IMPLICATIONS OF IRRIGATION BAY MANAGEMENT FOR SALT EXPORT

A STUDY OF IRRIGATION BAY PROCESSES IN THE BARR CREEK CATCHMENT

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PREFACE

The work presented in this report is part of the Cooperative Research Centre for Catchment Hydrology's Salinity Program, within the Project A1: *Runoff and Solute Processes in High Watertable Areas: Measurement, Modelling and Management*. This project focused on the Barr Creek catchment near Kerang in northern Victoria, an irrigated farming region severely affected by shallow groundwater and salinisation.

The project aimed to determine the mechanisms of salt movement in flood irrigation areas and to develop a modelling movement framework to evaluate salinity management approaches. This involved a series of experiments aimed at determining how much water and salt is flowing out of catchments at Cohuna (Barr Creek) and Tragowel (east and south of Kerang, respectively), and how these flows are related to soil properties, irrigation practices and drain design. This would help in the development of a catchment model to predict the effect of changes in management on salt export and land salinisation in irrigated catchments.

This report presents details of the irrigation bay experimental monitoring programme from Project A1, aimed at determining the processes for the flow of water and transport of salt to surface drainage from an irrigation bay. The manner in which these irrigation bay flows related to soil properties and irrigation practices is linked to improved understanding of the wider issue of catchment salt export processes.

The report is based on the amalgamation of three manuscripts that have been prepared from work undertaken by the CRC for Catchment Hydrology, and which have been recently submitted for publication (Section 1 & 2: *ASCE Journal of Irrigation and Drainage Engineering*; Section 3: Australian *Natural Resource Management Journal*). The report also reflects a summary of Mat Gilfedder's PhD thesis, *Irrigation Bay Processes Leading to Salt Export*, which was accepted in September 1998.

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EXECUTIVE SUMMARY

This report presents the results from a detailed field experiment of water movement and salt transport within a border-irrigated bay in northern Victoria, an area characterised by shallow groundwater tables and salinisation problems. The aim of the study was to assess the impact of change in irrigation management on salt and water movement from the bay, including recharge to the region's shallow groundwater table.

An irrigation bay in the Barr Creek catchment was instrumented to monitor irrigation events throughout the 1996/97 irrigation season. The bay was carefully selected to ensure that its physical size, slope and irrigation arrangement were fairly typical of bays in the subcatchment. Surface and subsurface water and salt movement variables and processes were measured, together with supply and drainage volumes and salinities, at an irrigation event scale. These detailed data, from an entire irrigation season, have been used to improve our understanding of irrigation bay behaviour and the implications of irrigation management changes on both the bay's salt export and the bay's soil salinity.

Salt Balance

The monitored irrigation bay was in an approximate surface salt balance for the 1996/97 season. Although the seasonal surface salt balance was close to unity, individual irrigation events showed salt export ratio variability from 50% to 200%.

The bay 'salt balance' was far below the Drain 14 subcatchment salt export ratio of 400% for the same period, indicating that irrigation runoff was only a minor component of regional drain salt load. If irrigation runoff was assumed to be equivalent to supply salt load, then irrigation runoff accounted for only 25% of total subcatchment drainage salt load. Direct groundwater seepage into the deeper regional drains was likely to have been responsible for the remaining 75% of the irrigation season drainage salt load, as well as the large regional salt export ratios. This suggests that improved control of irrigation supply will not decrease the regional salt export ratio, unless it is able to lower the regional groundwater table.

Salt Transport

Salt transport during irrigation events at the monitored bay is dominated by the lateral washoff of salts, mainly from the soil surface. The heavy – clay soils prevented significant washing of salt deeper into the soil profile. The high salinity at the start of drain flow dropped quickly, as a result of the 'first flush' of salt being removed from the bay.

If irrigation volumes were reduced significantly, the lateral removal of washoff salt would be compromised. The low permeability of the soil matrix, combined with the shallow groundwater table and the presence of soil cracks, would remove the opportunity for vertical leaching of soil salt through the profile. Hence, overland flow 'mobilised' salt from the soil surface, and transported it in the surface water. This lateral washoff of soil salt was a significant process in the 'leaching' of bay soil. Significant reduction in irrigation volumes would continue to mobilise soil salt, but would be less effective in removing this salt from the bay in drainage and lead to a build-up of surface salt in the lower part of the bay. These findings highlight the importance of lateral washoff in salt

export from irrigation bays, suggesting that reduction in irrigation event volumes is likely to reduce salt export and thus affect the sustainability of irrigation in this area.

Groundwater Recharge

Water movement results showed that the evapotranspiration volume almost wholly explained the soil moisture deficit between irrigation events; deep drainage was negligible. Infiltration was mainly confined to the advance stages of irrigation, with the soil rapidly becoming saturated across the bay, due to the presence of soil cracks. This implies that more efficient management of supply to irrigation bays will not lead to the lowering of the region's shallow groundwater table. The relationship between irrigation practice and regional groundwater appears more complex than previously anticipated, a finding which has important implications for irrigation management.

Re-use to Improve Efficiency

'Re-use' of on-farm irrigation runoff appears to have significant benefits. This 're-use' can allow irrigators to maintain sufficiently high volumes of irrigation supply water, preventing excessive build-up of surface salt in the lower part of the bay, while minimising their contributions to regional drainage. The 're-use' of irrigation runoff would also concentrate flows to the downstream regional drain network, allowing more efficient use of large disposal schemes.

Study Limitations

While this study's research findings have provided insight into the mechanisms operating within irrigation bays, practitioners should be careful when translating these results to other irrigation areas or within the Barr Creek catchment without further validation studies. Particular care should be taken when considering bays with lighter, sandier soil types than those present at the monitored bay.

The report is based on the amalgamation of three manuscripts which have been recently submitted for publication (Section 1 & 2: *ASCE Journal of Irrigation and Drainage Engineering*; Section 3: Australian *Natural Resource Management Journal*). The report also reflects a summary of Mat Gilfedder's PhD thesis (*Irrigation Bay Processes Leading to Salt Export*) which was passed in September 1998.

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INTRODUCTION

This report examines the processes of water and salt movement which lead to salt export into surface drains from an irrigation bay (irrigated border). It focuses primarily on a detailed ‘irrigation bay scale’ monitoring programme within the Barr Creek catchment of the Kerang irrigation area in northern Victoria (Figure 1). Here, problems with excessive soil salinity and the disposal of saline drainage water from irrigation areas have a large effect on the productivity and environmental quality of the local area and areas downstream. This study examines the timing and quantity of drainage salt load from irrigation runoff, to enable estimation of the sensitivity of irrigation bay drainage to irrigation management change.

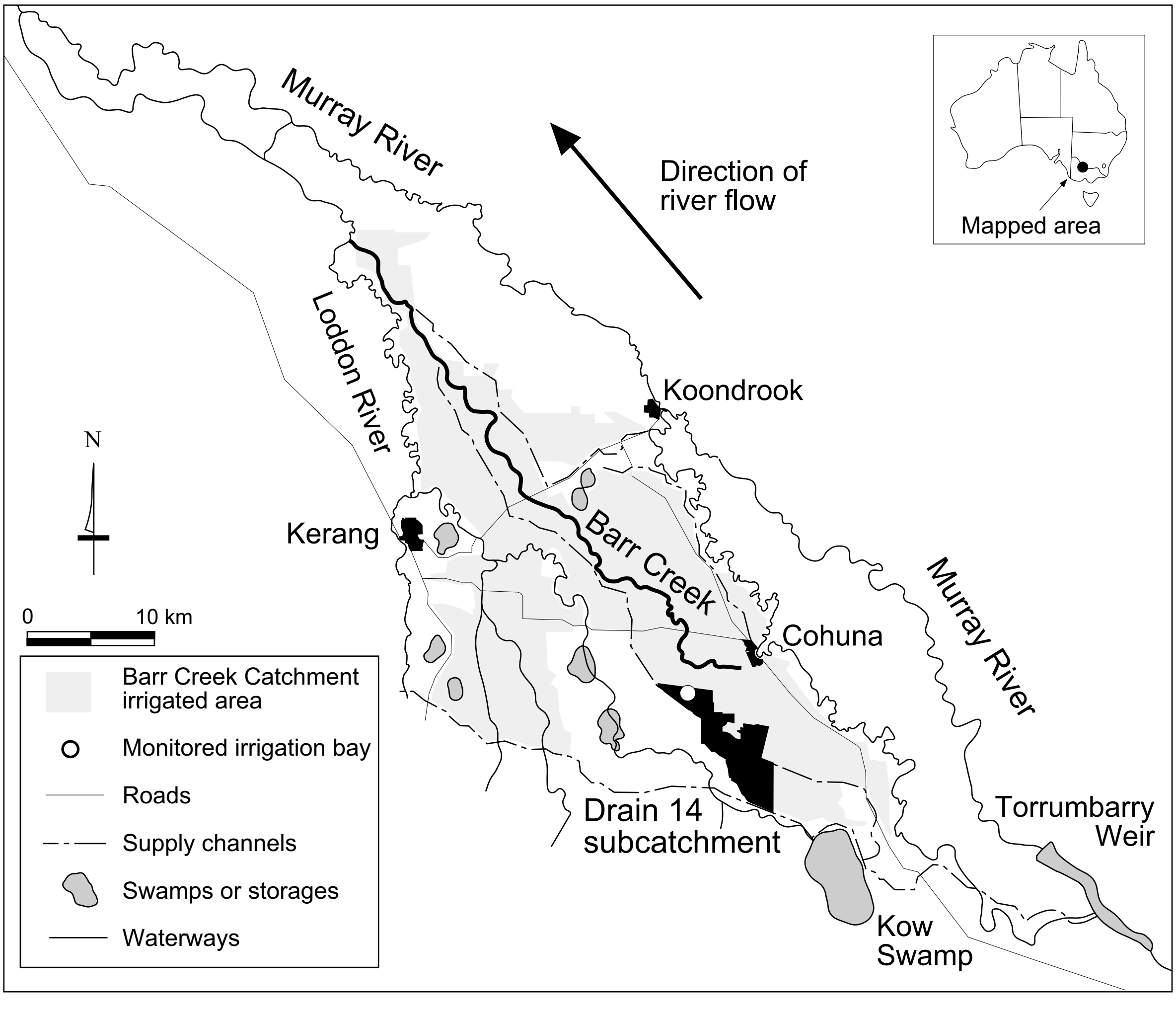

Figure 1. Map of Barr Creek catchment irrigated area (northern Victoria) and the monitored irrigation bay in the Drain 14 subcatchment.

In this research project, the knowledge gained from larger scale studies was built upon and refined using an irrigation bay scale approach. The study measured data rather than applying estimates of variable averages to calculate salt contributions. It used an 'irrigation bay' small enough to allow detailed monitoring of physical processes, and yet large enough to visualise the effects of changes in irrigation practice on drainage discharges and groundwater movement. These irrigation bays also form the scale at which water is applied, so the effect of management decisions can be seen directly.

The study built on a previous irrigation bay monitoring programme in the Tragowel Plains (south of the Barr Creek catchment) in which water movement and salt transport from an irrigation bay were measured (Mudgway *et al.* 1997). That study identified 3 mechanisms leading to drainage salt load: entrainment of surface salt by overland flow, groundwater seepage directly into the drain, and exfiltration of groundwater onto the bay surface.

To more clearly identify the generation of these drainage processes, Section 1 of this report considers water movement throughout the irrigation bay. Since salt is transported as a solute, local water movement processes can be used as a basis for identifying accessions to regional drainage, discussed in Section 2. Section 3 then examines management options for the control of salt export in irrigation runoff.

SECTION 1. WATER MOVEMENT

1.1 INTRODUCTION

In this section, the design of the monitoring programme is described, together with instrumentation and measurement techniques. This is followed by a discussion of regional and local groundwater behaviour, and surface water flow during irrigation. Measured data and analysis of the infiltration of irrigation water using different methods is then presented, to estimate the possibility for achieving groundwater control from improved irrigation management.

1.2 THE BARR CREEK CATCHMENT

The application of irrigation water for pasture in the Barr Creek catchment, northern Victoria (Australia) is predominantly through border flood irrigation. Since this form of irrigation was established in the 1880s, the regional water balance has changed, leading to a rise in groundwater level and an increase in salinity and waterlogging problems by the turn of the century (Jones 1990). In the 1930s, government water agencies responded by constructing a comprehensive surface drainage system to augment natural drainage throughout the Barr Creek catchment (see Figure 1). The larger, regional drains are commonly 2 – 3 m deep, intersecting the shallow groundwater table. While the installation of these drains has reduced the local effects of waterlogging, they have increased the salt export from surface runoff and groundwater seepage into Barr Creek, and the Murray River.

Victoria’s Barr Creek catchment contributes a large amount of salt to the River Murray, and has been the subject of several salt and water balance studies (Gutteridge, Haskins & Davey *et al.* 1985; Woodland & Hooke 1993). These studies have concentrated mainly on the regional effects of irrigation areas on drainage behaviour, and have identified key processes that result in water and salt accessions to regional drainage: groundwater exfiltration, groundwater seepage, irrigation and rainfall runoff, channel outfalls and leakages. This knowledge of processes has prompted the need for management changes within the Barr Creek area to target those hydrologic processes that contribute significantly to regional drainage. However, since the relative contribution of the various processes is unknown, smaller scale studies are required that are able to quantify the contributions more accurately. Intensive monitoring at a subcatchment scale is necessary to identify changes in Barr Creek’s salt load as a result of irrigation management changes (Trewhella 1984).

1.3 EXPERIMENTAL DESIGN AND MEASUREMENTS

An irrigation bay was selected for study within the Drain 14 subcatchment of Barr Creek, after a detailed site selection process. Potential locations were investigated with regard to their layout, soil type and salinity, groundwater elevation, and access. The chosen bay was considered representative of others in the area, being 280 m by 55 m in size, with a 1:750 slope. Measurements taken within this bay between 1995-1997 allowed a range of hydrological and salinity processes to be quantified, as well as surface water balances to be calculated during irrigation events. These results were then used to analyse the timing of infiltration during irrigation, and to investigate the possibility of achieving a reduction in groundwater elevation.

Reliable field measurements can be difficult and time consuming to obtain, since irrigation bay processes occur across a range of time-scales. Hence, sampling rates were tailored to allow for a combination of both long-term (*e.g.* groundwater movement) and event scale processes (*e.g.* overland flow) to be monitored sufficiently. Figure 2 shows a plan view of the bay with the layout of instrumentation and measurement locations. It was considered appropriate to use a central longitudinal transect for measurements, since the irrigation bay has a constant slope with no lateral gradients [with the exception of regional groundwater gradients which were assumed to have a negligible effect on conditions within a single bay]. Previous bay studies have also used a central transect measurement approach and found this method satisfactory (Mudgway *et al.* 1997). Measurements were also concentrated near the drain for greater spatial detail in this salt affected area.

