise large amounts of salt. The rate of seepage is a function of the hydraulic gradient and the hydraulic connectivity between river and groundwater system. For a phreatic aquifer, the Dupuit-Forchheimer

Table 2. Mass of Salt Mobilised (t/ha/y) as a Function of Sub-surface Drainage Rate and Groundwater Salinity.

Drainage Rate (ML/ha/y)	**Groundwater Salinity (dS/m)**					
	1	**2.5**	**5**	**10**	**20**	**50**
0.5	0.3	0.75	1.5	3.0	6.0	15.0
1	0.6	1.5	3.0	6.0	12.0	30.0
2	1.2	3.0	6.0	12.0	24.0	60.0
5	3.0	7.5	15.0	30.0	60.0	150.0

discharge formula (Equation 4) is commonly used to calculate seepage (Q) to a watercourse. The total volume of seepage will be affected by the length of watercourse intersecting the groundwater body. Actual salt load depends on the volume of seepage and salinity of the groundwater body.

$$Q = K\frac{h_o^2 - h_L^2}{2L} \tag{4}$$

where:

h_o = watertable level in aquifer (m),

h_L = water level in watercourse (m),

L = distance (m),

K = hydraulic conductivity (m/day).

An extensive range of conceptual and physically based groundwater models used in the MDB have recently been described (Robins *et al.,* 2003). A recent modification to these traditional approaches was developed to describe the impact and timing of changes in recharge on groundwater discharge using a step response function. This approach calculates the flux to the river as a function of distance to river, hydraulic conductivity, average height of watertable, porosity of water bearing strata and recharge. Limited testing of this approach indicates that it could be a useful tool for describing water quality impacts of irrigation areas on incised river systems (Knight *et al.,* 2002).

2.4 Channel Outfall

Overflow from the irrigation supply system can directly enter the surface drainage system through channel outfall. Channel outfall is a relatively small source of salt to drains within irrigation areas due to the typically low volumes discharged and low salinity concentrations (0.1 - 0.8 dS/m). Within the NSW Murray Irrigation area, the lowest salinity concentrations in surface drains are recorded when channel outfall is highest indicating a dilution of flows (Marshall 2003). Large volumes of channel outfall occur within the Murrumbidgee Irrigation Area (MIA) to improve water quality for downstream irrigators. Elevated channel water salinity can occur when sub-surface drainage water is pumped directly into the channel system or where direct groundwater seepage into the channel system occurs.

3. Salt Mobilisation Processes from Irrigation Areas

3.1 Overview of Salt Mobilisation Studies

There is limited published data available on the quantification of salt mobilisation processes from irrigation regions within the MDB. The majority of work has been completed during the development and implementation of land and water management plans in major irrigation areas. A range of modelling and salt balance approaches have been adopted to describe salt mobilisation and export (Table 3). Most of this data exists as technical reports and has not been published in scientific literature. Collated in this review is data describing salt mobilisation from major irrigation regions in the Murray-Darling Basin (Figure 1).

The hydrogeological setting in each region is a key factor affecting salt mobilisation (Table 4). The Sunraysia Region is located on the edge of an incised river system. Irrigation induced recharge has led to groundwater pressures above the water level in the river system. Permeable materials result in high connectivity between the groundwater and the river system. The groundwater system is highly saline (60 dS/m). In contrast, the hydrogeological settings of the Shepparton Irrigation Region (SIR), Coleambally Irrigation Area (CIA), Murrumbidgee Irrigation Area (MIA) and Kerang Irrigation Region (KIR) are described as alluvial plains (Table 4). Salinities of the groundwater systems in the alluvial plains are variable, influenced by geology and geomorphology. The KIR is identified as contributing a disproportionately large amount of the salt load (9.6%) to the Murray River (Close 1990), when compared to other irrigation areas on alluvial plains. The KIR has large areas of saline soils caused by discharge of a highly saline groundwater system at the soil surface. The Shepparton, Coleambally and Murrumbidgee irrigation areas are underlain by less saline groundwater systems.

Table 3. Details of Modelled Studies Partitioning Salt Mobilisation Processes from Major Irrigation Areas in the Murray-Darling Basin.

Study	Region	Time Period	Method
[1]Sinclair Knight Merz (2003b)	Four sub-catchments of the Shepparton Irrigation Region (Victoria)	1990 -1999	Lumped conceptual model
[2]Coleambally Land and Water Management Plan Committee (1996)	Coleambally Irrigation Area (NSW)		Conceptual salt balance model
[3]van der Lely (1994)	Murrumbidgee Irrigation Area (NSW)	1978 -1990	Conceptual salt balance model
[4]Nathan and Mudgway (1997)	Calivil Creek sub-catchment of Kerang Irrigation Region (Victoria)	1979 -1989	Lumped conceptual model (MIDASS)
[5]Gilfedder *et al.* (2000b)	Drain 14 sub-catchment of Kerang Irrigation Region (Victoria)	1996/1997 irrigation season	Findings of irrigation bay monitoring experiment applied to sub-catchment
[6]Sinclair Knight Merz (2003a)	Sunraysia Region (Victoria and NSW)	2002	Conceptual salt balance model

[1]Sinclair Knight Merz (2003b); [2]Coleambally Land and Water Management Plan Committee (1996); [3](van der Lely (1994); [4]Mudgway *et al.,* (1997) [5]Gilfedder *et al.,* (2000b), This study did not measure rainfall wash-off; [6]Sinclair Knight Merz (2003a).

3.2 Quantification of Salt Mobilisation Processes

Review of the available data indicates salt loads mobilised from irrigated land in the MDB vary between 0.04 and 10 t/ha/yr (Table 5).

The magnitudes of salt mobilisation processes vary considerably between and within irrigation areas (Table 5).

The magnitude of the different process can also vary considerably year to year as a function of climate and management. Salt mobilisation from irrigated land can be relatively large compared to that generated from dryland areas. Salt loads from dryland catchments are typically less than 0.1 t/ha/yr (Crabb 1997). Higher rates of salt mobilisation from localised dryland areas have been recorded, for example regions within the Loddon river catchment (0.18 t/ha/yr) and Goulburn river catchment (0.31 t/ha/yr) in Victoria (Sinclair Knight Merz 1999; Earl 1988).

Table 4. Hydrologic Attributes and Management Factors for the Shepparton Irrigation Region, Coleambally Irrigation Area, Murrumbidgee Irrigation Area, Kerang Irrigation Region and Sunraysia Irrigation Regions in the Murray-Darling Basin.

Region	**Dominant Land use**	**Hydro-geologic setting**	***Total area (x1000 ha)**	**Drain Flow (x1000 ML/yr)**	**Drain Salt Load (x1000 T/yr)**	***Area with surface drainage (%)**	***Area with sub-surface drainage (%)**	***Type of sub-surface drainage**
Shepparton	Perennial Pasture	Alluvial Plain	500	490	175	54	14	Vertical
Coleambally	Rice	Alluvial Plain	95.2	161	142	100	0	-
Murrumbidgee	Large area farms	Alluvial Plain	207	222	62.2		10	Horizontal
Kerang	Perennial Pasture	Alluvial Plain	360	109**	198**	30	1	Surface drains
Murray	Perennial Pasture	Alluvial Plain	330		15.9*	84	16	Vertical
Sunraysia	Viticulture	Incised River	13	14.5	111	0	85	Horizontal

*(ANCID 2004) ** estimated from (TPSRWG 1989b).

Table 5. Modelled Annual Salt Mobilisation to Drains in Different Irrigated Catchments.

Irrigation Area	Area	Salt Wash-off		Groundwater Seepage		Sub-surface Drainage		Channel Outfall		Total	
	ha	ML/ ha	T/ ha	ML/ha	T/ ha	ML/ ha	T/ ha	ML/ ha	T/ ha	ML/ ha	T/ ha
Shepparton Irrigation Region											
Toolamba[1]	3,000	0.24	0.04	0	0	0	0	0	0	0.24	0.04
Murray Valley[1]	19,100	1.27	0.23	0.02	0.02	0.03	0.05	0.19	0.01	1.51	0.31
Upper Deakin[1]	16,000	0.97	0.26	0.04	0.10	0.09	0.30	0.04	0	1.15	0.66
Lockington[1]	26,400	0.42	0.14	0.02	0.05	0.01	0.02	0.14	0.01	0.59	0.22
SIR Average[1]		0.72	0.17	0.02	0.04	0.03	0.09	0.09	0.01	0.87	0.31
Murrumbidgee/Coleambally Irrigation Areas											
CIA[2]	79,000	0.80	0.17	-	-	0	0	1.24	0.1	2.04	0.18
MIA[3]	207,500	0.47	0.10	0.005	0.002	0.07	0.15	0.53	0.05	1.07	0.30
MIA - farms without sub-surface drainage[3]	188,000	0.42	0.10	-	-	-	-	-	-	0.42	0.10
MIA - farms with sub-surface drainage[3]	15,000	1.2	0.13	-	-	0.97	2.12	-	-	2.17	2.25
Kerang Irrigation Region											
Calivil Creek[4]	46,500	1.86	3.58	0.01	0.17	0	0	0	0	1.87	3.74
Drain 14[5]	2,700	-	1.60	-	4.60	0	0	-	-	-	6.20
Sunraysia Region[6]	10,974			0.36	9.20	0.96	0.91	-	-	1.32	10.11

[1] Sinclair Knight Merz (2003b); [2] Coleambally Land and Water Management Plan Committee (1996); [3] (an der Lely (1994); [4] Mudgway *et al.,* (1997) [5] Gilfedder *et al.,* (2000b), This study did not measure rainfall wash-off; [6] Sinclair Knight Merz (2003a).
- denotes not assessed.

Groundwater Seepage

The highest salt mobilisation per hectare occurs in the Sunraysia Region (Table 5). In this region groundwater seepage accounts for 90% of the salt mobilised in the irrigation area, with groundwater flowing directly to the river Murray as well as via its floodplain (Figure 3) (Sinclair Knight Merz 2003a). Approximately 9.2 t/ha/year of salt is mobilised as irrigation recharge passes through the underlying saline Parilla Sand aquifer (50 - 65 dS/m).

Salt mobilised through groundwater seepage is highly variable within irrigation areas located on alluvial plains. The Drain 14 sub-catchment of the Barr Creek in the KIR has been estimated to mobilise 4.6 t/ha/yr salt (Table 5) (Gilfedder *et al.,* 2000b; Gilfedder 1999). Deep surface drains (> 2 m depth) were installed to manage waterlogging and salinisation of the region in the 1930s. These deep drains intersect a highly saline watertable located typically 1 m below the surface. This causes substantial seepage of groundwater into drains. Conversely, shallow surface drains (0.3 m) in the nearby Calivil Creek mobilise only 0.2 t/ha/year of salt (Table 5). It is likely that the difference in drain depth is the primary cause of the difference in salt mobilisation between the Drain 14 and Calivil Creek sub-catchments.

Drain depth may also contribute to substantial groundwater seepage into the Box Creek (Murray Irrigation Region). Box Creek is recognised as the key source (approximately 72%) of salt load mobilised from the region (Marshall 2003). Groundwater seepage is considered the dominant process as 70% of the drainage channel is below the watertable (Marshall 2003).

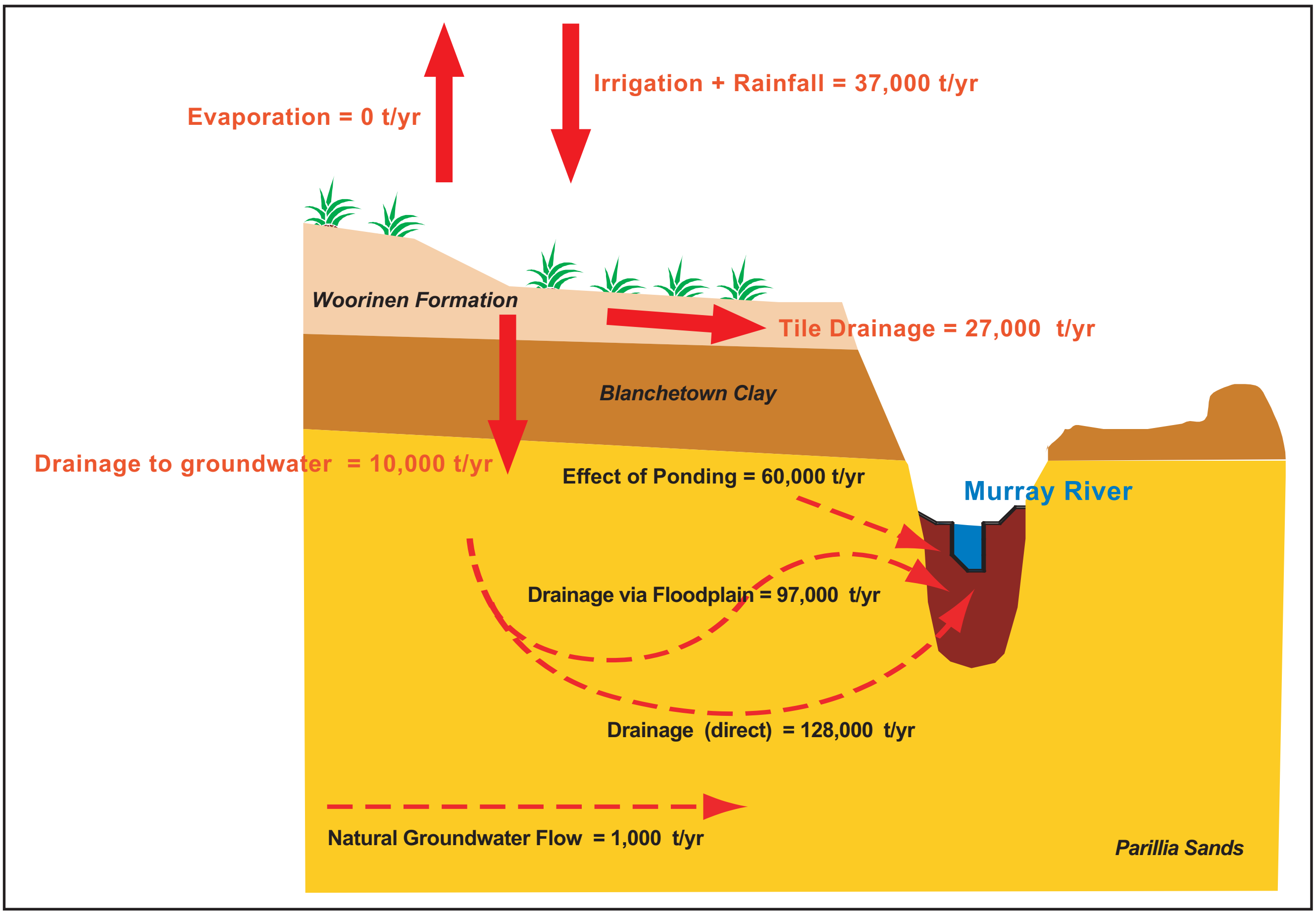


Figure 3. Salt Transport Pathways within the Sunraysia Region.

Source: (Sinclair Knight Merz 2003a) Fig. 6.9.

Groundwater seepage is generally considered a small source of salt in surface drains of the Shepparton, Coleambally and Murrumbidgee irrigation area (Table 6). Variation in groundwater seepage is evident in the Shepparton area, where groundwater seepage contributes between 0 t/ha/year (0%) in the Toolamba sub-catchment to 0.1 t/ha/year (23%) in the Lockington sub-catchment (Sinclair Knight Merz 2003b). The difference is likely to be caused by relatively deep drains and more saline watertables in the Lockington area than found in the Toolamba sub-catchment.

Salt Wash-off

The highest rate of mobilisation through salt wash-off occurs in the KIR, estimated to be of the order of 1.6 to 3.6 t/ha/yr (Table 5) (Mudgway *et al.,* 1997; Gilfedder *et al.,* 2000a). This relatively high level of salt wash-off is a result of the highly saline soils and shallow saline watertables. The lower rate of salt wash-off (1.6 t/ha/yr) occurred in an area with deep surface drains, which would lower watertable levels and rootzone salinity. Higher salt wash-off occurred in an area with shallow drains where watertables (and soil salinity) are likely to be greater. The deep drains appear to lower salt wash-off, but at the same time contribute to greater mobilisation through groundwater seepage. This implies that there is a trade-off between the two salt mobilisation processes. Management practices targeting reduced salt mobilisation need to consider this interaction between the different salt mobilisation processes and try to minimise their combined contribution. For the SIR, CIA and MIA salt wash-off is estimated to be 0.04 to 0.26 t/ha/yr, significantly lower than the areas dominated by shallow saline watertables (Table 5).

Table 6. Modelled Partitioning of Annual Salt Mobilisation to Drains in Different Irrigated Catchments as a Percentage of Total Salt Load Mobilised.

Irrigation Area	**Salt Wash-off %**	**Groundwater Seepage %**	**Sub-surface Drainage %**	**Channel Outfall %**
Shepparton Irrigation Region				
Toolamba[1]	100	-	-	-
Murray Valley[1]	74	6	16	3
Upper Deakin[1]	39	15	45	-
Lockington[1]	64	23	9	5
SIR Average[1]	54	14	30	2
Murrumbidgee/Coleambally				
CIA[2]	94	-	-	6
MIA[3]	33	1	50	17
MIA Farms without sub-surface drainage[3]	100	-	-	-
MIA Horticultural farms with sub-surface drainage[3]	6	-	94	-
Kerang Irrigation Region				
Calivil Creek[4]	96	5	-	-
Drain 14[5]	26	74	-	-
Sunraysia[6]	-	91	9	-
AVERAGE	**57**	**19**	**21**	**7**

[1]Sinclair Knight Merz (2003b); [2]Coleambally Land and Water Management Plan Committee (1996); [3](van der Lely (1994); [4]Mudgway *et al.,* (1997) [5]Gilfedder *et al.,* (2000b), This study did not measure rainfall wash-off; [6]Sinclair Knight Merz (2003a)

Sub-surface Drainage

The highest reported salt mobilisation through sub-surface drainage occurs under tile drained horticultural land in the MIA (Table 5), with over 2 t/ha/year of salt being discharged directly into surface drains (van der Lely 1994). Horticultural land represents less than 10% of the total area in the MIA, but accounts for approximately half of the salt entering the surface drainage system (Table 6). This indicates large reductions in salt mobilisation may be achievable by targeting small areas of sub-surface drainage (Figure 4a). Tile drained horticultural land in the Sunraysia irrigated area also mobilises a substantial amount of salt (1 t/ha/year) (Sinclair Knight Merz 2003a), which is disposed to the river through surface drains (Table 6).

Tube well sub-surface drainage has been found to mobilise approximately 0.1 t/ha/yr of salt to the SIR surface drainage system (Table 6), calculated from an average of four sub-catchments (Sinclair Knight Merz 2003b). This value underestimates the total impact of sub-surface drainage on salt loads in drains in the SIR as it does not include the impact of farm reuse of groundwater on salt loads in irrigation runoff. For example, the Murray Valley area (sub-catchment of the SIR) has an average sub-surface drainage rate of 0.5 ML/ha/year, which mobilises 0.6 t/ha/year of salt (Table 2). Only part of this salt load (0.05 t/ha/yr) is directly exported from the region as the drainage water is reused for irrigation (Table 5).

The Upper Deakin drainage district has relatively higher salt mobilisation (Table 5) entering surface drains through sub-surface drainage (0.3 t/ha/year) than the other districts studied in the SIR (Sinclair Knight Merz 2003b). Approximately 1,440 ML/yr of sub-surface drainage is disposed directly to surface drains in the Upper Deakin (Sinclair Knight Merz 2003b). Based on a sub-surface drainage rate of 1 ML/ha (Salinity Pilot Advisory Council 1989), 1,440 ha of land is protected by sub-surface drainage in the Upper Deakin sub-catchment. This indicates that sub-surface drainage protects 10% of the land, but contributes approximately half of the salt load to the drain in the Upper Deakin (Figure 4b).

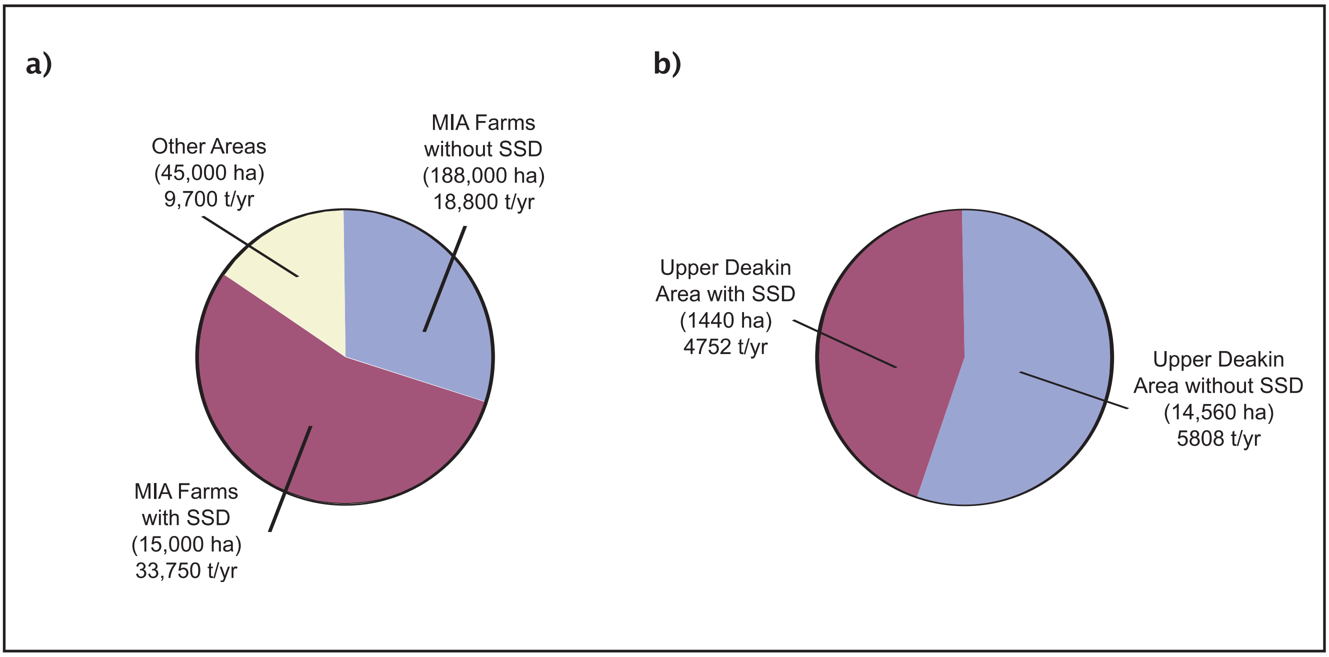


Figure 4. a) Contribution of Farms with and without Sub-surface Drainage (SSD) to Total Salt Load Leaving the Murrumbigee Irrigation Area per Year. (Adapted from van der Lely 1994)
b) Contribution of Farms with and without Sub-surface Drainage (SSD) to Total Salt Load Leaving the Upper Deakin Drainage Catchment within the Shepparton Irrigation Region per Year. (Adapted from Sinclair Knight Merz 2003b)

3.3 Identification of Processes from Historical Surface Drainage Data

The results reported in the previous section relate to studies that attempted to partition salt loads into the contributing mobilisation processes using a range of modelling approaches (Table 3). Each of these studies was based on a number of key assumptions required to simplify the complex physical environment using limited observed data. The different time periods covered in each study makes direct comparison difficult due to the highly variable climatic conditions found in the Murray-Darling Basin. Additionally, the dominant salt mobilisation processes are likely to change over time as a result of climate and/or management. Consequently, the applicability of studies conducted twenty years ago to current climatic and management conditions should be considered before management scenarios are developed.

To address this, supporting evidence of the dominant salt mobilisation processes is sought from historical stream flow and salinity records. Analysis of temporal changes in stream flow, salinity and salt load assist in identifying key mobilisation processes (Walker *et al.,* 1998). This is possible due to the differences between the salinity of rainfall (about 0.05 dS/m), river diversions for irrigation (0.1-1.0 dS/m) and groundwater (2-40 dS/m). Groundwater salinity can be as low as 10 times, but up to 1,000 times greater than the salinity of irrigation runoff. Salt supplied to a watercourse in episodic events such as surface wash-off following a low rainfall summer season can cause a pattern of increased stream salinity with increased salt load (Williamson *et al.,* 1997). Salt supplied to a watercourse at a constant rate from groundwater discharge or a point source (e.g. sub-surface drainage) will cause a pattern of increased stream salinity with decreased salt load (Williamson *et al.,* 1997).

Drainage hydrographs of the Barr Creek indicate that salt load, salinity and flow are highly variable over time (Figure 5).

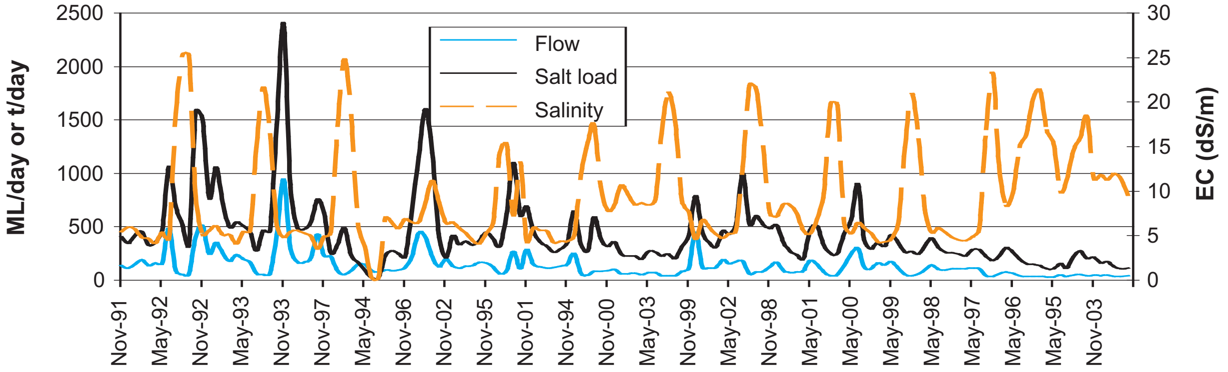


Figure 5. Time Series of Salinity, Flow and Salt Load in Barr Creek (407252), Kerang Irrigation Region (1991-2004).

It is difficult to ascertain relationships between salt load, salinity and flow from this temporal presentation of data. Williamson *et al.,* (1997) propose that graphing the relationship between salt load and salinity could help elucidate the dominant process contributing to stream salinity. The relationship between salt load and salinity in Barr Creek indicates a pattern of increased salinity with decreasing salt load (Figure 6). This pattern is consistent with that caused by groundwater seepage into the watercourse. The dominant salt source can also be assessed by comparing mean (9.75 dS/m) and median (6.22 dS/m) drainage salinity, a higher mean than median being characteristic of a watercourse affected by groundwater seepage. (Williamson *et al.,* 1997).

The relationship between drain salt load, salinity and flow data was analysed for both irrigation-dominant (October to May) and rainfall-dominant (June to September) periods. Data for four drains are reported, each displaying a different dominant salt mobilisation process:

1. Groundwater seepage - Barr Creek (KIR).
2. Surface wash-off - Murray Valley Drain 6 (SIR).
3. Sub-surface drainage - MDJWE Drain (MIA).
4. Mixed processes - Lockington Main Drain (SIR).

Groundwater Seepage Dominant - Barr Creek

Barr Creek is a deep surface drain located in the Kerang Irrigation Region (KIR). The peak salt load and flow from Barr Creek occurs during September to November (Figure 7) while salinity peaks during the period of lowest flow in July.