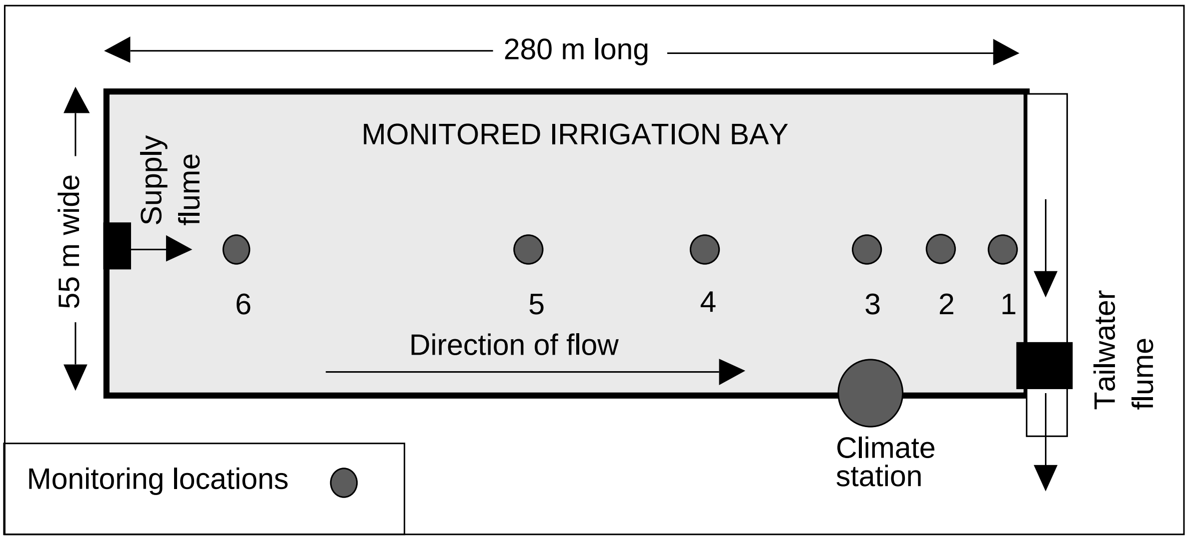

Figure 2. Plan of the monitored irrigation bay, showing the various measurement and instrument locations.

Measurements of water input and output at the irrigation bay scale were made, with detailed monitoring for 11 irrigation events in the 1996/97 irrigation season. Measurement of irrigation supply volumes was possible using a rectangular flume (1,150 mm width; see Photograph 1), because of the sufficient head difference between the supply channel and the bay.

Photograph 1. A large rectangular flume was used to accurately measure the flow of supply water onto the bay during each irrigation event. For a given depth of water flowing through the flume, an accurate flow-rate can be determined.

Some problems were encountered in the measurement of drainage tailwater volumes. The limited gradient in farm drains within the local area, and the low flow velocities and variable water elevations, created difficulties with drainage flow measurements. In Mudgway *et al.*'s (1997) previous study in the area, the lack of drain gradient precluded the use of any direct drainage flow measurements. In less extreme cases, RBC flumes have been used to calculate open channel flow rates in irrigation drains (Bos *et al.* 1984); a method this study also used (200 mm trapezoidal flume). The presence of the flume in the drain altered the natural drain flow to a small extent, as the height of the weir prevented the last of the drainage water from draining freely. Water ponded in the last 10 m of the drain after the flow had dropped below the level of the flume, although this did not cause extra ponding on the irrigation bay surface. An additional concern was that it was sometimes necessary to restrict the drainage from neighbouring bays to keep the level of tailwater in the drain to a level below that required for the accurate working of the flume.

In addition to measurement of supply and drainage volumes, surface water volumes were estimated from overland flow depths recorded during each irrigation event. Readings of surface water depth (and salinity) allowed calculations of surface water dynamic behaviour. These depths were recorded manually at surveyed pegs along the central transect of the bay. A benefit of the manual technique was that measurement intervals could be altered to focus on times of rapid depth change (such as arrival of irrigation front, cut-off of irrigation supply). This flexibility in measurement provided details on the surface water front advance, recession, and allowed estimation of changes in surface water volume with time.

Long-term, automated measurements of groundwater elevation (~2 m deep wells) and soil moisture content were taken at each of the 6 monitoring sites (see Figure 2). These data allowed the examination of the irrigation bay's subsurface response to wetting and drying. Regular soil samples were also taken to check the accuracy of the automated soil moisture measurements (using capacitance probes).

The following subsections deal with groundwater table movement, surface water behaviour and infiltration during irrigation events; they document many of the measurements and analyses made in this project. The findings show the timing and quantity of infiltration during irrigation, and add to the understanding of the effects of changes in irrigation management on the bay's behaviour.

1.4 GROUNDWATER TABLE MOVEMENT

The Barr Creek area is an extremely flat riverine plain, as well as a regional groundwater discharge zone. For much of the area the piezometric head of the deeper aquifers is approximately 1 m above the soil surface, while the shallow water table aquifer is between 1 – 2 m below the soil surface; nevertheless the net discharge from the deeper aquifers is considered relatively low. The main effect of this deep regional groundwater pressure is to prevent drainage of the shallow aquifers (Gutteridge, Haskins & Davey *et al.* 1985); however, little is understood about the effect of irrigation on the movement of salt from the shallow aquifers to surface drainage. This shallow system fluctuates gradually in a seasonal manner, with peaks during the early and late parts of the summer irrigation season, and a drop in level over the winter period, depending upon rainfall (Sargeant *et al.* 1978). The shallow regional groundwater table intersects the surface drainage network, and direct seepage to drains is considered to be one of the significant components of salt load exported from the area. Lowering the groundwater table in the area is therefore seen as an attractive management option to reduce regional salt export.

Figure 3 shows that the shallow groundwater table beneath the monitored bay underwent rapid and distinct elevation change between successive irrigation events. During the non-irrigated season, the groundwater level beneath the bay dropped to its maximum depth below the soil surface (although a high winter rainfall can result in a level close to the soil surface). In the figure, the effect of the above-average rainfall in 1995 contrasts with the response during the much drier winters of 1996 and 1997. The rainfall over most of the monitored period was below average, allowing the level to drop substantially during the non-irrigated winter periods. Long-term mean monthly rainfalls, and measured monthly rainfalls for the local area are shown in Figure 4.

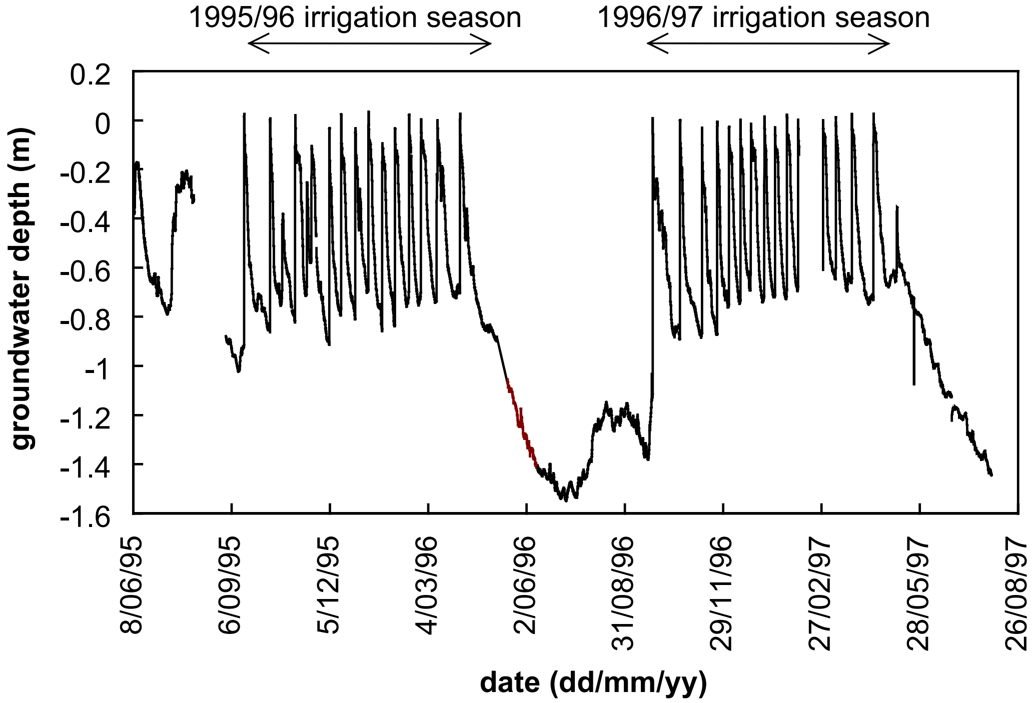

Figure 3. Changes in shallow groundwater elevation at Site 6 (32 m from supply channel) over 2 irrigation seasons. The effect of each irrigation season can be seen clearly.

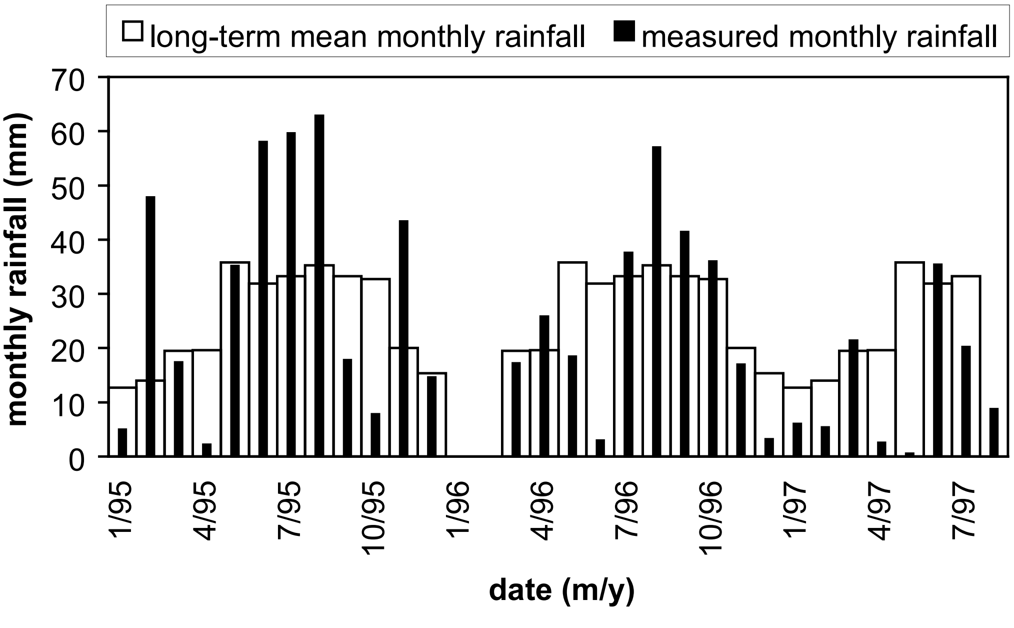

Figure 4. Monthly rainfall for study site (long-term mean monthly and actual monthly). The dry period from December 1997 – May 1998 coincided with the monitored irrigation season.

Immediately prior to each irrigation event, the depth to the groundwater table at the monitored bay was typically around 40 cm in the lower part of the bay (close to the drain), and 80 cm in the upper part. Irrigation caused a rapid and distinct rise to the soil surface over most of the bay, followed by a more gradual recession between events. This rise was not as distinct over the lower 50 m of the bay due to the more saline and compacted surface soil; there, the groundwater table rose to within 10 cm of the soil surface.

Figure 5 shows the elevation of the shallow groundwater table at Site 6 (located 30 m from the supply channel). It can be seen that groundwater table response to irrigation over all but the lowest 50 m of the bay is rapid; levels have risen within minutes of the irrigation front passing, and reached the soil surface within 2 – 3 hours. Initially this quick response was thought to be an artefact of preferential flow of irrigation water down the piezometer casing. To check if this was the case, a single well was shielded from surface water with a collar while a nearby well was left as constructed. The timing and magnitude of the groundwater increase in both wells showed the same response. Hence, the rapid rise of the groundwater table was attributed largely to the presence of soil cracks that allowed surface water to infiltrate rapidly at the onset of ponding and the small soil moisture deficit. This rapid preferential flow of surface water into the soil highlighted the difficulty of achieving groundwater table control in this area. A reduction in the amount of water applied during an irrigation event may reduce the amount of surface irrigation runoff, but infiltration and shallow groundwater table elevations would remain unaffected.

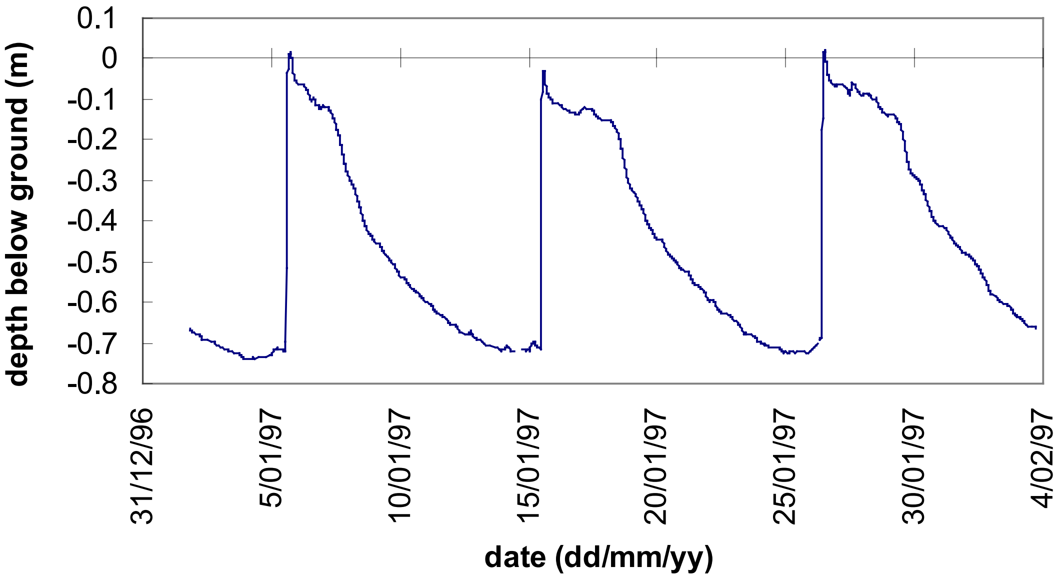

Figure 5. Fluctuation in shallow groundwater elevation over 3 irrigation events. Note the rapid rise with each irrigation (Site 6: 32 m from supply channel).

1.5 SURFACE WATER BEHAVIOUR

Surface water behaviour for the monitored irrigation bay is depicted in Figure 6, with overland flow depths shown for an irrigation event measured at 9 points along the central transect. The elevation of the water is shown, rather than the actual depth below the soil surface, to enable all points to be plotted on the same chart. Note the extended period of recession. This is due to several factors, including the shallow surface gradient and water depths, and the uneven soil surface in the lower part of the bay as a result of cattle disturbance.

The measurement of surface water depth allowed the calculation of surface water volumes which, when combined with irrigation supply and drainage measurements, could be used to estimate surface water balance. During irrigation, the surface water behaviour followed a similar 4-stage pattern, *i.e.*

- rapid increase in depth after the arrival of the advancing front;
- gradual slowing of this rise until irrigation supply is cut off;
- decrease in depth after cut-off, which becomes less rapid, further down the bay;
- distinct change in recession rate when the water depth becomes shallow, from a dynamic-lateral recession to a more gradual static-vertical recession (Turral 1993).