The relationship between salt load and salinity shows a pattern of increasing salinity with decreasing salt load during both the irrigation-dominant and rainfall-dominant seasons (Figure 8a,c). This suggests that groundwater seepage is likely to be a major salt source to the drain supporting findings of Gilfedder (1999) for Drain 14, a sub-catchment of Barr Creek (Table 5). The slope of the salt load versus flow relationship is greater in the rainfall-dominant season, indicating higher salinity drain flows at this time than during irrigation-dominant season (Figure 8b,d). The lower average salinity in the irrigation-dominant season (7.1 dS/m) compared to the rainfall-dominant season (13.5 dS/m) is indicative of dilution due to irrigation runoff and channel outfall (Figure 8a,c).

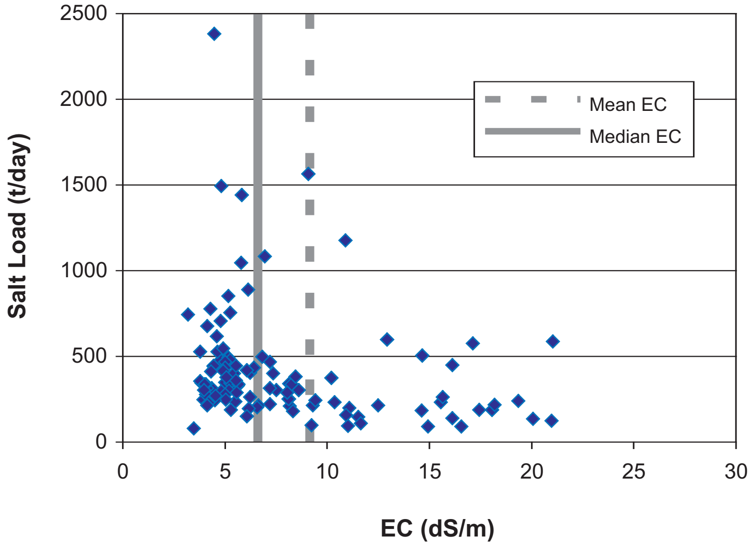


Figure 6. Relationship between Salt Load and Salinity for Barr Creek (407252) from 1991 - 2004.

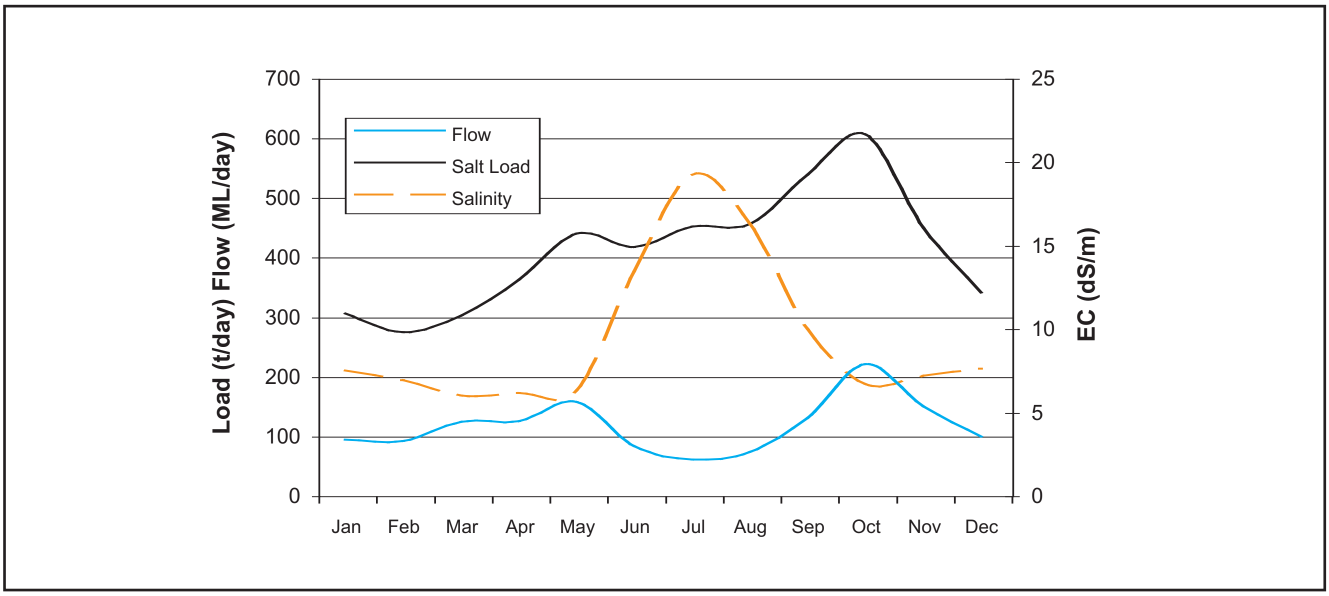


Figure 7. Average Daily Salt Load, Salinity and Drainage Volume Data per Month for Barr Creek (407252) (1991-2004).

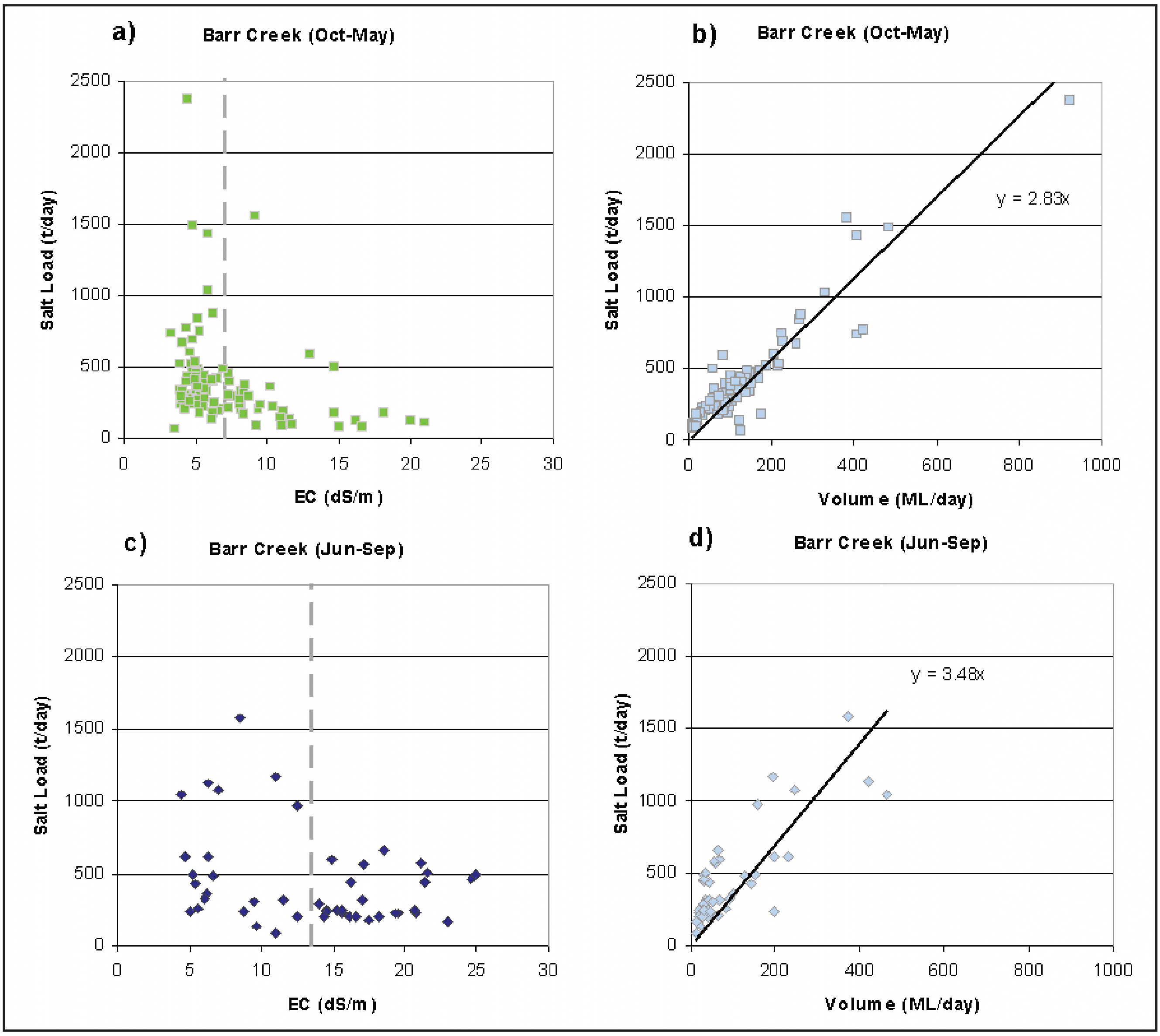


Figure 8. Relationship between Monthly Salt Load, Salinity and Drainage Volume in the Irrigation-Dominant Season (Oct- May) and Rainfall-Dominant Season (Jun-Sep) for Barr Creek (407252) (1991- 2004). Mean salinity is indicated.

Surface Wash-off Dominant - Murray Valley Drain 6

Murray Valley Drain 6 is located in the north-east of the SIR. Average salt loads and drainage flows are greatest during the irrigation-dominant season (Figure 9). Similar to the Barr Creek, drain salinity peaks during the rainfall-dominant season when drain flow is at a minimum (Figure 7).

Drainage flow is substantially higher during the irrigation-dominant season than rainfall-dominant season (Figure 10), suggesting that irrigation runoff contributes substantially to drainage flows. During this period there is no clear relationship between salt load and drain salinity (Figure 10a), but salt load shows a linear relationship with flow (Figure 10b). This indicates that the salinity of water entering the drain is relatively constant (average salinity of 0.3 dS/m) and independent of flow over the irrigation-dominant season. Water delivered to the farm gate is of the order of 0.1 dS/m. The average volume of groundwater pumped for irrigation in the area is 0.5 ML/ha/year at a salinity of 2.1 dS/m. The blended mix of groundwater and channel supply water will thus have a salinity of 0.3 dS/m. Therefore, drain salinity is consistent with salinity of irrigation water applied after adjustment for groundwater reuse. This suggests that salt loads in the Murray Valley Drain 6 are dominated by irrigation runoff during the irrigation season.

The relationship between salt load, drain salinity and flow is not well defined during the rainfall-dominant season, indicating that a number of processes are likely to contribute to salt loads in the drains over this period.

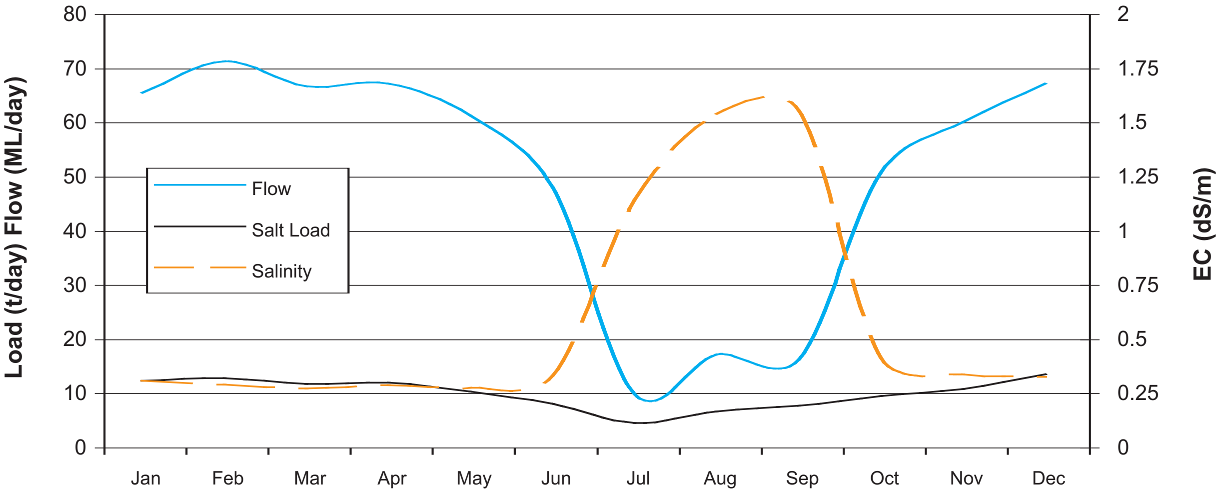


Figure 9. Average Monthly Salt Load, Salinity and Drainage Volume Data for the Murray Valley Drain 6 (409712) (1990-2004).