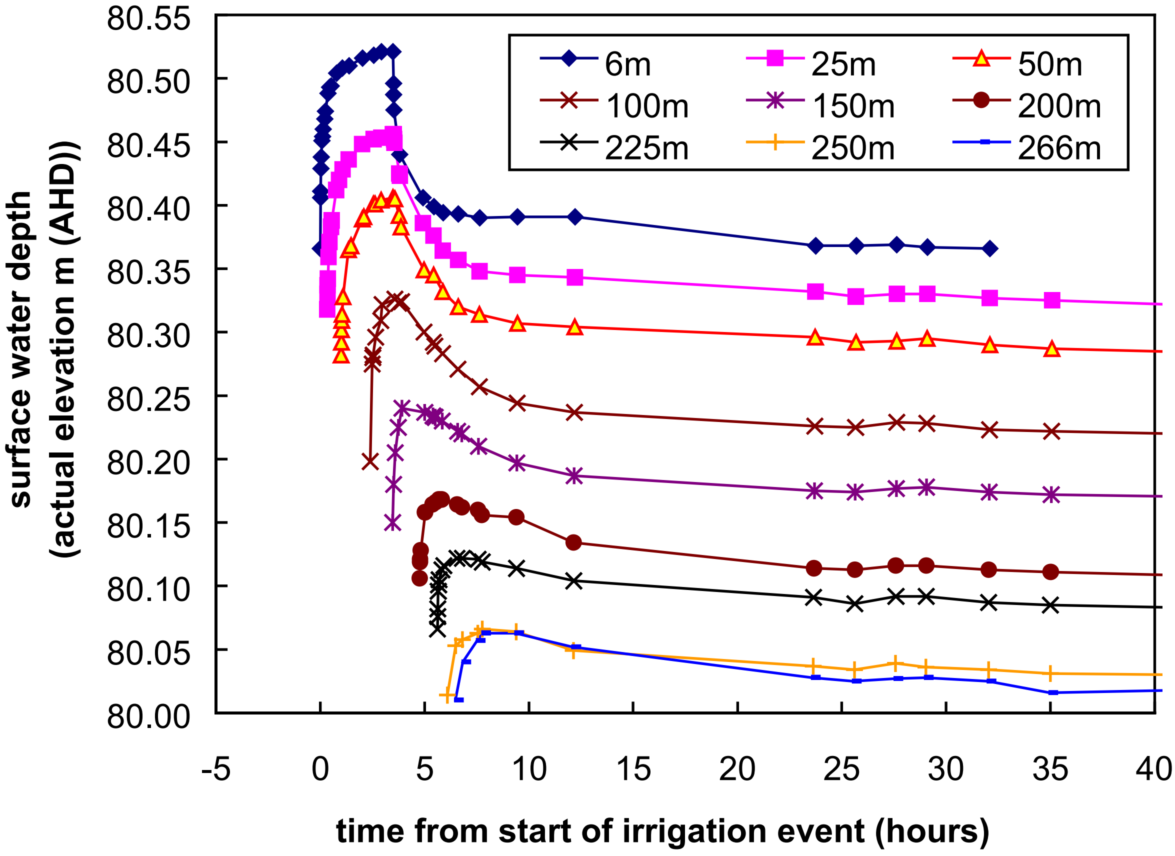

Figure 6. Surface water depths at 8 locations along central bay transect during irrigation (26/1/97). Legend gives the distance from supply channel (supply cut-off at 3.5 hours).

1.6 INFILTRATION

The infiltration characteristics of the bay are crucial in understanding the possible effects of changes in irrigation management on its behaviour, and on the bay contribution to regional drainage. Soil hydraulic conductivity is now considered, followed by calculations of total infiltrated volume; finally, a surface water balance is used to estimate the timing of infiltration during irrigation.

1.6.1 Rate of infiltration - soil hydraulic conductivity

Most of the monitored bay was covered with pasture species, although the lower 80 m was highly salt affected (with very little vegetation). The distinct change between the two parts of the bay was partly the result of a change in soil type. Most of the upper part of the bay was classified as a sandy clay loam, while the lower part of the bay is a medium clay (Sargeant *et al.* 1978). To determine infiltration behaviour, the saturated hydraulic conductivity was measured at several points along the central transect of the bay. Two methods were used; an *in situ* ponded ring infiltrometer, and laboratory analysis of large soil cores.

The ponded ring infiltrometer was used to estimate the infiltration rate of surface ponded water into the soil profile according to Bouwer (1986). To minimise divergence errors, the ring was made as large as practicable (1,600 mm diameter). The recession of the ponded depth within the ring was measured over time, and saturated hydraulic conductivity (K_s) of the surface soil calculated.

In addition, large soil cores (140 mm diameter, 190 mm length) were removed from the soil at various locations along the bay. Ponded water (falling head) infiltration tests were carried out on these cores in the laboratory to calculate K_s for comparison with values gained using the *in situ* ring infiltrometer method. The results from the lower and upper parts of the bay show markedly different values of K_s, consistent with the published results for the soil types present (*e.g.* sandy clay loam 0.54 md^{-1}, silty clay 0.09 md^{-1} (Clapp and Hornberger 1978)). Figure 7 shows the results for both tests at several locations along the bay.

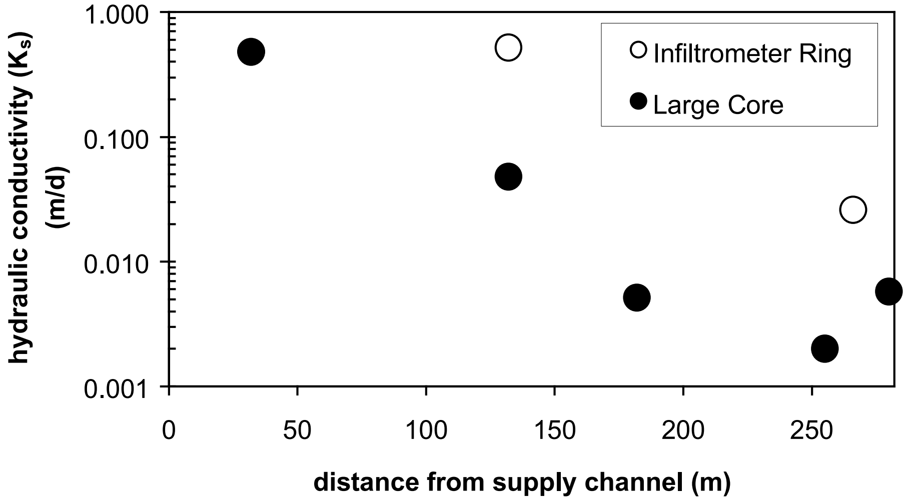

Figure 7. Soil hydraulic conductivity along the central transect of the irrigation bay. This shows the large difference between the upper and lower parts of the bay.

The differences between the estimates of hydraulic conductivity obtained from the two surface infiltration techniques were likely to be due to the presence of soil cracks or macropores which affected the field measurements but not the smaller laboratory cores. Nevertheless, both methods indicated changes of at least an order of magnitude in surface hydraulic conductivity between the upper and lower parts of the bay.

1.6.2 Volume of infiltration (measured soil moisture deficit)

The infiltrated volume during an irrigation event was estimated from the changes in soil moisture content throughout the bay. Soil samples were taken at intervals to 550 mm before and after irrigation (for January 26 & 28, 1997) at 6 locations along the central transect (see Figure 2). These data were then used to provide gravimetric soil moisture content, which was converted into a volumetric value using bulk density values (measured previously) for each location. Based on the earlier assumption that lateral groundwater movement or deep drainage of the soil profile was relatively minor compared to the vertical unsaturated flow, the infiltrated volume was inferred from the changes in measured soil moisture content.

A typical example of the increase in the soil volumetric moisture content (θ) from irrigation is presented for a single event (January 26th 1997) in Table 1. The average amount of water in the upper 550 mm of the soil profile increased from 180 to 236 mm (θ: 33% to 43%), an average infiltrated volume of 56 mm of water over the entire bay. During irrigation, there was a large increase in the soil moisture of this surface soil (upper 200 mm), but little increase at depth since the deeper soil was already close to saturation.

Table 1. Increase in soil moisture due to an irrigation event (January 26 1997).

Depth (1)	Site number, and distance from supply channel [a] Site 6 32 m (2)	Site 5 132 m (3)	Site 4 180 m (4)	Site 3 230 m (5)	Site 2 255 m (6)	Site 1 280 m (7)
25 mm	14%	33%	55%	18%	48%	40%
100 mm	12%	21%	28%	11%	11%	6%
200 mm	8%	16%	16%	4%	2%	1%
300 mm	5%	13%	3%	5%	0%	1%
400 mm	2%	7%	7%	6%	0%	3%
500 mm	0%	6%	6%	4%	0%	2%

[a] see Figure 2 for site map

Note: The unshaded part of the table shows the part of the soil profile which showed an increase of more than (an arbitrary) 7% in soil moisture content due to an irrigation, highlighting the near saturation of the bay soil below 200 mm, throughout the irrigation season

The assumption of negligible deep drainage was validated by a comparison of soil moisture content change (during the drying phase between events), with estimates of cumulative actual evapotranspiration (AET). Potential evapotranspiration (PET) was calculated from measured climate data using a combination method based on the Penman-Monteith equations (Grayson *et al.* 1996, Smith 1991). AET was then determined by reducing the PET estimates by both a crop factor and a soil factor. The crop factor was initially set at 0.8, however the harvesting of the pasture on 25 February suggested its reduction to a value of 0.6. The soil factor was set at unity for soil moisture contents greater than 70%, but this factor reduced linearly from 1 to 0 as soil moisture content reduced from 70% to 0% (Prathapar *et al.* 1994). The comparison between AET and soil moisture deficit (Figure 8) showed that the estimated AET was sufficient to account for the soil moisture deficit at Site 4 (180 m from supply channel). The drying of the soil profile between irrigations compared extremely well to total AET between events at this location. This close comparison supported the presumption that deep or lateral drainage of shallow groundwater is a relatively small component of the soil moisture change at this bay.

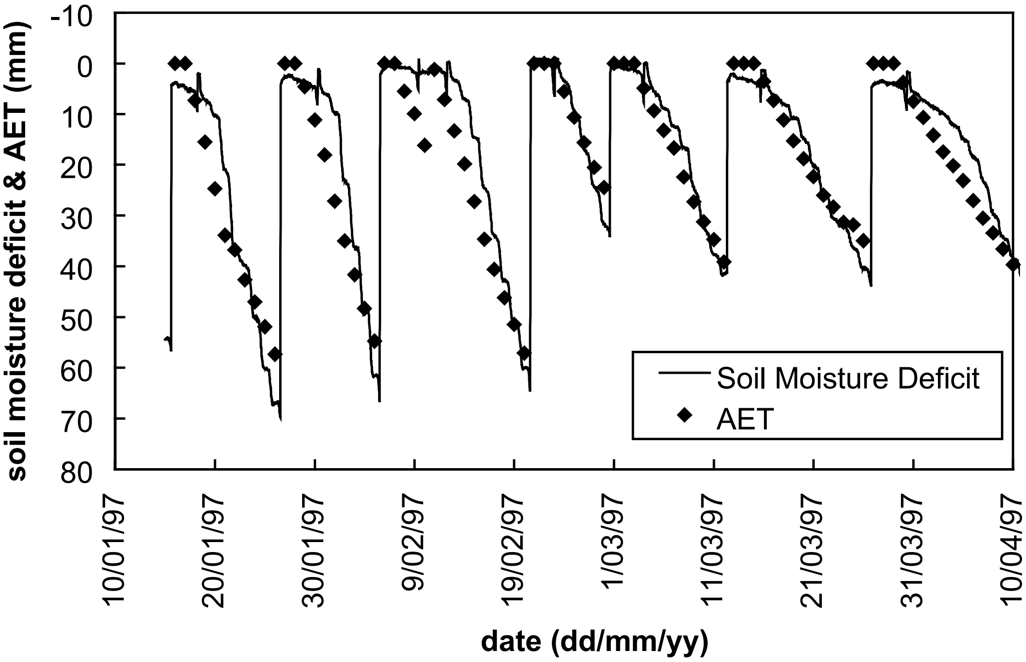

Figure 8. Comparison of estimated evapotranspiration (AET) with soil moisture deficit in the top 600 mm of soil profile. The close match suggests that evapotranspiration is the main water removal process from the bay (*i.e.* deep drainage is negligible). (182 m from supply channel)

1.6.3 Timing of infiltration – surface water balance

Supply and tailwater data, and ponded surface volumes were obtained by interpolating the results of measured depth at a range of closely spaced intervals along the bay. These data were then used to calculate the surface water balance with time during irrigation events. The difference between these terms provided an estimate of infiltrated volume and evapotranspiration. This balance followed a similar pattern for each of the measured irrigation events at the monitored bay. Figure 9 shows the cumulative supply hydrograph (105 mm average depth over the bay area), and the changing water components as the event progresses. It can be seen that, at 20 hours after irrigation, 20 mm remained on the bay surface, 30 mm had been removed as tailwater drainage, and 5 mm evaporated. The remaining 50 mm of water (balancing term) was attributed to infiltration. Tailwater drainage and evapotranspiration almost wholly explained the removal of water from the bay surface during recession, since the soil profile was almost entirely saturated.

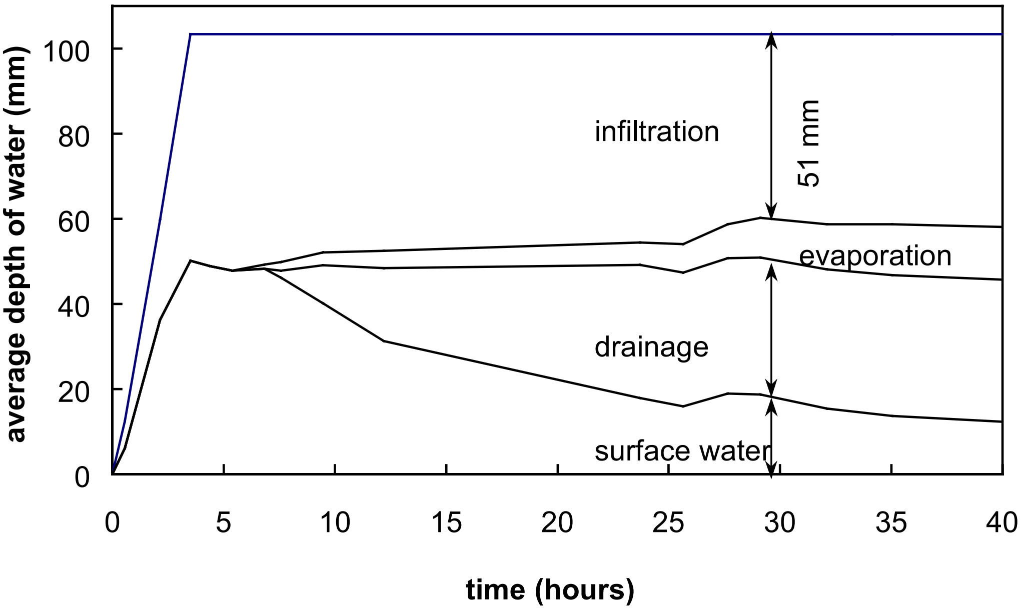

Figure 9. Surface water balance for irrigation event on 26/1/97. The timing of infiltration of irrigation water can be estimated for each event by measuring the total supply volume and subtracting the volume of water present on the bay surface, in the drain, and evaporation.

The infiltrated volume of 51 mm (average depth over the entire bay), calculated from the surface water balance, compared well with the estimated 56 mm that was calculated from the measured soil moisture content changes presented above. This corroboration between the two independent measurements added confidence to the experimental results.

As well as providing an estimate of the total infiltrated volume, the surface water balance allowed infiltration variation in time to be estimated for the wetted area of the bay. This showed that infiltration mostly occurred during the early advance stages of irrigation (0 – 3.5 hours from the start of an irrigation event). Figure 10 shows the timing of irrigation front advance, and the cumulative infiltrated volume as determined from surface water balance (averaged over *whole bay* and averaged over *wetted area* of bay). It clearly distinguished the change in infiltration behaviour between the upper and lower part of the bay, as expected from the different soil hydraulic conductivities. This change was shown by the dramatic reduction in *wetted area* average cumulative infiltrated volume, and a levelling off of the *whole bay* average infiltrated volume after 3.5 hours, when the front had reached half way down the bay.

The estimate of infiltrated volume for the upper part of the bay was also supported by the measured hydraulic conductivities. Figure 10 shows that approximately 100 mm of water infiltrated in the upper part of the bay during the first 3.5 hours of irrigation. This corresponded with an average hydraulic conductivity of 0.7 m d^{-1} which was approximately equal to the results of the infiltrometer tests, and indicated that the infiltration rate quickly approached the steady state rate of saturated hydraulic conductivity. Importantly, the sudden cessation of infiltration after 3.5 hours indicated that the soil profile was saturated soon after the passing of the irrigation front.

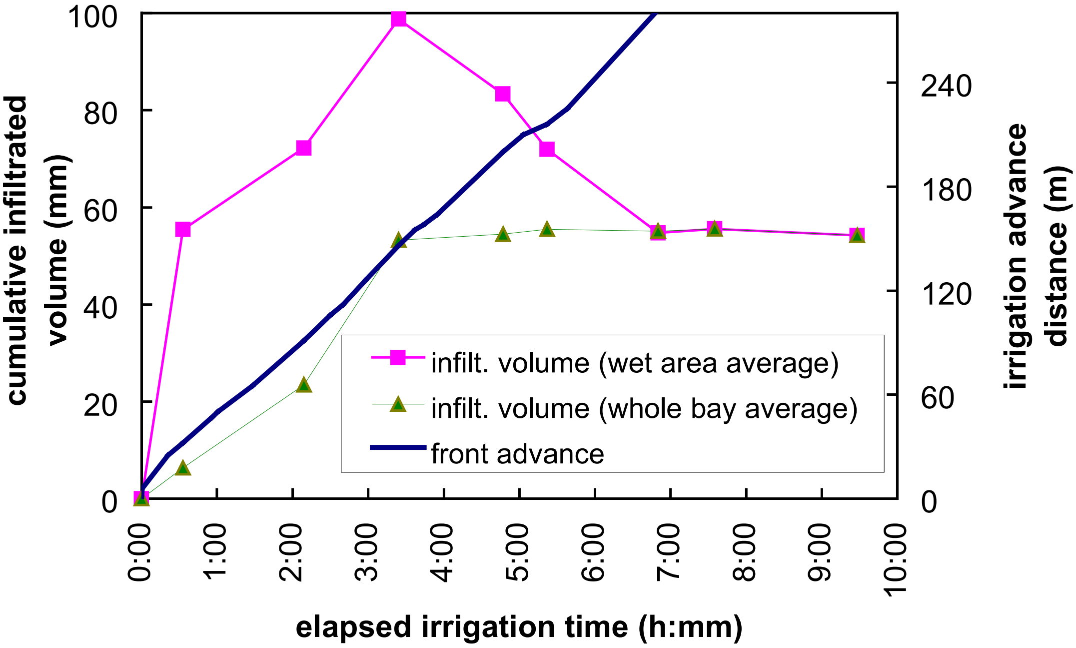

Figure 10. Cumulative infiltrated volume and irrigation front advance during irrigation. Most of the infiltration during this event occurred before the front had reached the lower part of the bay.

This rapid infiltration was also shown by the groundwater elevation change as a result of irrigation. For such a fast groundwater response, factors such as soil cracks dominated (see Section 1.6.1). However, although the groundwater table rose quickly to the surface, there was evidence to show that there was no significant lateral or deep movement of groundwater from the bay. This suggested that a reduction in the amount of water applied to irrigation bays will not lower the water table beneath the bay, nor will it impact on the seepage of groundwater into the deeper – regional surface drainage network.

1.7 MAIN FINDINGS - WATER MOVEMENT

This study used a variety of monitoring techniques to investigate the movement of water within an irrigation bay. The measurement results allow several conclusions to be drawn with regard to irrigation bay water movement processes, and their effect on both local and regional hydrology.

- *The rapid infiltration of irrigation water was shown by both the surface water balance, and by the quick response of the shallow groundwater table to ponding surface water. Soil cracks provide the pathways for significant volumes of preferential flow in the early stages of each irrigation event. Since almost all of the infiltration occurred in the initial stages of irrigation, and that infiltration filled the soil profile to saturation, it seems unlikely that slight changes in irrigation bay management in this area will have any effect on controlling the groundwater table.*
- *There was a match between the removal of water from the soil profile (at a site in the bay) with estimated actual evapotranspiration (AET). This showed that AET could account for the soil moisture deficit between irrigation events, and indicated that deep drainage was most likely only a small component.*
- *The finding of negligible deep drainage was also supported by the close match between estimated infiltrated volume using a surface water balance, and measured changes in soil moisture content due to an irrigation event. The independently measured infiltration volume data provides confidence in the measured results, with the infiltration of irrigation water being controlled by the available soil moisture deficit in the upper parts of the bay's soil profile.*

These findings highlight the difficulties of lowering the shallow groundwater table in this area. The lack of deep drainage through the soil profile, and the influence of soil cracks on infiltration rate suggest that groundwater accessions from irrigation will remain largely unaffected by improved management of border irrigation, as will the seepage of groundwater into the deeper regional surface drains.

SECTION 2. SALT TRANSPORT

2.1 INTRODUCTION

This section highlights the salt transport aspects of the irrigation bay monitoring experiment; it utilises the analysis of water movement results presented in Section 1. Detailed results are discussed for salt movement into the surface water during irrigation, and into the runoff in the drain, highlighting the variability between and during events.

A key concern for the management of an area's salinity problems is determining salt transport processes important to regional salt export. Although these processes are well known, their relative contributions to salt export are not. Large-scale regional studies often rely on broadly applied assumptions to quantify the individual components of regional salt export (*e.g.* Gutteridge, Haskins & Davey *et al.* 1985). As the salinisation of irrigated areas becomes an increasingly serious and widespread problem, the growing awareness of the connection between local catchment and regional salinity issues has led to a re-evaluation of salinity management strategies. In particular, linkages have been made between the use of engineered drainage to reduce and manage the impact of salinisation on local irrigated farmland, and the adverse effects of drainage disposal on the entire catchment. Such management concerns highlight the need to account for local, catchment and regional salinity issues in any assessment of the costs and benefits of irrigated agriculture (van Schilfgaarde 1996).

The objectives of this section are to investigate the timing and location of salt movement from the soil and groundwater into surface water and into drainage water, from which the relative importance of key salt transport processes on salt export can be assessed. In order to quantify the contribution of key salt transport processes, this study of surface and subsurface water and salt movement processes is given at irrigation bay scale. This choice of scale allowed detailed measurements of key processes to be obtained, on an area large enough to reflect the influences of changes in irrigation management.

The section begins with a discussion of some previous salt transport studies conducted at an irrigation bay scale, before describing this study's monitoring programme. Results are then presented for salt transport into surface water during irrigation advance and recession, and the mobilisation of salt from the bay soil into surface water. The relationship between salt mobilisation and salt removal with irrigation runoff drainage is then discussed. Finally, the effects of irrigation on bay soil salinity are examined for both a single irrigation event and an entire irrigation season.

2.2 PREVIOUS WORK

Irrigation water usually contains significant amounts of salt, and, for productive irrigation farming practice to continue, adequate leaching and drainage are necessary to remove salt left in the root zone after transpiration (Hoffman 1985). The natural drainage capacity of the soil and the groundwater system in irrigation areas is usually insufficient to remove water that has infiltrated in excess of crop requirements; engineered drains are often necessary to prevent waterlogging (Tanji 1996). Such surface drains or subsurface drains act to remove water from the soil profile and allow leaching of salts from the crop root zone. However the ability of drains to manage irrigation salinity is limited to 'exporting' the salt problem away from the local area. While the importance of drainage to successful long-term irrigation cannot be understated, the problems of the ultimate disposal of drainage lie with environmental water quality restrictions and costs (Ayars *et al.* 1997). Earlier studies have examined and modelled the water behaviour within irrigation bays, both numerically and analytically, to predict irrigation advance (*e.g.* Hall 1956; Philip and Farrell 1964). Further studies refined this prediction, to include irrigation recession (*e.g.* Strelkoff 1977; Fonken *et al.* 1980). However there has been little work that focuses on the movement of salt from an irrigation bay during advance / recession processes. Van der Tak and Grismer (1987) examined both soil salinity and subsurface drainage from an irrigation bay in the Imperial Valley (California). They concluded that the presence of soil cracks in the heavy bay soils had a large impact on irrigation behaviour, both by severe reduction in the leaching of the upper soil profile, and by the faster response of subsurface drainage to irrigation application. A study into the effects of soil cracks on irrigation runoff from irrigation bays was also undertaken by Rhoades *et al.* (1997), whereby the salinity of irrigation bay runoff drainage water for different soil types, at several times during drain flow, was examined. Their results showed substantial lateral washoff of bay salt into overland flow, particularly from the lower end of the bays with heavy textured soil. While highlighting the variability of salt export processes, their study did not attempt to measure drainage volumes, and hence did not quantify water and salt movement processes.

A study to quantify water and salt transport processes within an irrigation bay was undertaken in the Tragowel Plains area (immediately south of the Barr Creek catchment) by Mudgway *et al.* (1997). The SHE model (*Systeme Hydrologique Europeen*) was used to describe the hydrologic and salt transport behaviour at irrigation bay scale in response to changes in irrigation water and land management. Based on detailed measured field data, they estimated the effect of a redistribution of irrigation water away from salinised soils, and the effects of enlarging surface drains on drainage discharges. The authors estimated that direct seepage of groundwater into the shallow drain at the lower end of the bay was negligible compared to both the washoff of surface salt by overland flow and the groundwater exfiltration to the bay surface. However, only total drainage volume was measured, and not the actual flow-rate, due to the low surface gradients.

In this study, a combination of surface water and salt balance analysis, together with a quantification of irrigation runoff, provided information in regard to the effect of irrigation on conditions within the bay, and on regional processes of salt export. In particular, the links between irrigation events and groundwater movement were investigated, to examine whether exfiltration or deep recharge was occurring. Details of the salinity monitoring programme for this study are now discussed.

2.3 METHOD

The field monitoring programme was set up in an irrigation bay in the Barr Creek catchment of northern Victoria (Australia). The study aimed to measure salt and water movement within a single border-irrigated bay (280 m by 55 m), to investigate the timing and quantity of salt transport into the surface drainage network. The main processes which can influence salt transport at an irrigation bay scale are shown in Figure 11.

Detailed data were obtained for surface and subsurface water and salt properties over the 1996/97 irrigation season; these included irrigation supply and drainage volume and salt load, detailed surface water salinity and depth measurements, soil water content and salinity analysis, and groundwater monitoring. A detailed description of the field site and instrumentation for water movement can be found in the Section 1 of this report. However, for salinity and salt transport analysis, additional instrumentation and techniques were used and are described below.

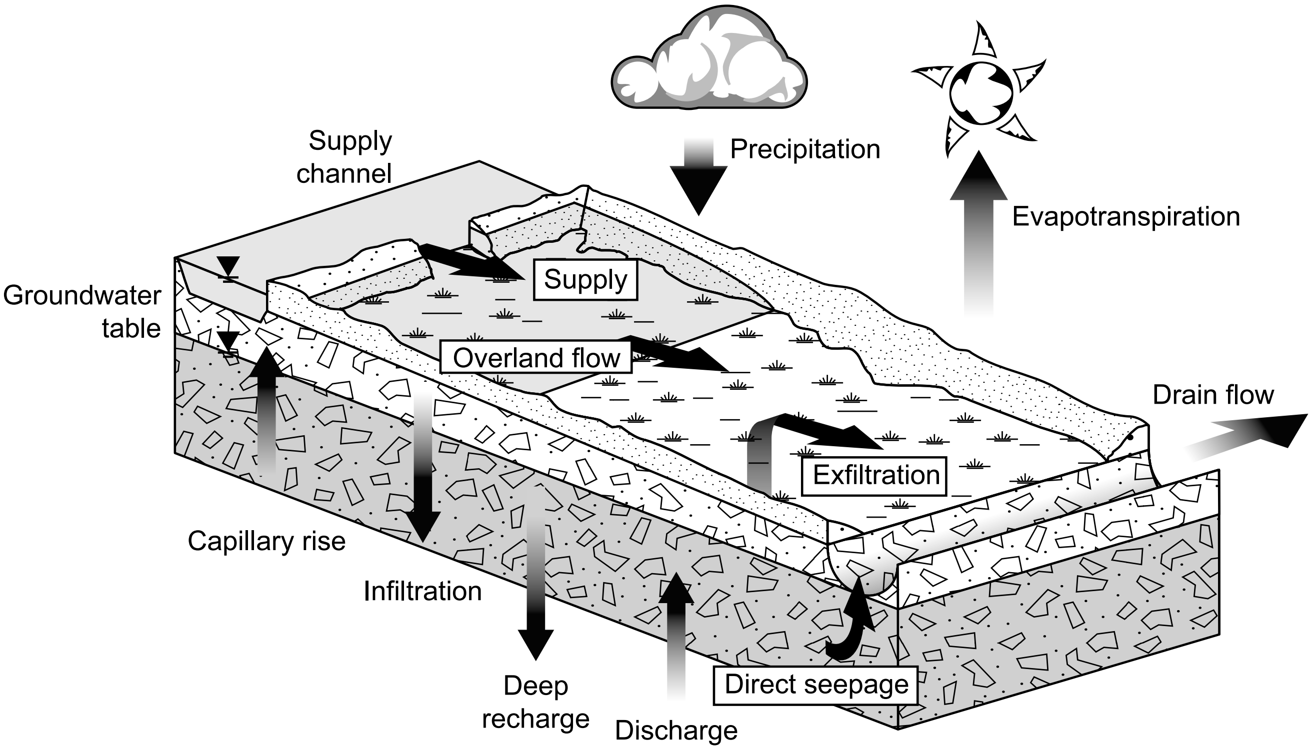

Figure 11. Conceptualisation of the water and salt transport processes occurring within an irrigation bay.