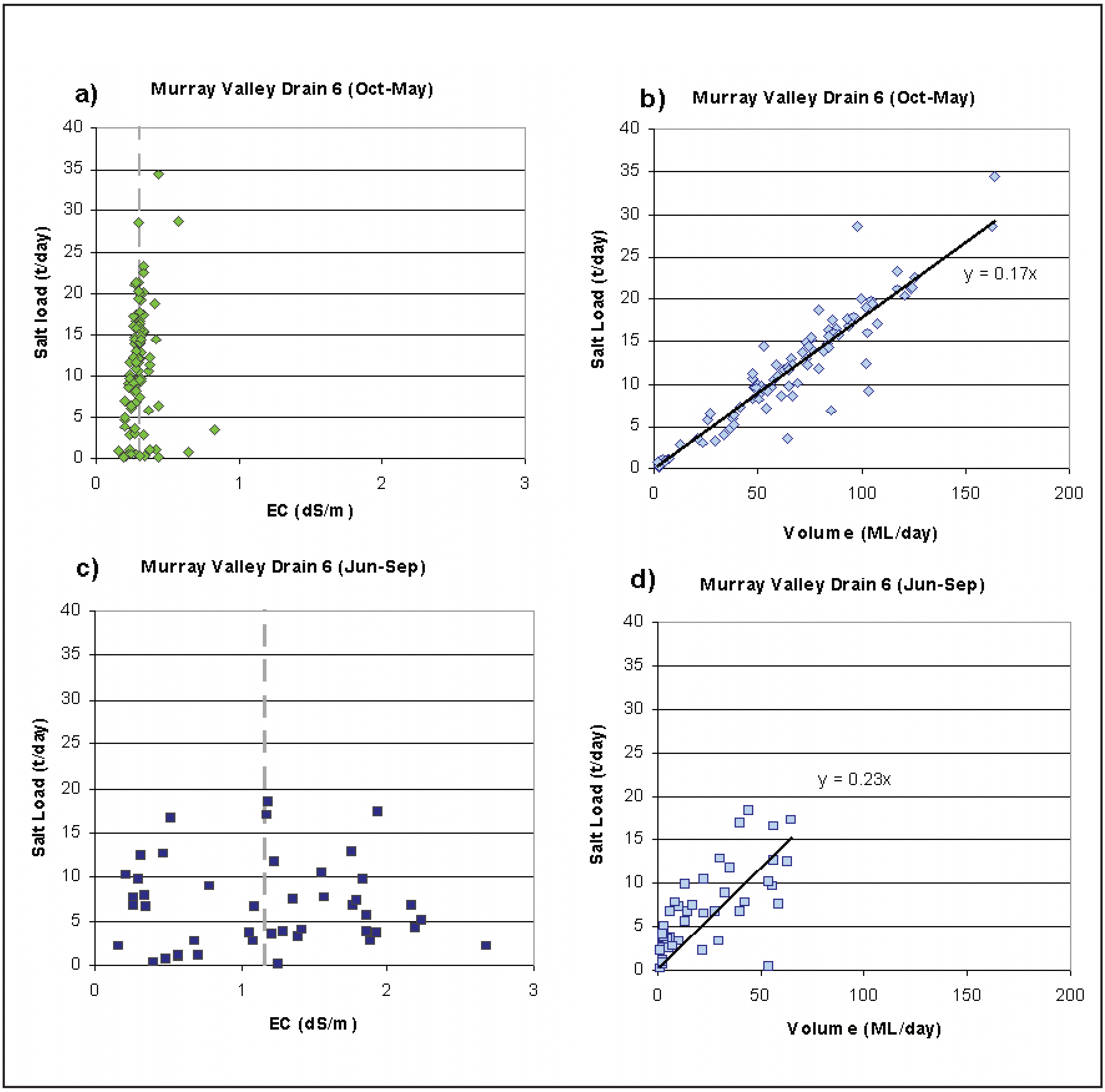


Figure 10. Relationship Between Monthly Salt Load, Salinity and Drainage Volume in the Irrigation-Dominant Season (Oct- May) and Rainfall-Dominant Season (Jun-Sep) for the Murray Valley Drain 6 (409712) (1990-2004). Mean salinity as indicated.

Sub-surface Drainage Dominant - MDJWE

Drain MDJWE is located in the horticultural area of the Murrumbidgee Irrigation Area (MIA). Salt load and drain flow are greatest during the irrigation-dominant season (Oct-May) (Figure 11). High drain flow is attributable to relatively large channel outfall. Average drain salinity during the irrigation-dominant season is of the order of 0.3 dS/m. This is twice as saline as channel supply water (0.15 dS/m) in the irrigation region. There is no clear pattern between salt load and drain salinity (Figure 12a), rather salt load is a linear function of flow (Figure 12b). This relationship indicates that the salinity of water entering the drain is relatively constant (average salinity of 0.3 dS/m) and independent of flow over the irrigation-dominant season. This drain services an area of intensive horticulture where sub-surface drainage discharges to the drain. A drain salinity of 0.5 dS/m would be expected if average rates (1 ML/ha/year) and salinity (0.6 dS/m) of sub-surface drainage were discharged to the drain and it is assumed that the rest of the drainage flows are attributable to low salinity channel outfall. Recent calculations of sub-surface drainage in the MIA indicate the average rate has reduced to 0.5 ML/ha/year. If this figure (0.5 ML/ha/year) is adopted in the analysis, a drain salinity of 0.35 dS/m is expected, assuming the rest of the drainage flows are attributable to low salinity channel outfall. This calculated drain salinity is consistent with average measured drainage salinity during the irrigation-dominant season (Figure 12a).

Drain salinity peaks during the rainfall-dominant period at 0.9 dS/m, when there are less dilution flows from channel outfall (Figure 12c). While the number of data points are limited (only 4 years of monthly observations), the salt load and salinity data show a pattern of decreasing salt load with increasing drain salinity. This implies that sub-surface drainage is the dominant process contributing to salt loads. An average salinity of drainage flows of 1.1 dS/m is calculated from average rates (0.5 ML/ha/year) and salinity (0.6 dS/m) of sub-surface drainage and by assuming that the rest of the drainage flows during the rainfall-dominant season are low salinity (0.15 dS/m). This is slightly higher than the measured peak salinity of the drain, indicating that sub-surface drainage would account for all of the salts in the drain over this winter period. MDJWE drainage data support modelled salt mobilisation rates through sub-surface drainage (Table 3) under the tile drained horticultural areas in the MIA.

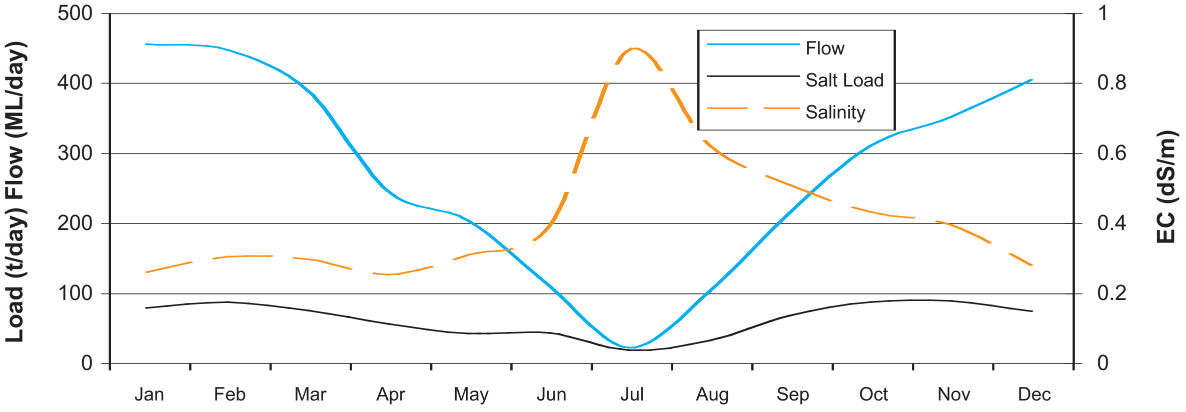


Figure 11. Monthly Salt Load and Salinity Data for Drain MDWJE (410174) in the Murrumbidgee Irrigation Area (1998-2003).

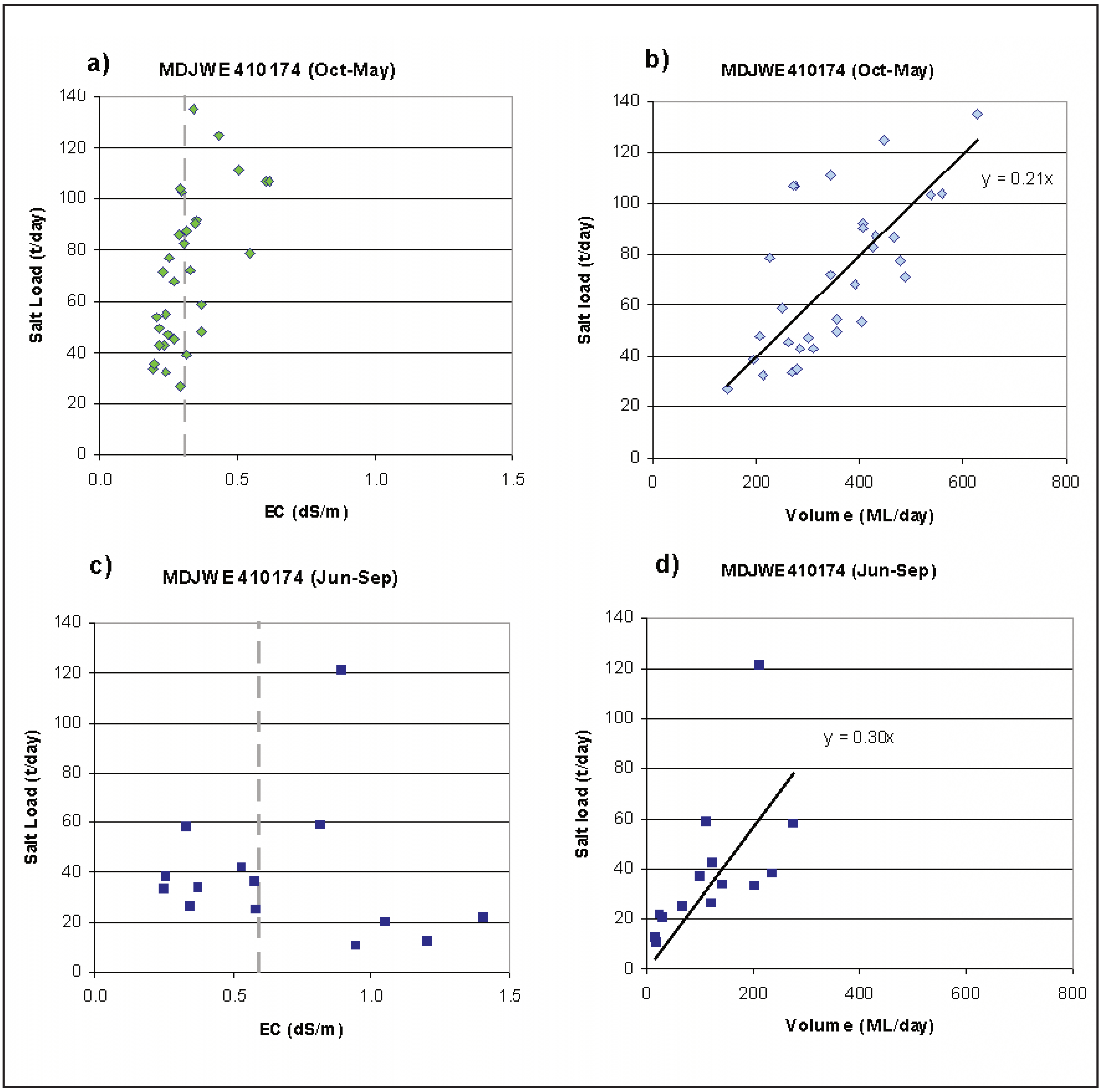


Figure 12. Relationship between Monthly Salt Load, Salinity and Drainage Volume in the Irrigation-Dominant Season (Oct-May) and Rainfall-Dominant Season (Jun-Sep) for MIA drain MDJWE (410174) (1998-2003). Mean salinity as indicated.

Mixed Processes - Lockington Main Drain

Lockington Main Drain is located in the north-west of the SIR. The average temporal trends suggest that flow and salt load increase over the rainfall-dominant season (May-Oct), with both drainage flow and salt load reaching a maximum in November. Drain flow and load gradually decline as the irrigation-dominant season progresses (Figure 13). Drainage salinity peaks during the rainfall-dominant season in September, but is relatively constant during the irrigation-dominant season.

Changes in salt load appear to be relatively insensitive to drain salinity over the irrigation-dominant season (Figure 14a,c), indicating that variable quantities of water of constant salinity are being supplied to the drain. This is consistent with a salt wash-off process. Drain salinity exceeds the average irrigation water salinity (0.18 dS/m, after adjustment for groundwater reuse) in the drainage catchment. This indicates that salt pickup from the soil in overland flow may be substantial.

Salt concentrations in drainage water in the Lockington Drain is greater during the rainfall-dominated season than during the irrigation-dominated season (Figure 14a,c). Groundwater seepage seems to be substantial during the late winter and spring period when watertable levels approach the surface due to rainfall excess and lower evaporative demand. The residuals between drain salt load and flow over the rainfall-dominant season were compared to the fraction of the Lockington drainage area with watertables within 2 m of the surface (Figure 15). High residuals (high load compared to flow) occur when large areas have shallow watertables, indicating that relatively large amounts of salt are being mobilised through groundwater seepage. Small residuals (most of salt load is described by flow) occur when watertables are deeper and unlikely to contribute groundwater to the drainage system (Figure 15).

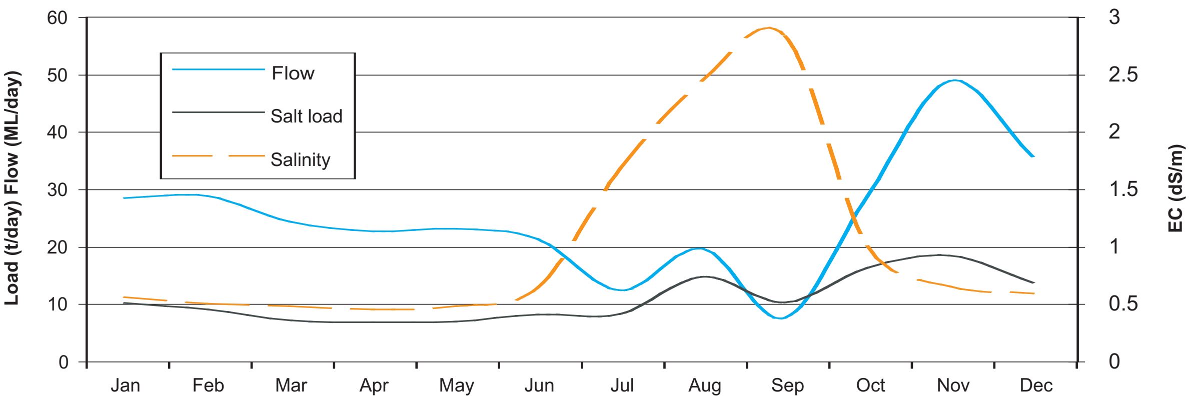


Figure 13. Average Temporal Pattern in Salt Load, Salinity and Drainage Volume Data for the Lockington Main Drain (407712), Shepparton Irrigation Region (1990-2004).