Soil salinity was measured using standard laboratory $EC_{1:5}$ tests on soil samples taken several times during the season, and before and after irrigation events, according to Rhoades (1982). The air-dried soil samples were crushed and mixed with water at a ratio of soil:water of 1:5. The $EC_{1:5}$ value is the salinity of the mixture after the soil has settled. These values were then adjusted to an approximate saturated extract salinity (EC_e) value using soil factors in Taylor (1996). Samples were taken at six depths, down to 500 mm, at the 6 measurement sites along the central transect of the bay (see Figure 2).

Surface water salinity, including irrigation supply and tailwater drainage salinity, was measured using portable sensors. The sensors' accuracy were verified later in the laboratory against selected water samples. The manual measurement technique for surface water salinity ensured that sufficient detail was collected to suit the conditions, and allowed detailed and relevant salinity data to be collected.

2.4 EXPERIMENTAL RESULTS

2.4.1 Salt transport – overland flow

As the irrigation front advanced down the bay, salt was entrained from the soil surface into the overland flow. The salinity of water in the advancing front increased as it moved closer to the drain, although this increase was restricted mainly to the leading edge. The salinity of the water 10 – 20 m behind the advancing front remained approximately equal to the salinity of the irrigation supply water.

Figure 12 illustrates surface water salinity during irrigation advance for 4 times during a single irrigation event (February 5 1997). The distinct increase of salinity of the front water with distance can be seen, with most of the increase confined to the lower 80 m of the bay. The salinity of the water at the leading edge of the advancing front showed an increase even in the upper parts of the bay, where infiltration was the highest. This pattern revealed that lateral movement of salt from the bay is an easily recognisable process that carries a clear 'first flush' of salt into the drain, with irrigation runoff.

After the initial washoff of surface salt during the irrigation advance, there was a gradual increase in the salinity of the surface water, partly due to the movement of salt from the soil. The greatest and most significant rise occurred in the lower (bare) part of the bay, after the surface water had become largely immobile and held in shallow puddles. Towards the end of recession, surface water salinities of more than 5,000 $\mu S\ cm^{-1}$ were common. The shallow depth and slow velocity at this late stage prevented much of this salt from being removed laterally from the bay surface into the drain. Figure 13 shows the surface water salinity at several times during recession (hours from start of irrigation) and is a continuation of the data presented in Figure 12. The large increase in surface water salinity over the lower 50 m of the bay indicates its importance in mobilising salt into the drainage water.

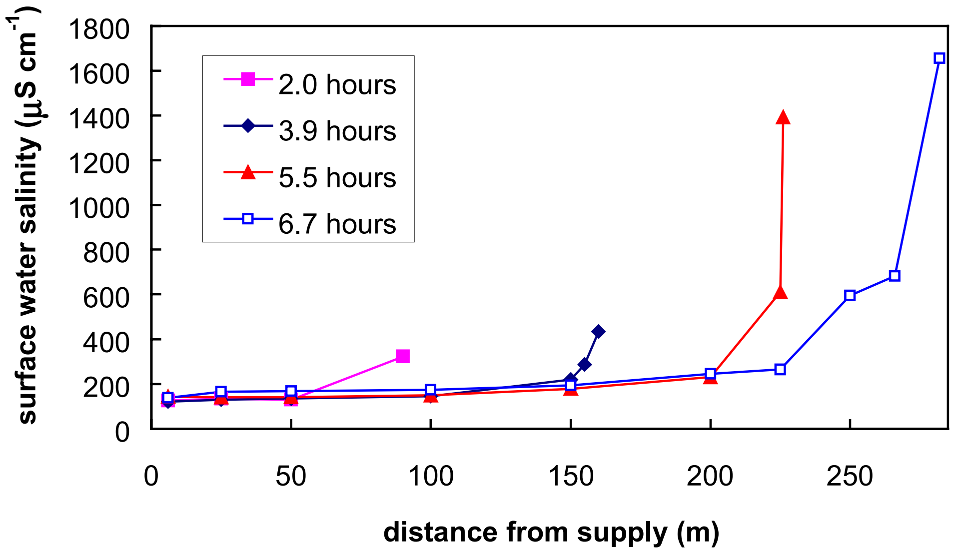

Figure 12. Salinity of surface water at selected times during irrigation advance (February 5 1997). The 'first flush' or mobilised salt can be seen immediately behind the advancing front.

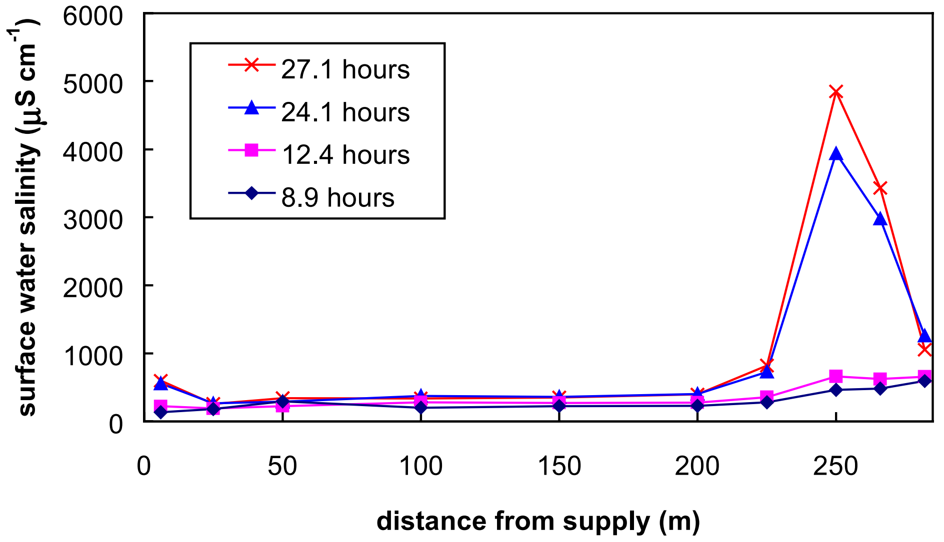

Figure 13. Salinity of surface water at selected times during an irrigation recession (5/2/1997). Surface water in the lower part of the bay increases dramatically in salinity, towards the end of each event.

The increase in surface water salinity during irrigation recession was also partly due to evaporative concentration. To allow for this effect, Figure 14 shows the surface water salt loads (at the same time intervals as Figure 13), since total salt load is unaffected by evaporative concentration. A large increase in salt load in the surface water occurred between 12 – 24 hours after irrigation commenced, as a result of the entrainment of salt from the near-surface soil layers. After this time, the salt load in the surface water decreased until the end of monitoring, which emphasised the relative importance of salt washoff during the early stages of irrigation.

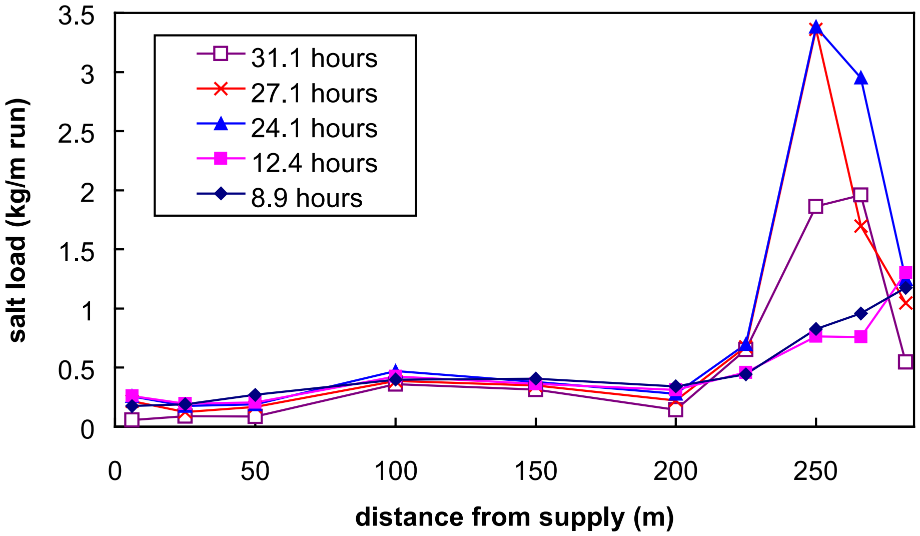

Figure 14. Surface water salt load at selected times during an irrigation recession (February 5 1997).

To further analyse the surface water salt load, the total mass of salt present on the bay surface and exported into the drain was examined. The mass of salt in the water ponded on the upper 175 m of the bay remained fairly constant, while the amount on the lower part of the bay increased rapidly after irrigation cut off, due to the washoff of surface crusted salt. As the drain flow commenced, the total combined salt mass of bay surface and drainage salt increased steadily. Salt in the ponded surface water increased only slightly with time, and most of the combined salt rise was accounted for by drainage salt load. Figure 15 shows the salt load in the upper and lower parts of the bay and the cumulative drainage salt load for an irrigation event. The results suggest that most of the salt movement into the surface water occurred in the early stages of irrigation.

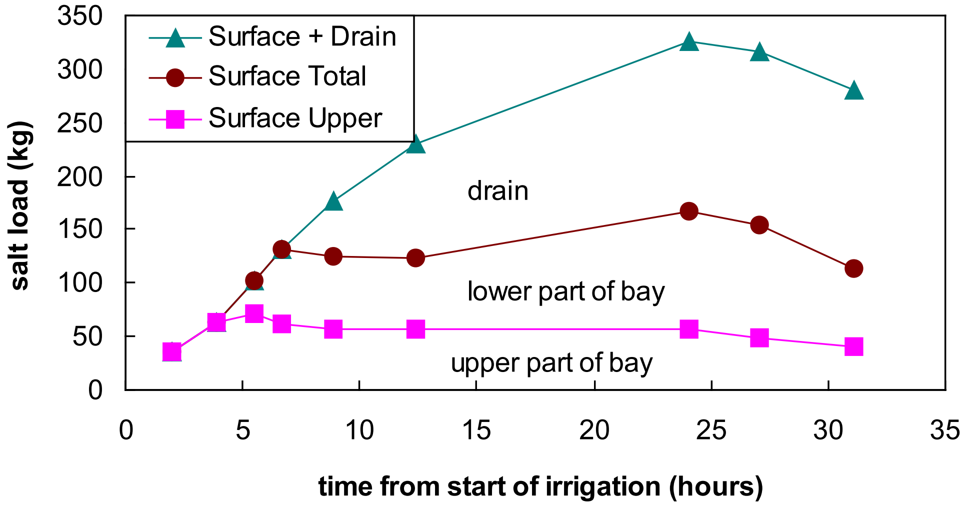

Figure 15. Total salt load in the surface water during an irrigation event (5/2/1997). Salt is mobilised into surface water more quickly during the early part of the event.

The gradual reduction of salt mobilisation into the surface waters suggests that surface and near-surface lateral washoff was the main process. It seems unlikely that direct groundwater exfiltration occurred during irrigation; this would be shown by an increasing trend in salt load towards the late stages of the event, after groundwater has had sufficient time to rise to the surface and contribute salt load to the surface.

2.4.2 Salt transport – surface drainage

Drainage volume and its salinity varied markedly between events, depending on the amount of irrigation water supplied to the bay, and the soil water deficit. The total drainage volume over the 1996/97 season varied between 0.14 kL and 0.47 kL per event, demonstrating the impact that changes in irrigation practice (timing, supply rate, total volume, *etc.*) can have on drainage volumes. Figure 16 illustrates the drainage volume and average salinity for each measured event over the 1996/97 season. An important observation from this figure is the complex relationship between the two variables, as high drainage volume did not necessarily mean low drainage salinity.

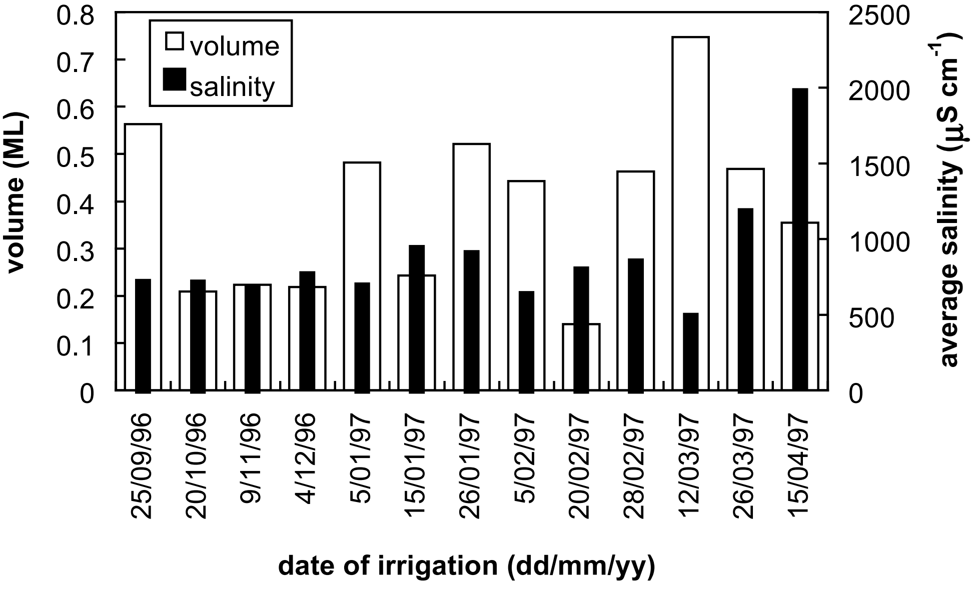

Figure 16. Drainage volume and salinity for each irrigation, 1996/97 season

Although the flow of water in the drain during irrigation varied between events, it always retained the form of a hydrograph with a steep rising limb and a more gently sloping falling limb. The flow in the drain typically reached its peak value within 2 hours of the commencement of flow in the drain. The recession took much longer, with drain flow ceasing at about 30 – 40 hours after the start of irrigation. Figure 17 shows the drain hydrograph and salinity changes for a typical irrigation event (flow was measured using the flume shown in Photograph 2). The salinity at the start of drainage flow was high (1,500 - 2,000 µS cm^{-1}) but dropped rapidly during the first part of the hydrograph's rising limb. This initial elevation in drainage salinity was due to washoff of surface salt by the advancing irrigation front as shown in Figure 12. As stated previously, this elevation in salinity was restricted to the leading edge of the advancing front, so the high salinity of the drainage flow dropped rapidly as lower salinity water from behind the front reached the drain.

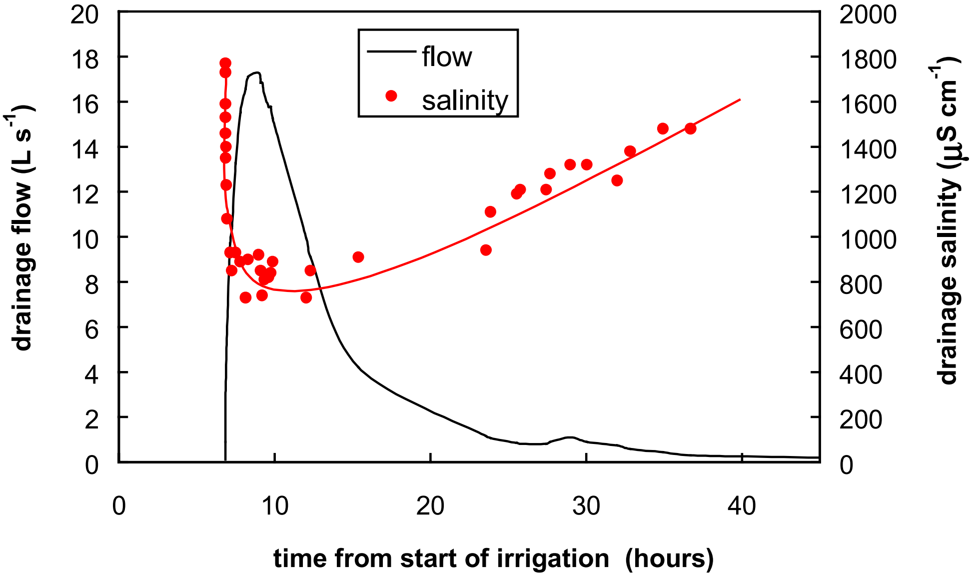

Figure 17. Drainage hydrograph and salinity levels for an irrigation event (28/2/1997).

Photograph 2. Flow measurement flume in the monitored bay's drain. This type of flume can measure low flows accurately, making it ideal for monitoring small farm drains.

Salinity fell to its lowest level during the peak drain flow; by this time the initial flush of washoff salt had passed, and large volumes of water diluted the salinity of the surface water. During the recession, drainage salinity increased, although not to the same level as the ponded surface water on the bay. Despite surface water salinity levels in the lower part of the bay of more than 5,000 µS cm^{-1} during the late stages of recession (*e.g.* see Figure 13), drainage salinity rarely rose above 2,000 µS cm^{-1}; this supports the idea that movement of salt into the surface water is a diffusional mixing with upper soil layers. High salinity surface water only occurred when the depth had become shallow and the water largely immobile. By this later stage, the water had a limited capacity to contribute actively to salt export in the drain.

Over the irrigation season, the total salt transported to the drain from this bay was 2,140 kg. The input salt, from the supply channel inlet, was 2,310 kg. This approximate salt balance shows that virtually no deep groundwater exfiltrated actively into the drain or onto the bay surface. The low hydraulic conductivity of the surface soil in the lower part of the bay, and the groundwater table remaining at 50 – 100 mm below the surface at both Site 2 and Site 3 (25 m and 50 m from the drain, Figure 2), supports this finding. It is further strengthened by the groundwater salinity in the near drain region, which had been measured at close to 20,000 µS cm^{-1}; clearly, it would require only a small exfiltration of groundwater to raise the drainage salinity. The observation that the drainage salinity never rose much above 2,000 µS cm^{-1} supports the conclusion that groundwater exfiltration from deeper levels did not occur to any great extent at this location during irrigation.

2.4.3 Salt transport – soil salinity

Variations of soil salinity within the bay show the areas which contribute to salt export, and can be used to estimate the effects of infiltration and capillary rise on salt movement. Figure 18 and Figure 19 show the values for the start and end of the season, respectively (September 24 1996, March 26 1997), indicating the distinction between the salinity of the upper and lower parts of the bay. The three upper locations (Sites 4, 5, 6) show a fairly constant salinity profile with depth of between 2,000 - 3,000 µS cm^{-1}. In contrast, the lower three sites (Sites 1, 2, 3) have much higher levels of soil salinity and a decreasing salinity gradient with depth. The measurements showed that the lower part of the bay was more saline than the upper, and that the highest amounts of salt were concentrated in the near surface soil where it could be entrained or diffused into the surface water during run off events.

Over the season, the upper part of the bay showed an increase in salinity level through the top 200 mm of the soil profile. This coincided with the main root zone of the pasture, likely to be due to evaporative concentration. In contrast, the lower part of the bay indicated a reduction in salt levels in the top 200 mm, possibly due to the low infiltration rate, the washoff of salt from the near surface with irrigation, and the bare and unvegetated nature of the area. Despite the very slight rise in salt level in the upper part of the bay, and the reduction in salt level in the lower part of the bay over the season, the two were still delineated clearly.

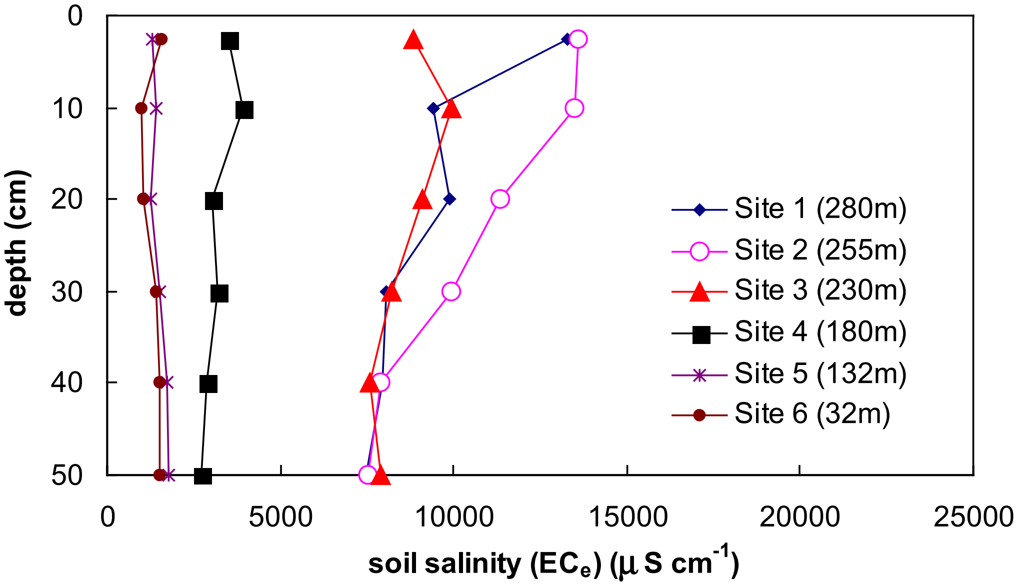

Figure 18. Soil salinity measurements at start of season (24/9/1996). The higher salinity of the lower part of the bay is clearly evident.

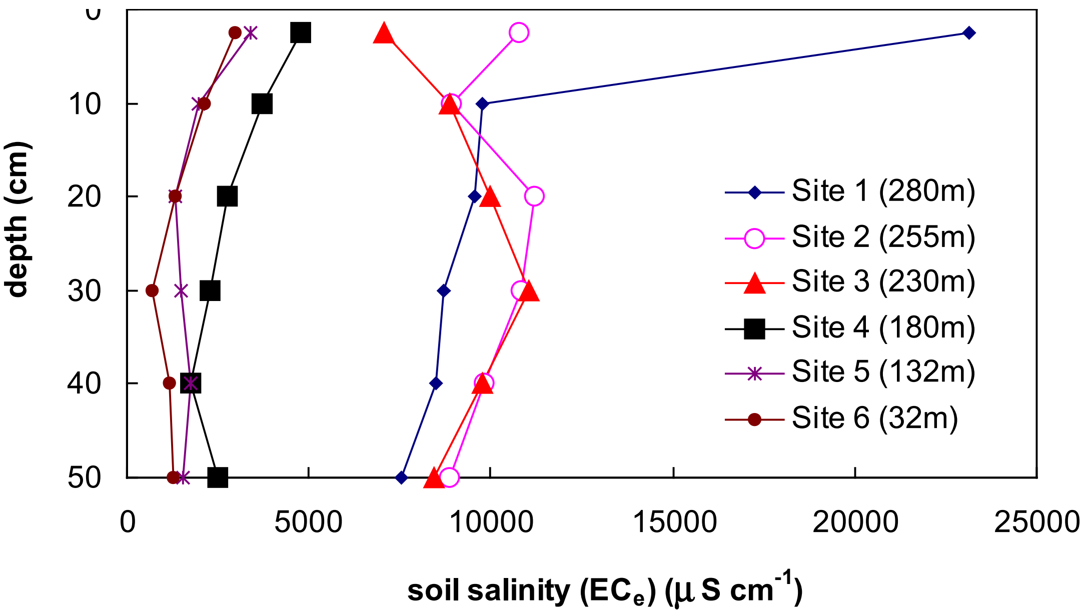

Figure 19. Soil salinity measurements near the end of season (approx. EC_e) (26/3/1997).

Changes of soil salinity in response to an irrigation event were observed in the salt load of the soil samples used in the $EC_{1:5}$ tests. To this end, a complete set of samples was taken both before and after the irrigation on January 26 1997. Figure 20 illustrates the pre and post irrigation soil salt load at each measurement location.

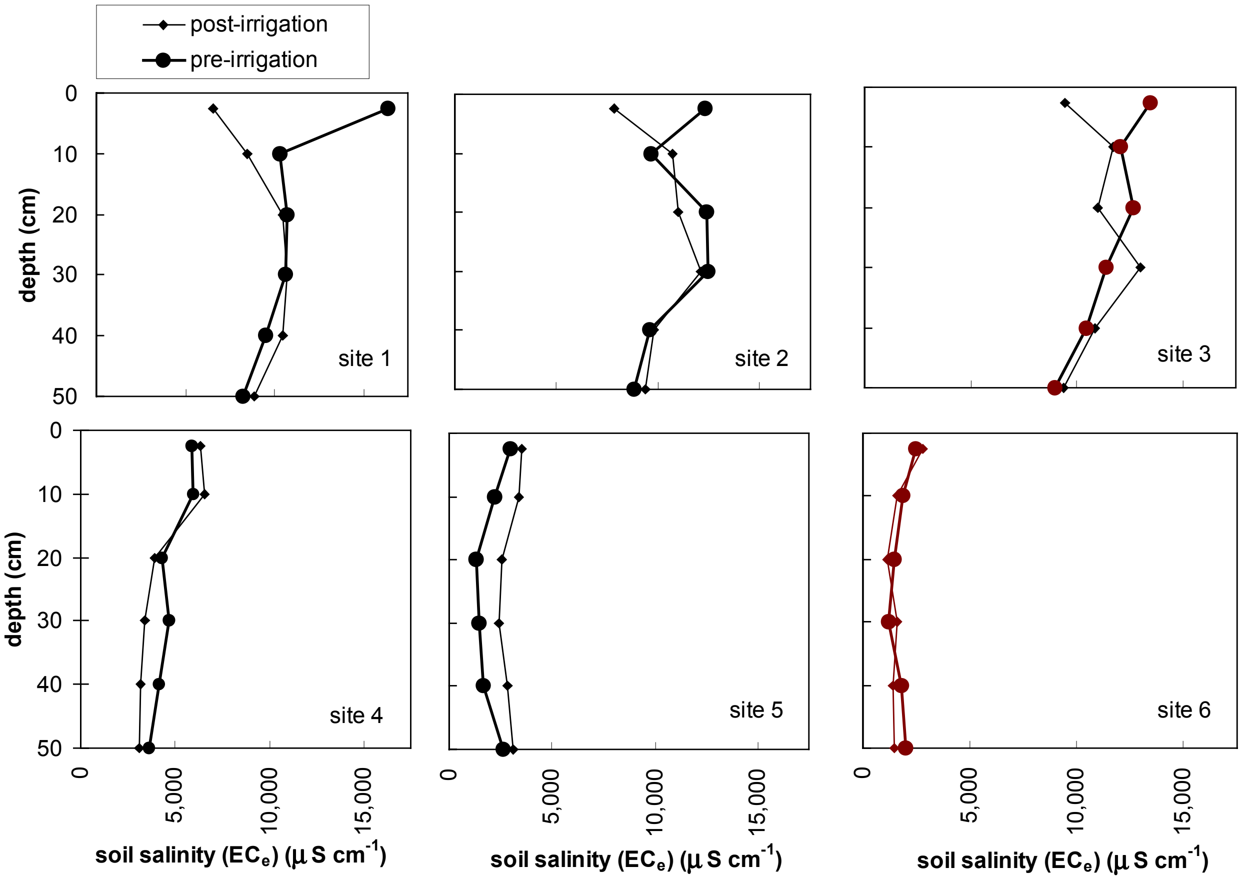

Figure 20. Soil salinity measured before and after irrigation at 6 sites in the bay.

In the upper part of the bay (Sites 4, 5, 6) there was very little change in the salt present in the soil profile. However in the lower part of the bay (Sites 1, 2, 3), salt levels decreased in the top 50 mm of the soil profile, while salt levels deeper in the profile remained unaffected by the irrigation. This was expected since the soil profile was already close to saturation in part of the bay close to the drain, and so there was negligible infiltration to leach the salt downward through the profile.

2.5 MAIN FINDINGS - SALT TRANSPORT

The following general findings on salt transport can be drawn from this monitoring study.

- *Salt transport during irrigation events is dominated by the lateral washoff of salts, mainly from the soil surface. As a result of this process, overland flow during irrigation advance exhibited a distinct and increasing rise in salinity, particularly as it passed over the lower part of the bay. This dynamic increase in surface water salinity was carried through into the tailwater drainage response. At the commencement of drain flow, the initially high salinity dropped quickly, showing clearly the 'first flush' of salt from the soil surface being removed from the bay.*
- *Infiltration of irrigation water was confined to the early stages of ponding, due to the near-saturation of the soil profile and the shallow groundwater table. Although soil salinity measurements showed a decrease in the top 50 mm of soil in the lower part of the bay, the deeper soil salinity remained relatively unaffected by irrigation. These soil salinity results reinforce the conclusion gained from the overland flow results, that the main process of salt removal from the bay was with lateral washoff from the upper soil profile by surface water and not through vertical leaching in the lower part of the bay.*
- *Active groundwater contribution to surface runoff during irrigation was negligible for this irrigation bay experiment. The low hydraulic conductivity of the surface soil over the lower part of the bay restricted groundwater movement and prevented any groundwater exfiltration. However, the shallow groundwater table reduced any deep drainage of water, preventing significant deep leaching of soil salts, and acted as a supply for capillary rise salt movement.*

This negligible vertical leaching, and the distinct lateral removal of salt from the bay, shows the overall importance of ensuring that sufficient irrigation water is applied to produce tailwater drainage. This is necessary to improve the likelihood of maintaining a sustainable level of surface soil salinity. When this result is combined with the conclusions stated in Section 1, the study suggests that a reduction in irrigation volumes will not only reduce the ability of each irrigation event to remove salts from the surface soil, but also fail to reduce groundwater table elevation.

It is clear that irrigation supply volume, irrigation salinity, and irrigation timing strongly influence the drainage salt load and drainage volume. Thus, while improved management of irrigation supply will aid the short term control of drainage salt load, the long term effects of reduced drainage salt loads will decrease lateral surface salt washoff, increase soil salinities, and reduce irrigation bay productivity. Generally, however, management of irrigation is a time consuming manual operation that must work within the constraints of general farming activities. Until automated forms of irrigation which allow greater control of irrigation supply are used, there is only limited scope for management advice with regard to improving irrigation to be effective in reducing irrigation drainage volumes and salt load.