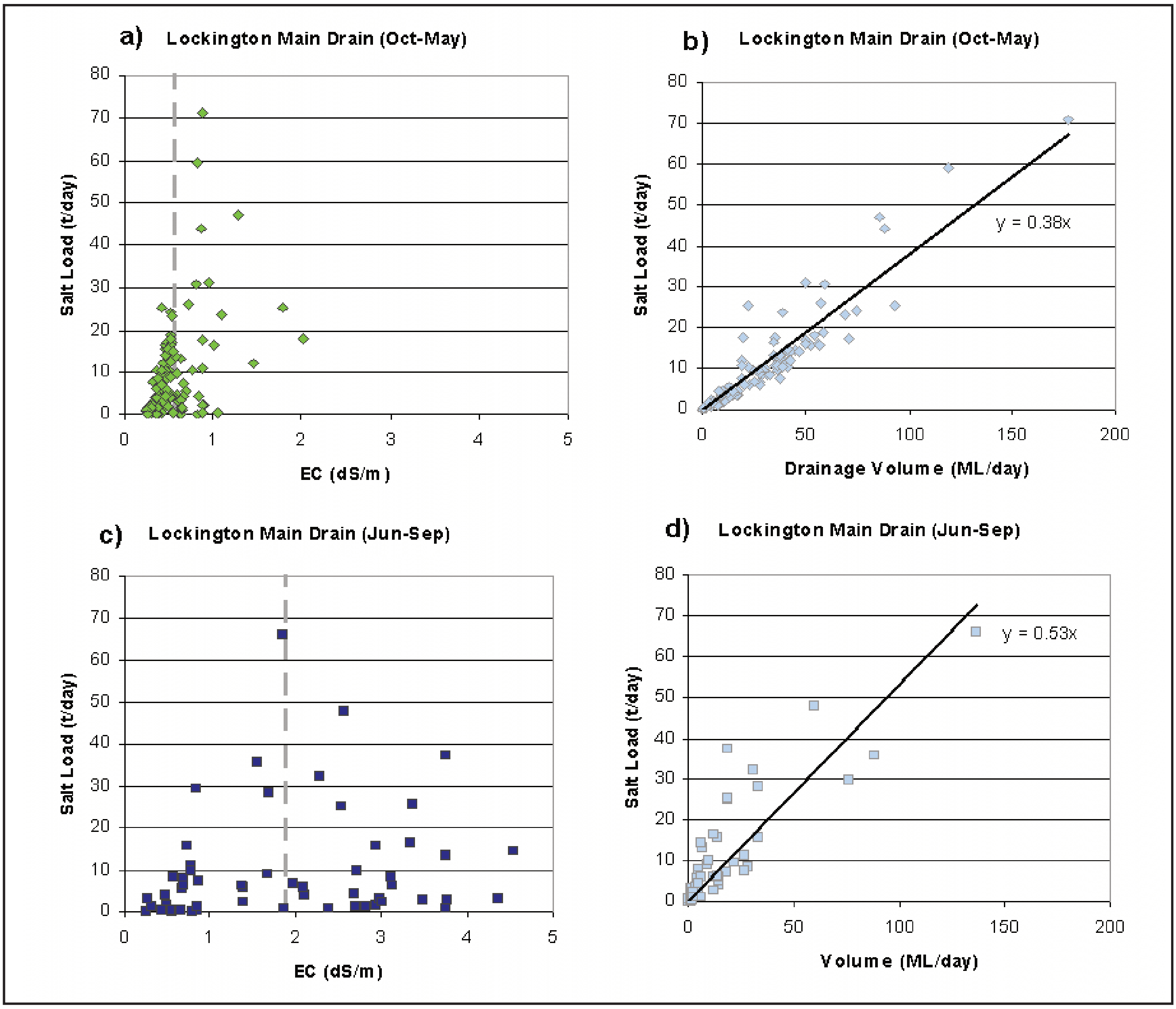


Figure 14. Relationship between Monthly Salt Load, Salinity and Drainage Volume in the Irrigation-Dominant Season (Oct-May) and Rainfall-Dominant Season (Jun-Sep) for the Lockington Main Drain (407712), Shepparton Irrigation Region (1990-2004). Mean salinity is indicated.

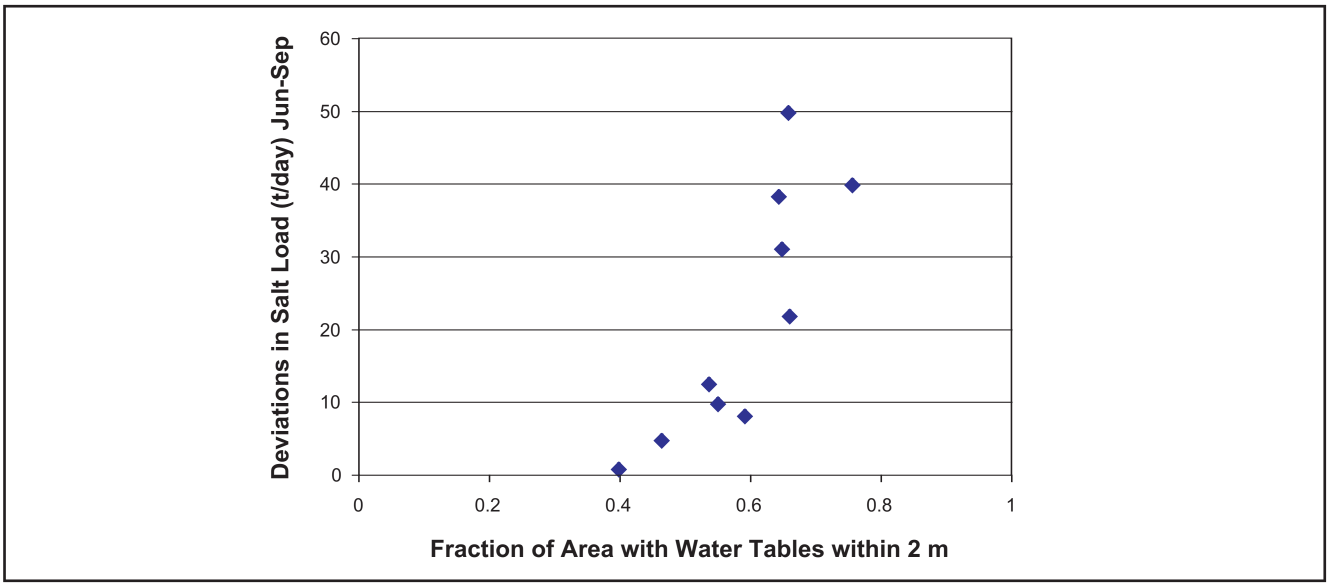


Figure 15. Relationship between the Fraction of Area with Shallow Watertables and Average Salt Load of Surface Drain between June to September for the Lockington Main Drain (407712), Shepparton Irrigation Region (1990-2004).

3.4 Consolidation of Salt Mobilisation Studies in Irrigation Areas

The greatest potential for salt mobilisation occurs in areas where highly saline groundwater systems are connected to surface water bodies. Such areas are found in the lower parts of the Murray-Darling Basin, where highly saline groundwater mounds have formed under irrigated land along the edge of the river or where deep surface drains intersect highly saline watertables.

High amounts of salt can also be mobilised through wash-off in areas where saline groundwater systems are near to the soil surface and capillary rise leads to large areas of saline soils. Installation of either surface or sub-surface drainage will help control watertable levels and reduce salt wash-off. However, substantial amounts of salt are mobilised by the sub-surface drainage system or through seepage into the surface drainage system. Clear trade-offs exist between the different salt mobilisation processes. Management practices that target one salt mobilisation process will impact on one of the other salt mobilisation processes.

Within an irrigation area, spatially non-uniform hydrogeology and management practices can lead to high variability in salt mobilisation at a local scale. Localised irrigation induced recharge in relatively small areas of permeable soils may create discharge areas within a few kilometres of the intake area (Bakker and Cockcroft 1974). High groundwater pressure in these localised discharge areas increases salt mobilisation by groundwater seepage and salt wash-off. Sub-surface drainage also mobilises large amounts of salt from relatively small areas. In some instances, salt discharge from these areas may represent a substantial component of total salt export from irrigation areas.

A trend in all of the analysed drains is that daily flow rates are typically lower, but more saline, during the rainfall-dominant season than the irrigation-dominant season. The lower salinity during the irrigation-dominant season is indicative of dilution due to irrigation runoff and channel outfall. The low salinity makes it more suitable for diversion for irrigation downstream. However, larger drain flow rates during the irrigation-dominant season mean that relatively large volumes must be diverted and used to reduce salt export from irrigation areas.

4. Temporal Trends in Salt Mobilisation from Irrigation Areas

Large reductions in drainage return flows for irrigation regions to the river system have been recorded in the Murray-Darling Basin since 1989 (Figure 16).

Drainage water volumes leaving these irrigation regions in 2003 are between 34 and 74% less than in 1989 (Figure 16) (Christen *et al.,* 2004). This reduction is due to a combination of drainage management interventions and climatic conditions, but the impact attributable to each factor is difficult to separate. The reduction in drainage leaving the SIR, MIA and CIA between 1989 (introduction of the MDB salinity and drainage strategy in 1988) and 2003 is of the order of 300 GL. If data on all irrigation areas in the Murray-Darling Basin were available, it is likely that the reduction in drainage return flows would be greater.

Corresponding reductions in salt load (Figure 17) were calculated for the Shepparton Irrigation Region (Sinclair Knight Merz 2002). Reductions in salt load exported from the Coleambally, Murrumbidgee and Sunraysia irrigation areas were calculated assuming a linear salt load/flow relationship for each of the irrigation regions (Figure 17). Linearity of the salt load versus flow has been shown to be applicable in these areas on an annual time step (Jolly *et al.,* 1997; Sinclair Knight Merz 2002; Williamson *et al.,* 1997). These approximate calculations clearly highlight that substantial reductions in salt loads from irrigation regions have occurred over the last 10-15 years. However, the causes of the reduction cannot easily be attributed to either management or climatic factors.

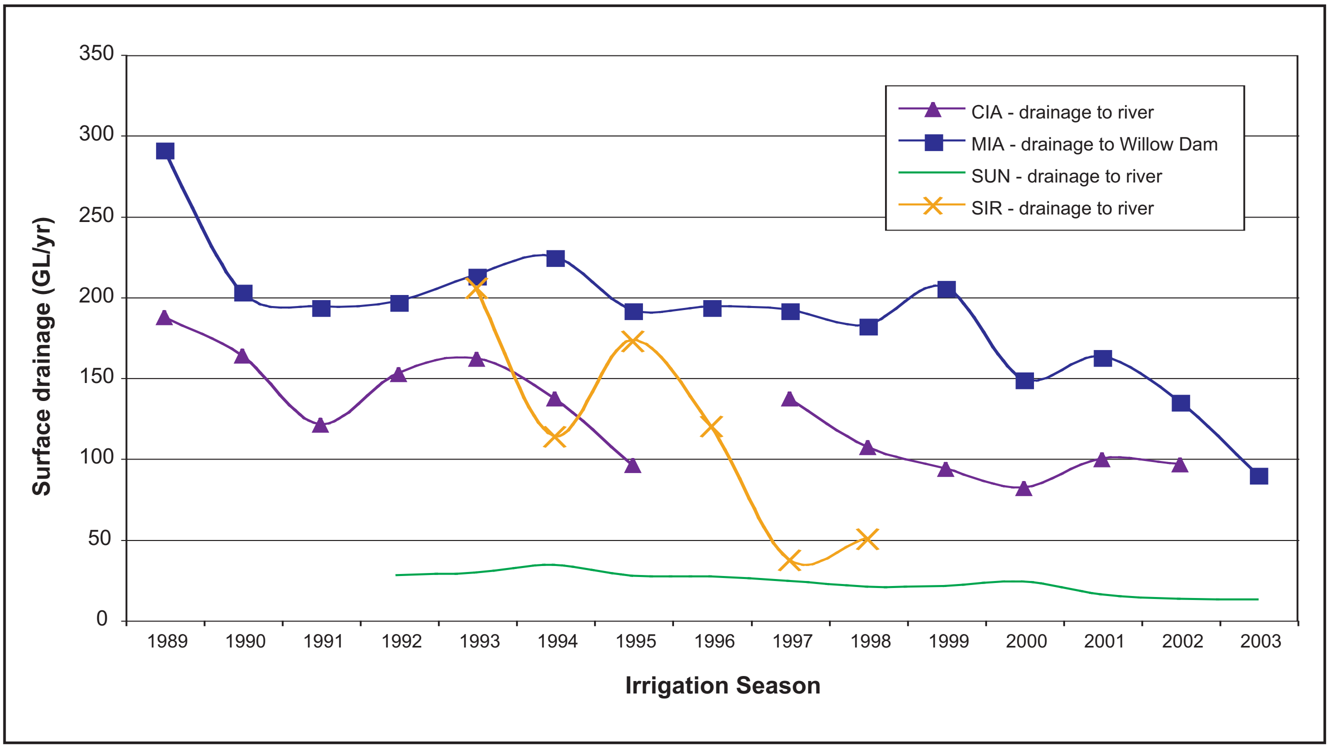


Figure 16. Estimated Change in Drainage Flows from the Shepparton (SIR), Sunraysia (SUN), Coleambally (CIA) and Murrumbidgee (MIA) Irrigation Regions as a Result of Decreased Drainage Return Flows.
(Sinclair Knight Merz 2002)

The sudden large reduction in salt load between 1997 and 1998 in the SIR is likely to be a consequence of low water allocations and prevailing drought conditions. The drier climatic conditions resulted in low water availability for irrigation and farmers used the available water resources more efficiently. A substantial reduction in irrigation runoff in surface drainage water leaving farms in the SIR has occurred since 1988 (Sinclair Knight Merz 2003b). The equivalent change in salt load was calculated from historical irrigation deliveries to the SIR and by assuming a linear salt/load flow relationship derived from twelve years of monthly flow and load data from the Upper Deakin, Murray Valley, Toolamba and Lockington Main drains (Figure 19). The estimated reduction in salt load directly associated with irrigation runoff is of the order of 20,000 t/year. While this number should only be considered indicative, it highlights the magnitude of potential reductions in salt load and associated large benefits in terms of salinity in the lower river system.

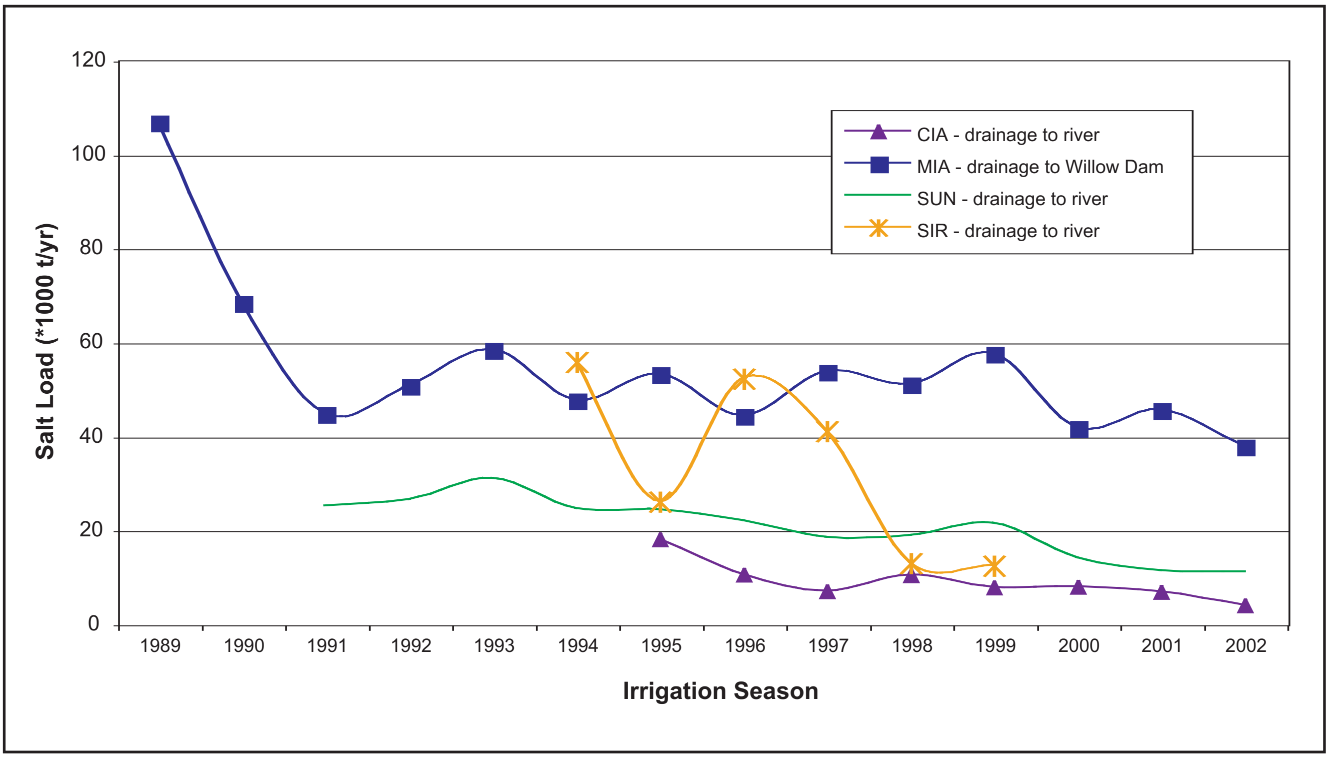


Figure 17. Estimated Change in Salt Load from the Shepparton (SIR) Sunraysia (SUN), Coleambally (CIA) and Murrumbidgee (MIA) Irrigation Regions as a Result of Decreased Drainage Return Flows.
(Sinclair Knight Merz 2002).

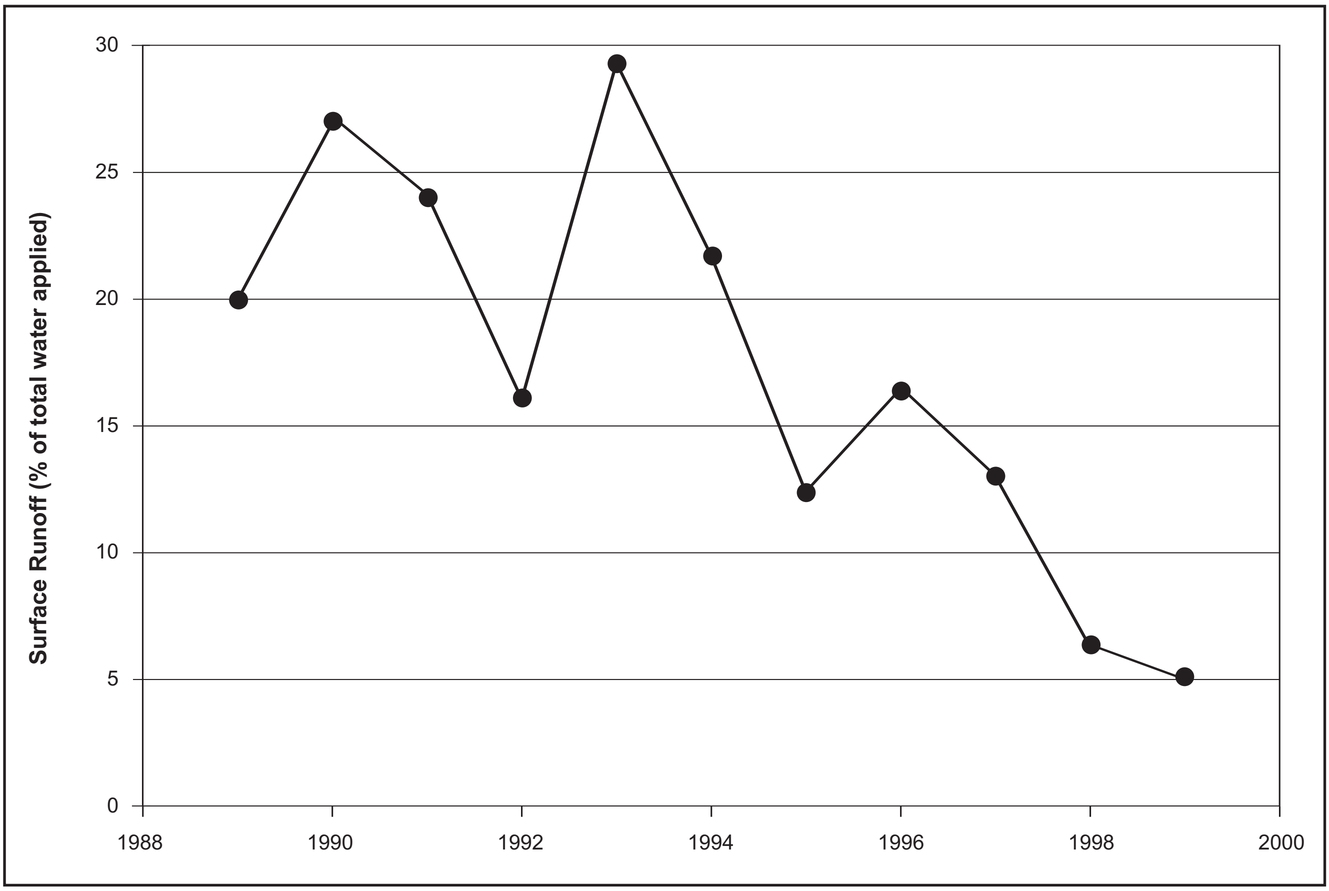


Figure 18. Temporal Pattern in Irrigation Water Runoff (% of applied irrigation water) in the Shepparton Irrigation Region.

(Sinclair Knight Merz 2003b).

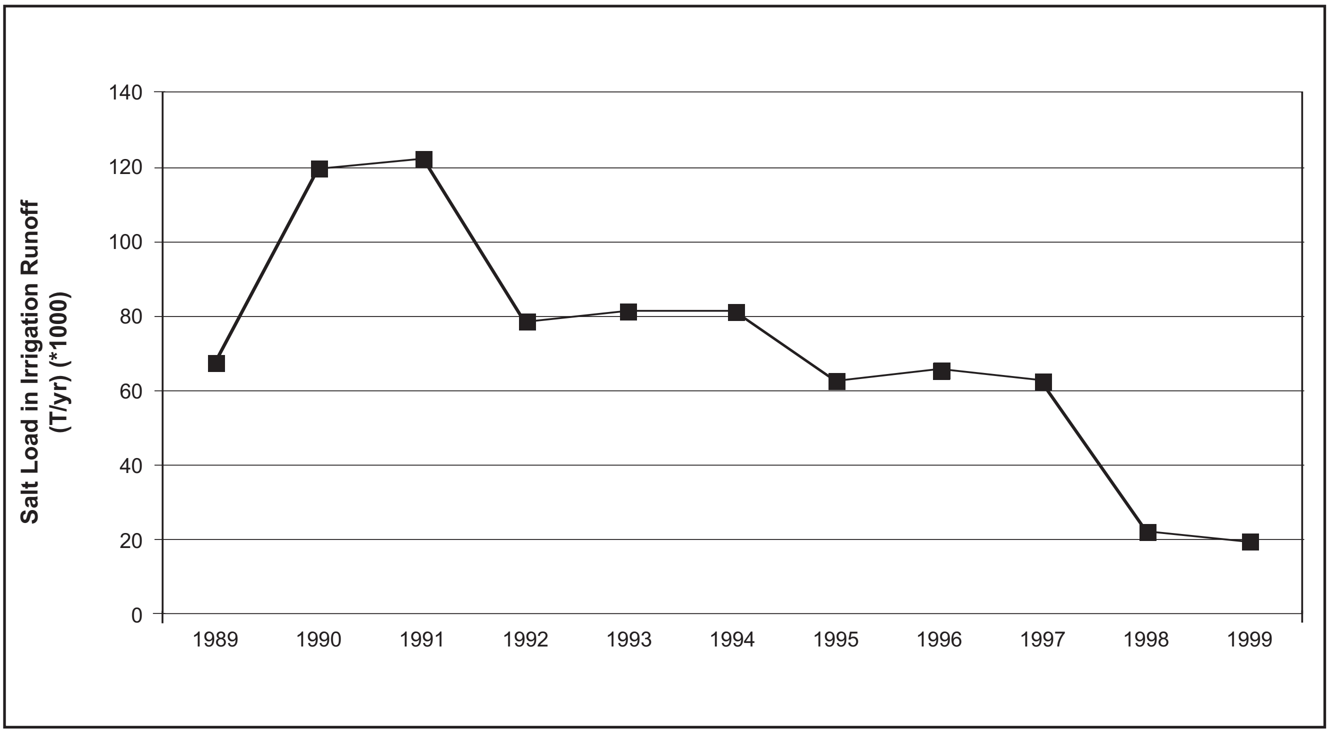


Figure 19. Temporal Pattern in Salt Load in Irrigation Runoff from Farms in the Shepparton Irrigation Region.

5. Implications of Salt Storage in Irrigation Areas for the Salt Balance

Drainage water leaving irrigation regions is generally of low to medium salinity and is of suitable quality for irrigating a range of crops of variable salt tolerance. Where drainage water is highly saline it can be diverted to evaporation basins. Diversion of drainage water reduces salt export from irrigation regions. This will lead to increases in salt storage and the potential for localised salinity outbreaks.

The salt balance of an area is often used to assess the status of catchment salinisation (Peck and Hurle 1973; Jolly *et al.,* 2001; Peck and Hatton 2003). The Salt Export Ratio (SER) is proposed as an indicator of salt accumulation within an area, where SER is a ratio of salt output from a hydrologic system divided by the input over the same time period (Gilfedder 1999). A SER of less than one indicates salt accumulation within a catchment, while areas where SER is greater than one are net salt exporters. Annual SER values were calculated for a range of irrigation areas in the MDB (Table 7). With the exception of the KIR-Drain 14 and Nangiloc-Colignan, all reported irrigation areas have a SER of less than one and are accumulating salt (Table 7). The majority of salt balance data have been calculated using only surface components, as indicated in Table 7.

Large amounts of salt occur naturally in soil profiles in the MDB. The amount of salt stored in the top 25 m of the profile is typically between 100 and 3,000 t/ha in the major irrigation areas in the MDB (Table 7), with salt storage estimated from the volume of water in the soil profile (assuming a porosity of 0.4 and depth of 25 m) and average groundwater salinity. Importantly, the amount of salt being imported annually in irrigated areas is generally small at a regional scale, relative to the amount of salt already stored in the profile. Over

Table 7. Surface Salt Balance (total salt in and out) of Irrigation Regions Compared to Estimated Salt Already in Storage. All values are Standardised to Hectares.

Irrigation Region	Area (1000ha)	Salt Input (t/ha/yr)	Salt Output (t/ha/yr)	SER	Difference (t/ha/yr)	Average Ground water EC (dS/mm)	Salt Storage in 25 m of Soil Profile (t/ha)	Change in Salt Storage (%/yr)
***Coleambally[1]**	95.2	0.53	0.16	0.31	0.37	4	240	0.15
***Murray Irrigation[1]**	801	0.07	0.02	0.27	0.05	16	981	0.01
SIR[2]	428	0.66	0.43	0.64	0.24	2.5	150	0.15
Campaspe West[3]	3.4	2.78	1.11	0.40	1.67	2.5	150	-1.11
KIR - Drain 14[5]	0.4	2.90	12.00	4.14	-9.10	40	2400	-0.38
Nangiloc-Colignan[6]	5.3	1.40	3.85	2.76	-2.45	30	1800	-0.14
Sunraysia[7]	109	24.53	22.25	0.91	2.27	35	2100	0.11
Berriquin[8]	320	0.09	0.05	0.6	0.04	10	600	0.01
Kerang Lakes[9]	120	2.07	1.91	0.92	0.16	45	2700	0.01

*SER calculation includes groundwater inflow and outflow

[1]ANCID (2004), [2]Sinclair Knight Merz (2002a), [3]Rendell (1988), [4]TPSRWG (1989a), [5]Gilfedder (1999b), [6]NCCSWG (1991) [7]Sinclair Knight Merz (2003a) [8]Berriquin Land and Water Management Plan Working Group (1995), [9]Erlanger (1991).