SECTION 3. MANAGEMENT IMPLICATIONS FOR SALT TRANSPORT & EXPORT

3.1 INTRODUCTION

In the final section of this report, two management scenarios for the control of salt load from an irrigation bay are examined. The impacts of these two options are described from both a farm and regional perspective.

- to directly reduce irrigation supply volume to the bay,
- to use recycled drainage water ('re-use') to improve irrigation efficiency without reducing the actual irrigation volume.

These scenarios are investigated using the detailed water movement and salt transport data obtained from the study and described earlier in Sections 1 and 2 of this report.

3.2 IMPLICATIONS OF IRRIGATION BAY RUNOFF

Irrigation runoff into the shallow surface drain system forms a significant component of the regional drainage salt load. The impact of changes in irrigation bay runoff on regional drainage salt loads were examined and related to the effectiveness of irrigation management changes on reducing regional drainage salt loads. The following subsections examine salt export from the monitored bay over an entire season, on an irrigation event basis, and then within the bay itself.

3.2.1 Seasonal analysis of irrigation bay runoff

The annual surface drainage from the Barr Creek catchment has been estimated as contributing 100,000 - 400,000 tonnes of salt to the River Murray, *i.e.* far higher than the 12,000 to 20,000 tonnes of salt supplied annually in the irrigation water (Gutteridge, Haskins and Davey *et al.* 1985). The salt export ratio (salt in the catchment outflow divided by the salt in the input irrigation water) for the catchment varied from 800% - 1,400% over the years of that study (1977 - 1982), confirming that Barr Creek catchment continues to be a large exporter of salt through surface drainage.

At the subcatchment scale, components of drainage from the Drain 14 subcatchment of Barr Creek were analysed using data obtained from Goulburn-Murray Water, showing that 17,600 ML of irrigation water was supplied during the 1996/97 season (approximately 7 months). This supply water was assumed to have a salinity of 110 μS cm^{-1}, and hence contained approximately 1,160 tonnes of salt. For the same period, 2,300 ML of water with 4,800 tonnes of salt were exported from Drain 14. The *irrigation season* surface salt export ratio for the subcatchment was thus 400% (and for the *entire 12 month period*, 750%), matching the earlier estimates of Woodland & Hooke (1993). This lower-than-average export ratio of 750% was due to the below average rainfall of that year. In contrast, the 1995/96 rainfall (close to the long-term annual mean) gave a salt export ratio for Drain 14 subcatchment of 1,380%. Higher amounts of rainfall runoff removed more salt from the catchment through both increased runoff and increased regional groundwater elevations.

To estimate the effect of irrigation bay runoff on the regional drainage salt loads, results of an intensive monitoring experiment on a single bay were analysed. In contrast to the massive salt export values at both a regional and a subcatchment scale, our data showed that the monitored irrigation bay did not have a 'net salt export' for the 1996/97 season. For the 11 measured irrigation events, a total of 2,310 kg of salt was supplied with irrigation water to the bay, while surface drainage removed 2,140 kg of salt. Figure 21 shows the cumulative supply and drainage salt loads for the bay (1996/97 season), highlighting the approximate balance. This cumulative comparison showed a total surface salt export ratio of 93% (a very slight salt import). The net salt 'balance' at an irrigation bay scale was considerably less than that of both the Drain 14 subcatchment and Barr Creek catchments, suggesting that irrigation bay surface runoff was not the major cause of the high regional salt export ratios.

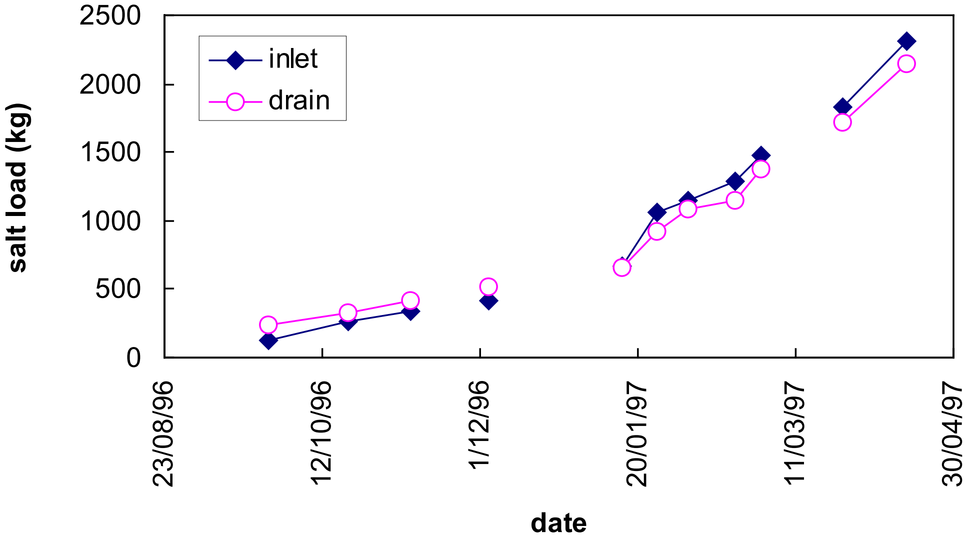

Figure 21. Cumulative irrigation supply salt & drainage salt, monitored bay, 1996/97.

Note: gaps indicate missed irrigation events

If it can be assumed that the saline conditions in the monitored bay are 'typical' of others in the area, the salt load in the irrigation water supplied to the subcatchment would be *in balance* with the irrigation runoff salt load. Under this assumption, irrigation bay runoff would have contributed only 1,160 tonnes to Drain 14, of the seasonal total of 4,790 tonnes (25%). Considering the below average rainfall over this irrigation period, it was suggested that most of the remaining 75% of the subcatchment salt load during the irrigation season could be from direct groundwater seepage into deeper regional drains (especially with typical groundwater salinities of 20,000 30,000 $\mu S\ cm^{-1}$). This value was consistent with other studies that have estimated direct groundwater contributions ranging between 61% - 84% of the total salt load (Woodland & Hooke 1993).

The depth of regional groundwater obviously impacted on these groundwater contributions to regional drains. While the groundwater level within a bay responded quickly to irrigation application, the precise link between local and regional groundwater was less clearly defined. Our observations showed that there was limited deep drainage of irrigation water; soil moisture deficit between events being explained by the total actual evapotranspiration. When this result was combined with the 'net salt balance' of the bay over the 1996/97 season, deep downward movement of *salt* as a result of irrigation practice was assumed to be limited. This supported the conclusion that drainage of high groundwater tables in the area is hampered by upward pressure from regional underlying aquifers, while a near-saturated surface soil profile is maintained by irrigation (Gutteridge, Haskins and Davey *et al.* 1985; Dwyer Leslie *et al.* 1984). Although irrigation over the last century is responsible for the shallow groundwater, marginal improvements in irrigation efficiency that fail to reduce groundwater accessions will have little effect on catchment salt export. Thus, while quantification groundwater salt movement into deep regional drains is beyond the scope of this study, we consider that this movement would be relatively unaffected by slight improvements in irrigation efficiency.

3.2.2 Event analysis of irrigation bay runoff

While the overall seasonal 'salt balance' at the monitored irrigation bay for the 1996/97 season showed that irrigation bay runoff was relatively unimportant in terms of regional salt export ratios, a closer analysis of the salt export ratio for each irrigation event presented a more variable picture. Figure 22 shows the irrigation supply and drainage salt loads for each irrigation event for the 1996/97 season, indicating a high degree of scatter in the data.

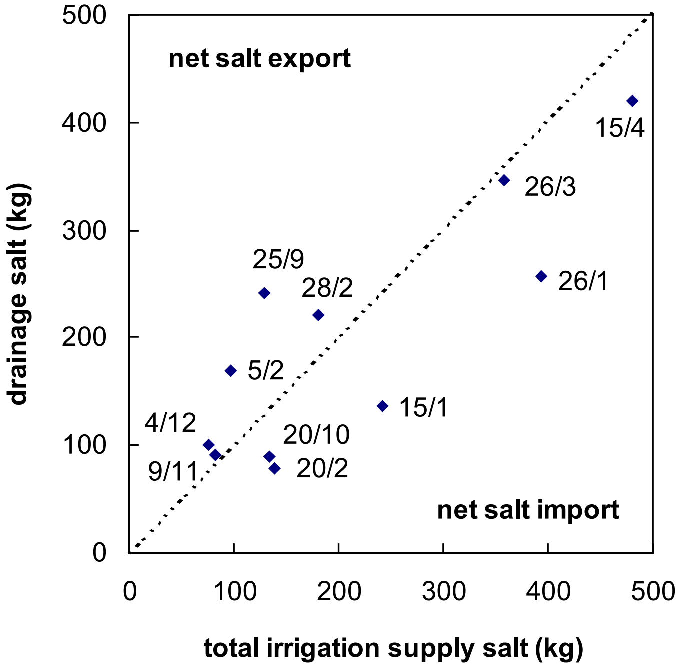

Figure 22. Measured surface salt export ratio for each irrigation event (day/month), 1996/97 season, showing the approximate salt balance.

The increased trend of salt export with increased salt import is expected, since irrigation supply runoff becomes drainage water; hence a direct reduction in supply salt load lowers the drainage salt load. Further complexity was revealed when Figure 22 was examined as a *salt export ratio* instead of *salt load*. This shows that the irrigation events which had a 'net salt export' were those with low irrigation supply salt loads and, although smaller events provided less drainage salt load, they often had a 'net salt export' (indicated by points above the salt balance line).

In summary, the seasonal salt balance of the monitored bay suggests that irrigation runoff is not directly responsible for the high regional salt export ratio.

3.2.3 Irrigation bay characteristics - the complexity of irrigation runoff

Seasonal and event irrigation runoff data showed that the relationship between salt movement in the irrigation bay and regional salt export was not a direct one. This section adds to the analysis by describing the influence of the bay's soil characteristics on infiltration, leaching and drying, and thus on salt transport processes.

Salt movement and storage was not uniform within the bay, the lower part of the bay being characterised by significantly higher soil salinity than the rest of the bay. This is shown clearly by the results of a soil salinity survey taken over a 10 m grid throughout the bay using an EM38 electromagnetic conductance sensor (Figure 23). The movement of salt in this lower area was dominated by the presence of cracks (Photograph 3). The low permeability of the soil matrix and negligible deep drainage, combined with these soil cracks, played an important role in the bay salt transport processes and allowed lateral removal of salt in the initial stages of irrigation (Gilfedder & Connell 1997; see also Rhoades *et al.* 1997).

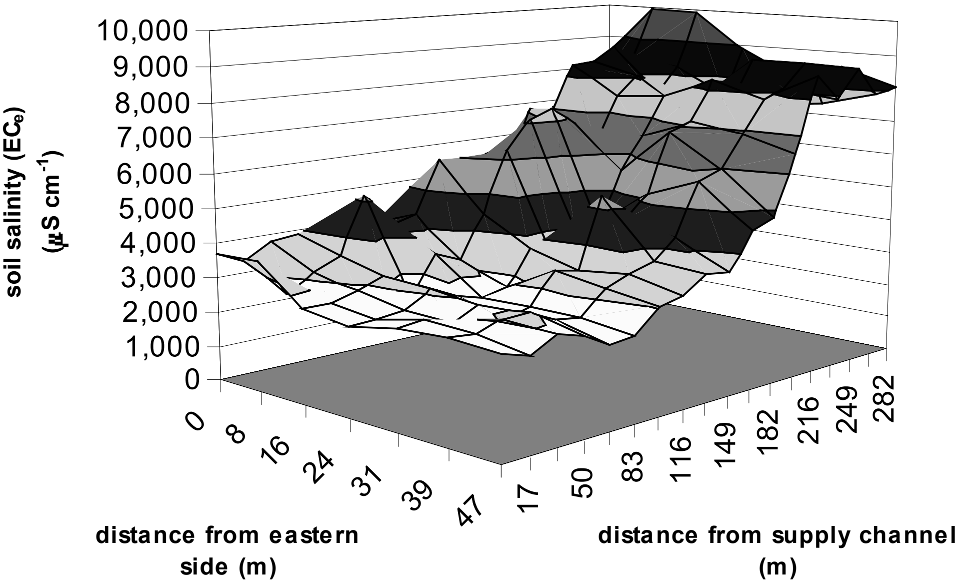

Figure 23 Soil salinity of the monitored bay (EM38 electromagnetic conductance sensor).

Photograph 3. Overland flow during an irrigation event at the monitored bay. Soil cracks, particularly in the lower - bare part of the bay can play an important role in salt transport processes.

The hydraulic conductivity of the soil matrix in the lower part of the monitored irrigation bay was low (measurements using ponded ring infiltrometer ranging from 2 - 25 mm day^{-1}), and the fast response of the shallow groundwater to surface ponding was attributed to crack infiltration. This was supported by the analysis of surface water balances, which showed that almost all of this infiltration was during the initial stages of each irrigation event. Infiltration occurred mainly through the crack network, before water infiltrated laterally into the surrounding soil matrix at a much slower rate. The 'bypassing' of the soil matrix had implications for the build-up of salt in the surface soil, affecting the vertical leaching of salts from the crop root zone. As a result, in the lower part of the bay, there was little change in soil salinity due to irrigation except in the upper 10 cm of the soil profile (see Figure 20).

The presence of cracks in the soil, particularly in the lower part of the monitored bay, has implications for any planned reduction in the amount of overland flow over the bay surface. The reliance on removing soil salt through lateral washoff processes, instead of by vertical leaching, means that smaller irrigation supply volumes that result in reduced overland flow will have difficulty in counteracting the build-up of soil salt in the bay.

3.3 IMPACTS OF IRRIGATION BAY MANAGEMENT

This section uses the measured results to evaluate the implications of possible changes in irrigation management on both the farm and on the regional totals. These changes involve two options: reduction of irrigation volume, and ‘re-use’ of irrigation runoff for irrigation supply. These options have been suggested previously as a means to reduce the impacts of irrigation on the regional salt export and will now be discussed in more detail.

3.3.1 Option 1: reduction in irrigation volume

Irrigation bay flood irrigation has a reputation as a particularly inefficient method of applying irrigation water. Reducing water application has been often cited as a practical means to increase the efficiency of irrigation, reducing both the salt supplied with irrigation and the salt removed as runoff. The analysis of this reduction in volume is assessed here in regard to both the *mobilisation* of soil salt within the bay and the subsequent *removal* of this salt in the drainage. These processes can affect both the bay productivity and salt accessions to regional drainage.

3.3.1.1 Impact of irrigation volume on bay salt mobilisation

An understanding of the mobilisation of bay salt into overland flow (and into irrigation runoff) is necessary to assess the impact of irrigation changes on the removal of salt from the bay. The *total* amount of salt mobilisation was examined, which included both the drainage salt and the surface water salt load mobilised from the irrigation bay during each irrigation event. Data were obtained from frequent manual measurements of surface water depth and salinity at various locations along the central transect of the bay, and used to calculate the changes in volume and salt load of surface water throughout the period of each irrigation event. The availability of mobilised salt was calculated independently of drainage volume, and represented an *increase* in salt load above that of supply water salinity. Analysis showed the timing and quantity of the entrainment of salt into the overland flow, and indicated the effectiveness of each event at mobilising salt. Figure 24 shows mobilised salt loads for seven of the irrigation events during the 1996/97 season.