100 years, the estimated rate of salt accumulation in the SIR would increase salt storage in the top 25 m of the profile by less than 15%. This corresponds to an increase in groundwater salinity from 2.5 to 2.9 dS/m. Similarly, salt accumulation in the Coleambally, Murray Irrigation and Sunraysia areas will also have only a small impact on groundwater quality at a regional scale. The available information suggests relatively large changes could be expected in the Campaspe West Irrigation Region, where an increase in groundwater salinity of more than 100% can be predicted, based on the rates of salt accumulation reported in the Land and Water Management Plan. However, the available salt balance data for the Campaspe West Irrigation Region is not well documented and further consideration of the salt balance in the area appears warranted.

The amount of salt annually accumulating in irrigation areas is small relative to the amounts of salt already stored in the profile and, of critical importance, salt can accumulate in the deeper profile without affecting the (shallow) rootzone salinity. This process can be managed by sub-surface drainage, especially vertical groundwater pumping. Thus it is likely that most of the irrigation regions can store greater amounts of salt than currently observed without substantial implications on groundwater salinity or productivity in the foreseeable future at a regional scale. However, environmental and productive losses due to accumulation of salt could occur within localised areas of the landscape. With careful planning, irrigation regions may be able to play a role in ‘buffering’ the Murray River against further salinisation from dryland areas.

6. Options For Managing Saline Drainage Water In Irrigation Areas

Two conceptually different approaches exist for managing salt disposal from irrigated areas. The first option is preventative through source control, achieved by improving irrigation efficiency and drainage system efficiency (Ritzema and Braun 1994). This approach reduces drainage flows and salt loads leaving the farm. The second option is responsive and involves diverting water from drains prior to discharge to the river system, thus reducing the downstream effects of drainage water disposal. Both source control and diversion control options are key elements of land and water management plans in the MDB and are widely implemented. Both approaches require careful consideration of potential negative environmental and production effects associated with salt accumulation. Any such costs need to be contrasted against the benefits of reduced salt loads in the river system.

6.1 Source Reduction

Salt is mobilised through salt wash-off, engineered sub-surface drainage, groundwater seepage and channel outflows. Salt wash-off is a function of the volume of runoff, soil salinity and irrigation water salinity. Reductions in salt wash-off can be achieved through more efficient irrigation practices that reduce surface runoff from fields and the installation of farm recycling systems, which capture field runoff for later irrigation. Practices that reduce soil salinity will also help to decrease salt wash-off. Increased leaching will generally be required to reduce rootzone salinity (Rhoades 1974). This in turn will lead to higher groundwater accessions, shallower watertables or increased need for sub-surface drainage. Management options for reducing soil salinity need to consider the potential increases in salt mobilisation through groundwater seepage or sub-surface drainage.

Salt wash-off is typically a diffuse process and requires widespread changes in management to substantially reduce salt loads leaving irrigation regions. Farms which use drainage water of higher salinity will contribute proportionally greater loads of salt wash-off. These farms should be targeted to reduce loads in wash-off by more efficient irrigation and recycling practices.

Irrigation efficiency will also impact on the actual volume of sub-surface drainage generated (Ritzema and Braun 1994). Reducing deep drainage through improved irrigated efficiency reduces the volume of water captured in sub-surface drainage systems. Reductions in deep drainage and surface runoff can be achieved in many areas (of lighter soil types and certain crops) by converting from surface irrigation to more efficient pressurised irrigation systems (Clemmens 2000; Bethune *et al.,* 2003). This process is clearly shown in water balance studies (Christen and Skehan 2000; Bethune *et al.*, 2003).

For example, drip irrigated vineyards had 100 mm/year less runoff and 200 mm/year less tile drainage than a flood irrigated vineyard (Christen and Skehan 2000). Sprinkler irrigated dairy pastures generated 310 mm/year less runoff and 150 mm/year less deep drainage than border-check irrigated pastures (Bethune *et al.,* 2003). Common to both these studies was that the pressurised irrigation system (drip or sprinkler) produced considerably lower surface runoff and consequently would have had lower salt wash-off. Additionally, lower deep drainage rates under the pressurised irrigation system would reduce the amount of salt mobilised through sub-surface drainage.

Pressurised irrigation systems are typically more expensive to install and operate than surface methods and so may not be attractive to farmers. Thus, there may be a case to provide incentives to farmers for converting irrigation systems on the basis that deep drainage and salt mobilisation to surface drains can be reduced. Further work is required to clarify the magnitude of the benefits and costs associated with such a scheme.

Large improvements in surface (e.g. border-check, furrow) irrigation efficiencies can also be achieved by improving irrigation design and management. The installation of farm recycling systems to capture irrigation runoff is recommended in most of the irrigation areas in the MDB. Prevention of irrigation runoff will considerably reduce salt wash-off. System design and management needs to be matched to soil hydraulic properties to reduce deep drainage. Theory exists to guide design and management for this purpose. However, design is typically driven by farm management issues (e.g. to save time spent irrigating) rather than to minimise deep drainage.

Sub-surface drainage systems typically extract more water than required to provide salinity and/or waterlogging control. The amount of salt drained through sub-surface drainage and the amount of salt applied was compared for 36 sub-surface drainage systems from across Australia (Christen *et al.,* 2001). The median Salt Export Ratio from these 36 systems is four (Figure 20). The majority (85%) of sub-surface drainage systems analysed had salt export ratios greater than one, indicating that more salt was exported from sub-surface drainage than imported through irrigation and rainfall. In some extreme cases, the salt export ratio indicated that 25 to 45 times more salt was drained than applied. These results indicate that more salt is being drained than required to maintain a favourable salt balance in the rootzone. Consequently, there appears to be considerable scope to reduce salt mobilisation through improved design and management of sub-surface drainage systems.

Sub-surface drainage systems should be designed and managed to provide the leaching requirement of irrigated crops. A set of best management practices for reducing salt loads from sub-surface drainage systems has been developed (Christen *et al.*, 2001). Reductions

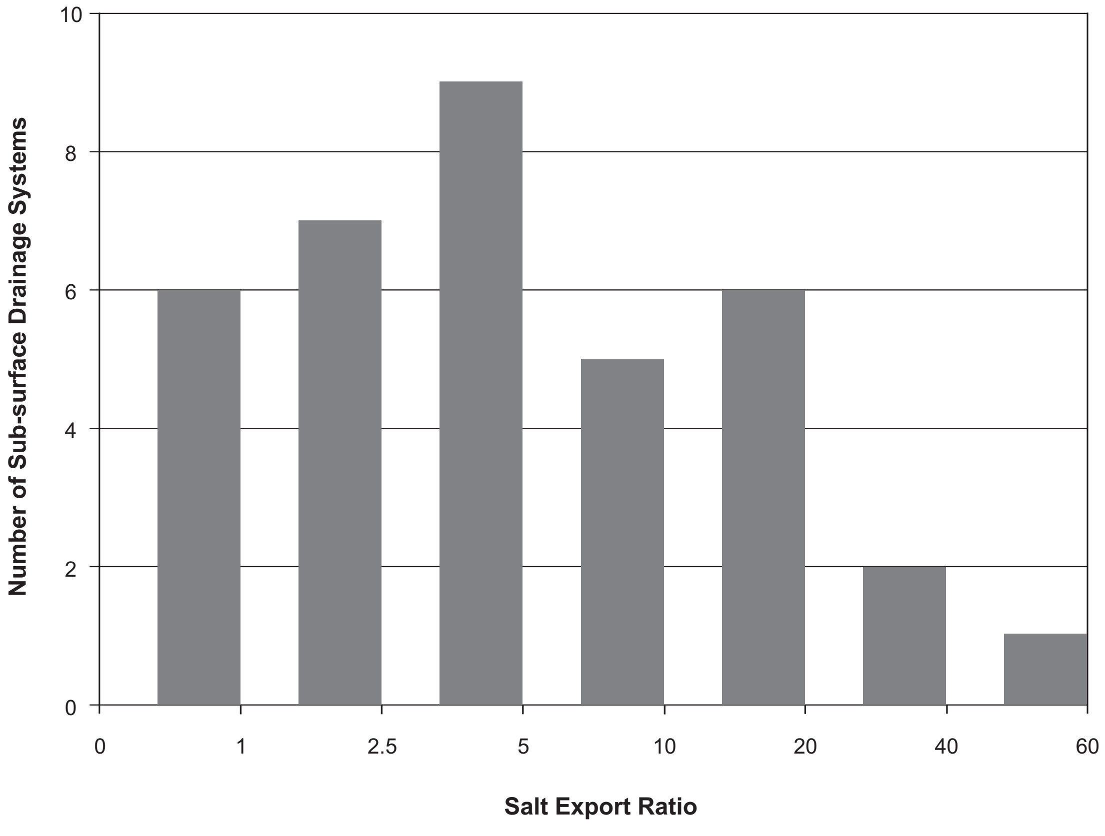


Figure 20. Salt Export Ratio from Different Sub-surface Drainage Systems Across Australia.
(Adapted from Christen *et al.,* 2001).

in salt loads of 40% have been achieved through improved management of drainage systems (Christen and Hornbuckle 2002). A potential conflict occurs in many areas where groundwater pumping is practiced primarily to provide a water resource. In these instances the aim is to maximise groundwater reuse so substantially higher extraction rates than the leaching requirement occur. Tighter control on discharge to drainage systems could be considered where groundwater is pumped in excess of the volumes required for salinity control. The difficulty comes in deciding how much is needed for salinity control, and whether off site benefits are received by higher pumping rates.

Substantial amounts of salt can be mobilised in areas where surface drains intercept shallow saline watertables. Installing shallow surface drainage systems that do not intercept the watertable will reduce salt mobilisation through groundwater seepage. An alternative approach in areas with deep drainage systems may be to maintain an artificially high water level in the drain to limit groundwater seepage into the drain.

Channel outflows are generally of low salinity and if discharged to the river should not lead to increases in river salinity. However, elevated salinity levels can occur in channel distribution networks when saline drainage water is discharged into the supply system. Restricting sub-surface drains from discharging into the channel system would reduce salt loads in channel outfall. A further option may be to improve irrigation delivery infrastructure so that channel outflows are prevented.

6.2 Drainage Diversion

Drainage water that has a low salinity level can be used for irrigation (Heuperman 1988; Prendergast *et al.,* 1994b). The use of drainage water for irrigation is a popular disposal option as it brings production benefits. However it may lead to secondary salinisation and reduced plant growth if incorrectly managed (Prendergast *et al.*, 1994b). Upper limit 'threshold' salinities have been set for a wide range of crops and pastures. For example for irrigated clover based pastures a threshold of 0.8 dS/m has been set (Salinity Pilot Advisory Council 1989; Berriquin Land and Water Management Plan Working Group 1995). There is potential to reuse higher salinity drainage water (Maas and Hoffman 1977; Ayers 1977; Bethune *et al.,* 2004). Drainage water of up to 5 dS/m can be used to irrigate Bermuda grass (Cynodon dactylon) without substantial impacts on growth (Table 8), provided a leaching fraction of 10% can be achieved (Bethune *et al.,* 2004). Tall wheat grass (Thinopyrum ponticum) and red gums (Eucalyptus camaldulensis) can be irrigated with water of 10 dS/m, providing sufficient leaching is possible (Su *et al.,* 2003). A range of other salt tolerant crops is also available for productively evaporating saline drainage water (Maas and Hoffman 1977). The disposal capacity of these salt tolerant crops should be of the order of 10-12 ML/ha/year in the MDB, providing sufficient leaching can be achieved.

The use of high salinity drainage water for irrigation will necessitate relatively high leaching fractions to maintain productivity (Rhoades 1974; Prendergast 1993). Sub-surface drainage is likely to be required to

Table 8. Impact of Irrigation Water Salinity on the Relative Yield of Bermuda Grass, Assuming Fully Irrigated Conditions and a Leaching Fraction of 10 Per Cent.

Irrigation Water Salinity	**1 (dS/m)**	**2.5 (dS/m)**	**5 (dS/m)**	**10 (dS/m)**	**15 (dS/m)**	**20 (dS/m)**
Perennial pasture	1.00	0.79	0.44	*	*	*
Bermuda grass	1.00	1.00	0.94	0.44	*	*
Red gum	1.00	1.00	1.00	0.69	0.38	*

enhance leaching or prevent leaching fluxes from having adverse environmental impacts on the surrounding areas. Installation of sub-surface drainage increases the cost of salt disposal and also generates more saline drainage water for disposal.

Where reuse would result in excessive soil salinity, evaporation basins can be considered as a disposal option. The disposal capacity of an evaporation basin is similar to that of a salt tolerant crop (10-12 ML/ha/year). Careful design, siting and management of evaporation basins has been identified as critical to efficient and safe disposal of drainage water (Christen *et al.,* 2000). To reduce the chance of lateral seepage, sub-surface drainage around the basin is necessary. Evaporation basins are costly to construct ($4,000-$20,000/ha) and can take up valuable farmland (Singh and Christen 1999).

Salt tolerant crops and evaporation basins are unlikely to be highly profitable enterprises (Bethune *et al.,* 2004), although such systems may realise substantial benefits in terms of reduced river salinity. Consideration could be given to subsidising farmers who prevent highly saline drainage water from entering the river system on the basis of reduced river salinity. The primary objective of these farms would be to manage drainage water rather than to grow highly profitable crops. Additional consideration also needs to be given to any costs associated with increased groundwater salinity under the saline reuse area and the potential for this saline groundwater to migrate laterally to the river systems.

7. Conclusions

Salt mobilisation and export is highly variable between irrigation regions of the Murray-Darling Basin, with rates ranging from less than 1 t/ha/yr to over 10 t/ha/yr. Salt mobilisation from irrigated land can be relatively large compared to rates mobilised from dryland areas. Processes contributing to high salt mobilisation of irrigation areas are salt wash-off, groundwater seepage, engineered sub-surface drainage and channel outfall. The relationship between these processes is influenced by hydrogeological, climatic and management factors specific to each region.

The greatest potential for salt mobilisation occurs through groundwater seepage where highly saline groundwater systems are connected to surface water bodies. This occurs in the Lower Murray River and where deep surface drains intersect highly saline groundwater tables. High amounts of salt can also be mobilised through salt wash-off in areas where salty shallow groundwater systems contribute to large areas of saline soil. Installation of surface or sub-surface drainage will help control watertable levels and reduce salt wash-off. However, substantial amounts of salt are mobilised by sub-surface drainage systems or groundwater seepage into the surface drainage system. There is a clear trade-off between the salt mobilisation processes; with changes in one mobilisation process likely to impact on other salt mobilisation processes.

Large reductions in salt load have occurred in the irrigation areas of the MDB over the last 10-20 years. These reductions are associated with a combination of management for increased irrigation efficiency and the climatic influence of extended below average rainfall. Reduction in salt loads exported from irrigation regions indicates increased salt accumulation. On a regional scale, irrigation areas should be able to store greater amounts of salt without substantial implications on groundwater salinity or productivity in the foreseeable future. On a local scale, spatial variability in hydrogeology and management practices may have the potential to redistribute salt causing localised environmental and productive losses.

The assessment of salt mobilisation processes in this report can only be considered as indicative. Most calculations of salt mobilisation were conducted during the formation and implementation of land and water management plans and were based on relatively short periods of data. The accuracy of these calculations is difficult to assess and interpretation should consider the prevailing climatic conditions during the study. The information quantifying groundwater seepage directly to tributaries of the Murray River is also limited.

The possible management options for preventing salt mobilised in irrigation areas from entering receiving environments are promising. One option is through improved irrigation and drainage system efficiency to limit salt loads leaving the farm and entering surface drainage systems. There is also large potential to achieve reductions in salt mobilised from irrigated land by changing the management and design of sub-surface drainage systems. The salinity of drainage water leaving irrigation areas is generally suitable for irrigating salt tolerant crops. There is potential to divert a greater proportion of current drain flows for irrigation before they discharge into the river system.

The suitability of particular management options depends on the spatial hydrogeologic, climatic and management characteristics of the irrigated area. The cost of diverting additional drainage water needs to be assessed against the benefits of improved water quality in the river system and the possible implications of increased salt storage. Such analysis should also consider other water quality benefits, such as reduced nutrient, sediment and pesticide loads. This is only one step in the process of finding a more sustainable place for irrigation amongst the complex web of environmental, social and economic processes.

8. References

Ayers RS (1977) Quality of water for irrigation. Journal of irrigation and drainage 103, 135-154.

Bakker AC, Cockcroft B (1974) Salting in the Goulburn Valley. Victorian Horticultural Digest 62, 9-15.

Berriquin Land and Water Management Plan Working Group (1995) 'Berriquin Community's Land and Water Management Plan.' (Berriquin Land and Water Management Plan Working Group, Deniliquin)

Bethune M (2004) Towards effective control of deep drainage under border-check irrigated pasture in the Murray-Darling Basin: a review. Australian Journal of Agricultural Research.

Bethune M, Finger L, Wood M, Wang QJ (2003) 'Sprinkler, Sub-surface Drip and Surge Irrigation Experiment (DAV11163 - extension of DAV422): Final Report, June 2003.' (Department of Primary Industries, Tatura, Australia)

Bethune M, Gyles O, Wang QJ (2004) Options for management of saline groundwater in an irrigated farming system. Australian Journal of Experimental Agriculture 44, 181-188.

Blackmore DJ, Goss KF, Newman RJ, Powell J (1999) Salinity Management in the Murray-Darling Basin. (Australian Academy of Technology Sciences and Engineering: Canberra)

Christen EW, Ayars JE, Hornbuckle JW (2001) Sub-surface drainage design and management in irrigated areas of Australia. Irrigation Science 21, 35-43.

Christen EW, Jolly ID, Leaney F, Narayan K, Walker G (2000) 'On farm and community scale salt disposal basins on the riverine plain - Underlying principles for basin use.' (CRC for Catchment Hydrology, Melbourne) Technical Report 99/15

Christen EW, Skehan D (2000) 'Design and management of sub-surface drainage to reduce salt loads (Final report to Murray-Darling Basin Commission).' (CSIRO Land and Water, Griffith)

Christen E, Bethune M, Hornbuckle JW, Khan S (2004) The Murray-Darling Basin - A case study of drainage impacts in a multifunctional resource system. (World Bank: Washington DC)

Christen E, Hornbuckle JW (2002) 'Irrigation Insights No. 2. Sub-surface drainage design and management practices in irrigated areas of Australia.' (Land and Water Australia, Canberra)

Clemmens AJ (2000) Measuring and improving irrigation system performance at the field level. pp. 190-199. (Irrigation Association of Australia: Melbourne)

Close A (1990) River salinity. In 'The Murray'. (Eds N Mackay and D Eastburn) pp. 127-144. (Murray-Darling Basin Commission: Canberra)

Connell LD, Jayatilaka C, Gilfedder M, Mein RG, Vandervaere JP (2003) Modelling flow and transport in irrigation catchments 1. Development and testing of subcatchment model. Water Resources Research 37, 949-963.

Crabb P (1997a) 'Murray-Darling Basin Resources.' (Murray-Darling Basin Commission: Canberra, Australia)

Earl GC (1988) 'Stream Salinities and Salt Loads in the Goulburn and Broken River Catchments.' (Rural Water Commission of Victoria)

Eastburn D (1990) 'The River Murray: History at a Glance.' (Murray-Darling Basin Commission: Canberra)

Environment Australia. National Land and Water Resources Audit: Australian Natural Resource Atlas V2.0. Environment Australia . 2001. Commonwealth of Australia. 26-3-2004. Ref Type: Electronic Citation

Finlayson (1988) Australia v the world: a comparative analysis of streamflow characteristics. In 'Fluvial geomorphology of Australia'. (Ed. RF Warner) pp. 17-40. (Academic Press: San Diego)

Gilfedder M, Connell LD, Mein RG (2000a) Border irrigation field experiment. I: Water balance. Journal of irrigation and drainage engineering 126, 85-91.

Gilfedder M, Mein RG, Connell LD (2000b) Border irrigation field experiment. 2: Salt balance. Journal of irrigation and drainage engineering 126, 92-97.

Gilfedder M, Connell L, Knight J (1999) 'Irrigation Bay Salt Export and Salinity Management.' (Cooperative Research Centre for Catchment Hydrology, Monash University Clayton) Industry Report 99/5

Havis RN, Smith RE, Adrian DD (1992) Partitioning solute transport between infiltration and overland flow under rainfall. Water Resources Research 28, 2569-2580.

Heuperman AF (1988) The Tongala groundwater pumping/re-use project: A pilot study for groundwater table control in the Shepparton Region in Northern Victoria. Agricultural Water Management 14, 513-523.

Hillel D (2000) 'Salinity Management for Sustainable Irrigation, Integrating Science, Environment and Economics.' (World Bank, Washington, D.C)

Jolly ID, Williamson DR, Gilfedder M, Walker GR, Morton R, Robinson G, Jones H, Zhang L, Dowling TI, Dyce P, Nathan RJ, Nandakumar N, Clarke R, McNeill V (2001) Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia. Marine and Freshwater Resources 52, 53-63.

Jolly ID, Morton R, Walker GR, Robinson G, Jones H, Nandakumar N, Nathan R, Clarke R, McNeill V (1997) 'Stream Salinity Trends in catchments of the Murray-Darling Basin.' (CSIRO Land and Water)

Knight JH, Gilfedder M, Walker GR (2002) 'Impacts of irrigation and dryland development on groundwater discharge to rivers: A unit response approach to cumulative impacts analysis.' (CSIRO Land and Water, Canberra)

Maas EV, Hoffman GJ (1977) Crop salt tolerance - current assessment. Journal of irrigation and drainage 103, 115-134.

Marshall A (2003) 'Environmental Report 2001/02.' (Murray Irrigation Limited, Deniliquin)

McLennan W (2000) 'Water Account for Australia 1993-94 to 1996-97.' (Australian Bureau of Statistics, Canberra)

McMahon TA (1982) World Hydrology: does Australia fit? pp. 1-7. (Institution of Civil Engineers Australia: Melbourne)

McMahon TA (1984) 'Irrigation and groundwater accessions. A report prepared for the Salinity Committee of the Victorian Parliament on the Proceedings of a Technical Seminar.' (Salinity Committee, East Melbourne)

MDBMC (1989) 'Salinity and Drainage Strategy ' (Murray-Darling Basin Ministerial Council, Canberra)

MDBMC (1999) 'Salinity and Drainage Strategy: Ten years on.' (Murray-Darling Basin Ministerial Council, Canberra)

Mudgway LB, Nathan RJ, McMahon TA, Malano HM (1997) Estimating salt loads in high watertable areas. 1: Identifying processes. Journal of irrigation and drainage engineering 123, 79-90.

Nathan RJ, Mudgway LB (1997) Estimating salt loads in high watertable areas. 11: Regional salt loads. Journal of irrigation and drainage engineering 123, 91-99.

Peck AJ, Hatton T (2003) Salinity and the discharge of salts from catchments in Australia. Journal of Hydrology 272, 191-202.

Peck AJ, Hurle DH (1973) Chloride balance of some farmed and forested catchments in south western Australia. Water Resources Research 9, 648-657.

Prendergast JB (1993) A model of crop yield response to irrigation water salinity: theory, testing and application. Irrigation Science 13, 157-164.

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. Soil Science Society of America Journal 59, 1531-1539.

Prendergast JB, Rose CW, Hogarth WL (1994a) A model for conjunctive use of groundwater and surface waters for control of irrigation salinity. Irrigation Science 14, 167-175.

Prendergast JB, Rose CW, Hogarth WL (1994b) Sustainability of conjunctive water use for salinity control in irrigation areas: theory and application to the Shepparton region, Australia. Irrigation Science 14, 177-187.

Rhoades JD (1974) Drainage for salinity control. In ‘Drainage for agriculture’. (Ed. JV Schilfgaarde) pp. 433-461. (American Society Agronomy: Madison, WIS USA)

Rhoades JD, Lesch SM, Burch SL, Letey J, LeMert RD, Shouse PJ, Oster JD, O’Halloran T (1997) Salt distributions in cracking soils and salt pickup by runoff water. Journal of irrigation and drainage engineering 123, 323-326.

Ritzema HP (1994) ‘Drainage Principles and Applications.’ (International Inst. Land Reclamation and Improvement (ILRI): Wageningen)

Ritzema HP, Braun HMH (1994) Environmental Aspects of Drainage. In ‘Drainage Principles and Applications’. (Ed. HP Ritzema) pp. 1041-1063. (International Institute for Land Reclamation and Improvement)

Robins L, Freebairn D, Sedger A (2003) ‘Groundwater Models: a community guide to a better understanding.’ (Murray-Darling Basin Commission, Canberra)

Salinity Pilot Advisory Council (1989) ‘Shepparton Land and Water Salinity Management Plan - Draft.’ (Government of Victoria, Melbourne, Australia)

Sinclair Knight Merz (1999) ‘Predictions of the Ultimate Salt Load from Victorian Dryland Catchments to the Murray River.’ (Sinclair Knight Merz, Armadale)

Sinclair Knight Merz (2002) ‘D841 Shepparton Irrigation Region Salt Load Monitoring for Goulburn Murray Water.’ (Sinclair Knight Merz Pty Ltd, Armadale)

Sinclair Knight Merz (2003a) ‘Integration and Optimisation of Salt Interception in the Sunraysia Region.’ (Department of Land and Water Conservation NSW)

Sinclair Knight Merz (2003b) ‘Shepparton Irrigation Region Salt Disposal Entitlement Review.’ (Sinclair Knight Merz, Armadale)

Singh J, Christen EW (1999) ‘On-farm and community-scale disposal basins on the Riverine Plain: Minimising the cost of basins: siting, design and construction factors.’ (CSIRO Land and Water, Griffith)

Su N, Bethune M, Mann L (2003) Assessment of an agronomic option for reducing salt export from irrigated regions. (ANCID: Shepparton Victoria)

Tanji KK (1990) ‘Agricultural Salinity Assessment and Management.’ (American Society of Civil Engineers, N.Y)

van der Lely (1994) ‘Evaluation of watertable control options MIA Land and Water Management Plan.’ (Dept Water Resources, Murrumbidgee Region)

van Hoorn JW, van Alphen JG (1994) Salinity Control. In ‘Drainage Principles and Applications’. (Ed. HP Ritzema) pp. 533-600. (ILRI: Wageningen, The Netherlands)

Walker GR, Jolly ID, Williamson DR, Gilfedder M, Morton R, Zhang L, Dowling T, Dyce P, Nathan R, Nandakumar N, Gates GWB, Linke GK, Seker MP, Robinson G, Jones H, McNeill V, Evans WR (1998) ‘Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin.’ (CSIRO Land and Water)

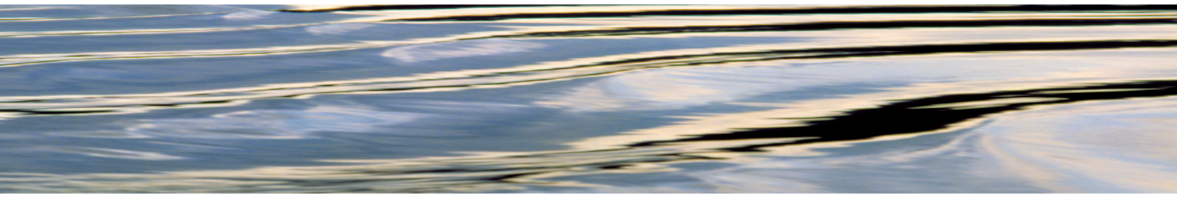
Webster A (1984) ‘Seepage measurements in commission channel systems 1962-83.’ (Rural Water Commission of Victoria, Tatura, Victoria)

Williamson DR, Gates GWB, Robinson G, Linke GK, Seker MP, Evans WR (1997) ‘Salt Trends: Historic Trend in Salt Concentration and Saltload of Stream Flow in the Murray-Darling Drainage Division.’ (Murray-Darling Basin Ministerial Committee, Canberra)

CENTRE OFFICE

CRC for Catchment Hydrology
Department of Civil Engineering
Building 60
Monash University
Victoria 3800
Australia

Tel +61 3 9905 2704
Fax +61 3 9905 5033
email crcch@eng.monash.edu.au
www.catchment.crc.org.au



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