The results in Figure 24 show that the greatest rate of mobilisation of bay salt into the surface water occurred during the early stages of the irrigation event, with a reduction in the rate as each event progressed. The main transfer to the overland flow was through lateral washoff from the soil surface, followed by a slower mixing with the upper part of the soil profile. Significant seepage of salt with direct groundwater movement to the surface was prevented by the low conductivity of the surface soils in the lower part of the bay. The presence of the crack dominated flow regime accounted for this high early mobilisation of salt into the overland flow.

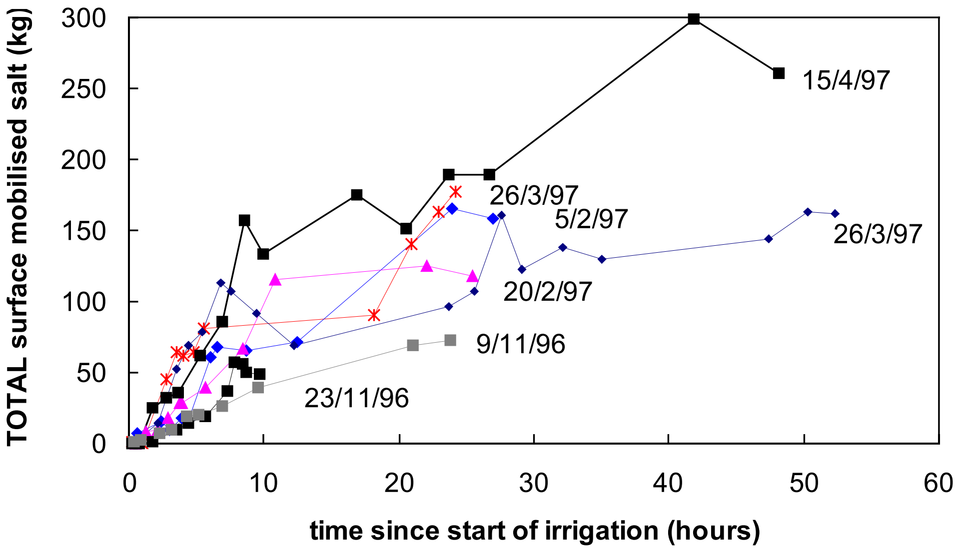

Figure 24. Total mobilised salt load into surface water (bay surface and drainage) for 7 events.

Note: Drain flow began 5 - 10 hours after irrigation commenced.

Increased amounts of salt were mobilised during the events later in the season, corresponding to a gradual increase in salt quantity over the 1996/97 season. This increase occurred despite a gradual decline measured in near-surface soil salinity in the lower part of the bay over this period. Changes in mobilised salt levels were not consistently explained by irrigation supply salinity; however, the last remnants of irrigation recession during each event left highly saline puddles which evaporated leaving accessible salt on the soil surface. The shallow bay surface gradient did not allow for complete drainage of overland flow and so these puddles remained on the bay surface in the late stage of recession, leaving significant amounts of surface salt. Hence, subsequent irrigations were able to redissolve this salt, which then contributed to a 'first flush' of salt into the overland flow.
Thus, reduced irrigation volumes were still able to effectively mobilise salt from the surface soil into overland flow. Because the soil-water profile in the bay was close to saturation during the irrigation season, more efficient irrigation reduced irrigation runoff rather than causing a reduction in the infiltrated volume.

3.3.1.2 Impact of irrigation volume on the removal of mobilised salt

The impact of drainage volume on the *removal* of salt from the bay was assessed by examining the mobilised component of drainage salt load. This was estimated for each event by separating drainage into its *irrigation supply* salt load, and *mobilised* salt load components. Drainage volume was then compared to the mobilised component of drainage salt load. The values obtained using these measurements showed that *lower* drain volumes (as a result of reduced irrigation supply) led to a *decreased* removal of mobilised salt from the bay (Figure 25). This relationship revealed that events with larger drainage volumes removed greater amounts of *mobilised* salt from the bay soil. Note however, the event on the 15/4/97, which had a much greater amount of mobilised salt than the other events of the season. A reason which may explain the excessive removal of mobilised salt during this event was that the previous irrigation event had been 20 days prior to the 15/4/97 (the average interval was 12 days), allowing a longer period for surface salt build-up to occur. Another reason may have been the unintentionally excessive salinity of irrigation supply for the previous event (900 µS cm^{-1}), which would have left more salt on the soil surface. Without disputing the accuracy of the result for the 15/4/97 event, it was excluded from the regression analysis in Figure 25. The results of Figure 25 suggest that large reduction in irrigation supply volume is likely to have a negative impact on the salinity of the irrigation bay. While such a strategy would (initially) reduce the amount of salt removed from the bay, it appears then that some *excess* irrigation volume is necessary both to *mobilise* and to *remove* salt from the bay (through lateral washoff). Consistent reduction in irrigation supply volume would eventually lead to increased salt build-up in the shallow soil profile (until a higher salt "equilibrium" was reached).

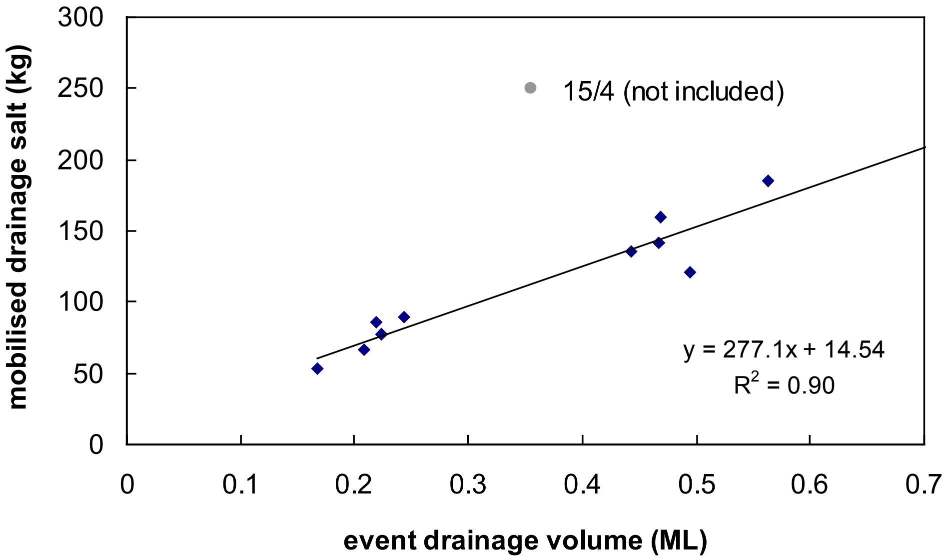

Figure 25. Influence of drainage volume on the removal of mobilised salt from the bay, for each event of 1996/97 season (direct drain salt balance).

3.3.2 Option 2: re-use of irrigation runoff

The second management option considered, involves the recycling (or 're-use') of irrigation runoff back into the irrigation supply channels of the farm. This practice has been proposed by regional catchment management authorities as a method to reduce irrigation runoff accessions to regional drainage, and thus decrease the impacts of irrigation practice at a regional level (Gutteridge, Haskins and Davey *et al.* 1985). Reduced runoff from irrigation would also increase the salinity of regional drainage water, and allow for improved salt removal efficiency from the downstream Lake Tutchewop diversion scheme. The effects of drainage 're-use' on both the irrigation bay and in reducing regional drainage accessions will now be investigated.

The combined effect of irrigation and rainfall runoff over the Barr Creek catchment has been estimated previously as making up 68% of total drainage volume, but only 15% of the total drainage salt load. Thus, the re-use of drainage water reduces accessions from irrigation runoff, and reduces the dilution of regional drainage (Gutteridge, Haskins and Davey *et al.* 1985). The irrigation bay studied showed that 're-use' can also counteract the inefficiency of large irrigation supply volumes. Large irrigation supply volumes can be maintained with the assistance of drainage re-use; these events will have the capacity to remove greater amounts of mobilised salt from the soil in the lower part of the bay, without causing large accessions to regional drainage.

At the monitored bay, salinity of the normal supply water (100 µS cm^{-1}) commonly increased to around 200 – 400 µS cm^{-1} due to the effect of the 're-use' of drainage water. The varying supply salinities for each event resulted in a range of drainage water salinities (upwards of 800 µS cm^{-1}) (Figure 26). This relationship showed that the elevation in average salinity above that of irrigation supply was consistent (between 400 – 600 µS cm^{-1} higher than that of irrigation supply) throughout the season (with the exception of the 15/4/97 event which rose 1,200 µS cm^{-1}; Figure 26). This indicated that the differences in drainage *salt loads* were caused by *volume* change and not *salinity* change; larger volume events removed greater amounts of salt from the bay, irrespective of the initial salinity of the irrigation supply water. The implications for this relationship are that slight elevation of irrigation supply salinity due to drainage 're-use' would have little effect on the mobilisation and removal of salt from the bay soil.

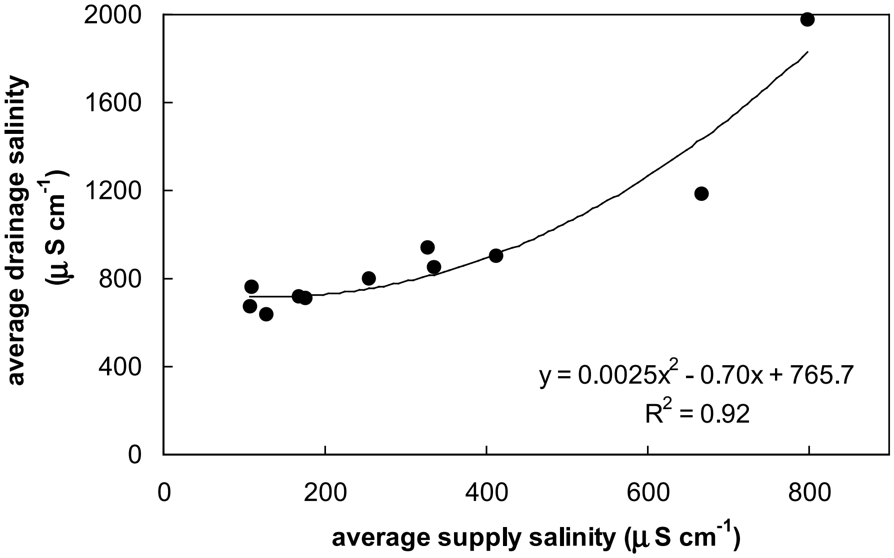

Figure 26. Effect of irrigation supply salinity on drainage salinity for each event, 1996/97 season.

Another benefit of drainage 're-use' is the potential to indirectly increase irrigation efficiency. This would allow the continued generation of large irrigation runoff from irrigation events, since it could be re-used for subsequent irrigation events. This ability to maintain high volumes of irrigation water was critical, given the need for lateral washoff to prevent salt build-up in the surface soil profile. 'Re-use' can absorb the irrigation inefficiency that is necessary to *remove* mobilised salt from the bay's surface during irrigation. However, irrigation runoff has been estimated as only 25% of the total regional drainage salt load, the regional effects of this change are likely to be minor (as discussed in Section 3.2.1). Drainage 're-use' was a suitable method for a reduction in the *volume* of irrigation runoff. However, since the monitored irrigation bay was in a 'salt balance' over the season, drainage re-use will not result in significant changes in the *salt load* of the eventual irrigation runoff accessions.

3.4 MAIN FINDINGS – MANAGEMENT IMPLICATIONS

Management implications of changes in irrigation practice, discussed in this section of the report have used measured data from an irrigation bay monitoring study to examine the complexity of the effects of irrigation management on both the irrigation bay and the wider region. The monitored bay had a net surface salt balance over the irrigation season, suggesting that groundwater seepage into deep drains, rather than irrigation runoff, was responsible for the large regional salt export ratio. The impacts of irrigation on the *mobilisation* and *removal* of soil salt were also discussed. This has enabled the following conclusions to be drawn:

- *The 'mobilisation' of soil salt during irrigation occurred mainly during the initial stages of each event. The rate of take-up of salt into the overland flow was high initially, but decreased over the period of the irrigation. Although large volume irrigation events removed greater amounts of salt from the lower part of the bay, ponding during the late stages of recession resulted in high concentrations of salt being retained on the soil surface for all events.*
- *If irrigation volumes were reduced significantly to improve irrigation efficiency, the lateral removal of washoff salt would be compromised. The low permeability of the soil matrix, combined with the shallow groundwater table and the presence of soil cracks, would remove the opportunity for vertical leaching of soil salt through the profile. Hence, overland flow 'mobilised' salt from the soil surface, and transported it in the surface water. This lateral washoff of soil salt was a large and significant process in the 'leaching' of bay soil. Significant reduction in irrigation volumes would continue to mobilise soil salt, but would be less effective in removing this salt from the bay in drainage and lead to a build-up of surface salt in the lower part of the bay. This would have adverse effects on crop productivity in this area.*
- *Re-use appeared to be a highly desirable option for bay and regional management, and could be used to maintain high volumes of irrigation supply water, allowing for the same removal of mobilised bay salt. The large irrigation volumes have the capacity to prevent excessive build-up of surface salt in the lower part of the bay. The re-use of irrigation runoff would also concentrate the flows to the downstream regional drain network, allowing more efficient use of large disposal schemes.*

CONCLUSIONS

This study used a variety of monitoring techniques to investigate the movement of water and salt movement within an irrigation bay. The results allow several conclusions to be drawn in regard to irrigation bay behaviour, and its effect both on local and regional hydrology and salt transport.

The main findings, drawn from the results of this study, are as follows:

- *The monitored irrigation bay was in an approximate net surface salt balance for the 11 measured irrigation events during the 1996/97 season.*
- *The bay 'salt balance' was far below the Drain 14 subcatchment salt export ratio of 400% for the same period, which suggests that improved control of irrigation supply will not decrease the regional salt export ratio, unless it is able to lower the regional groundwater table.*
- *Salt transport during irrigation events is dominated by the lateral washoff of salts, mainly from the soil surface.*
- *Significant reduction in irrigation volumes would continue to mobilise soil salt, but would be less effective in removing this salt from the bay in drainage, leading to a build-up of surface salt in the lower part of the bay. This would have adverse effects on crop productivity in this area.*
- *Re-use of on-farm irrigation runoff appears to have significant benefits. Re-use allows irrigators to apply sufficient volumes of water to reduce salt build up in the bay soil, while minimising their contribution to regional drainage.*

FUTURE WORK

The results highlight the significant influence that factors other than irrigation bays, such as deep regional drains can have on catchment salt export. Future research could focus on investigating the role of these regional drains. This could include a study of the interaction between regional drains and shallow groundwater, and a study of the variation in salt load contributions to deep drains throughout the Barr Creek catchment.

The scope of the work presented in this report could also be expanded by the measurement and modelling of irrigation bays in other areas, with different soil types. Such validation studies would help in the wider application of research findings.

This work was part of the CRC's Project A1, which focussed on the processes of salt and water movement at an irrigation bay scale, and is now complete. The CRC's current Project S1 is focussed on scaling this work up from a bay scale to a catchment scale using tools such as Geographical Information Systems (GIS).

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