Soil-Water and Salt Movement Associated with Precision Irrigation Systems

Research Investment Opportunities

CRCIF Technical Report 3.13/1

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Executive Summary

Background

The Board of the National Program for Sustainable Irrigation commissioned this scoping document to assist in its research investment deliberations. The key question addressed by this scoping study is: *What has to be developed or modified to understand and monitor the three dimensional flow of water and salt movement in:*

(a) the root zone when precision irrigation systems are used, and
(b) the soil profile, assuming that we are able to manage the preferred salt storage zones?

The key issues which the NPSI Board requested should be addressed in the document were:

- What are precision irrigation systems and what are the problems currently being encountered in relation to water and salt movement in these systems?
- What is the potential size of production and water losses associated with inappropriate water and salt management under precision systems?
- What is the latest research and what current soil-water models are being used to investigate water and salt movement in soils, including their usefulness and gaps?
- How well we can manage where salt is stored under precision irrigation systems? and
- What is the effect of rainfall under various climatic zones in determining where salt is stored?

Discussion

Precision irrigation is defined as: *the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact.* Hence, an important characteristic of a precision irrigation system is that the timing, placement and volume of water applied should match plant water demand resulting in reduced non-transpiration volumetric losses (eg. deep drainage and evaporation) and optimized crop production (ie yield quantity and quality) responses.

The concept of precision irrigation can be applied to all forms of irrigation application but is exemplified by a well managed and maintained drip irrigation system where the water is placed either on the surface or in the root zone (subsurface). Low energy precision applicators (LEPA) fitted to centre pivot and lateral move machines area are also increasingly being used in broadacre cropping situations where placement (relative to the crop) and application volumes may be spatially varied. In both of these systems, water and associated salt movement will vary spatially within the root zone. Hence, under these conditions, excess water application does not necessarily directly result in deep drainage and leaching of salt below the root zone. It should also be noted that the non-uniform distribution of water and salt in wetted zones has not been well documented under field conditions but has significant implications for sampling regimes under commercial conditions. Much more research is required to understand solute transport in drip systems especially over an irrigation cycle and the interaction with rainfall events. The implementation of precision irrigation practices also raises the following issues in relation to soil-water and salt management:

- adoption of precision irrigation technologies and practices can result in root zone salinisation problems which are different to those caused primarily by rising ground water systems;

- leaching calculated using one dimensional equations do not adequately describe leaching under some field conditions;
- given these shortcomings there is potential for regulatory requirements and management guidelines to be inappropriate for sustainable and/or improved irrigation practice and salinity management; and
- there is a need for better measurement methodologies that can be used in the field to characterize soil properties and assess salt management practices.

Analysis of impacts associated with spatially variable salt additions resulting from precision application systems demonstrate that impacts could affect about 10% of the current irrigated area, an area that could reasonably be expected to increase in proportion. However, the value of the production from these areas could be as high as 40% of total annual revenue. Expected grape production losses associated with inadequate salt leaching within the root zone due to the introduction of precision irrigation techniques were found to be in the order of 3 t/ha for each 1 dS/m increase in the electrical conductivity of the irrigation water used. Losses in pasture and maize production are likely to be in the order of 1.9 t/ha and 0.8 t/ha, respectively. The potential cost of increases in root zone salinisation in the Murray and Murrumbidgee irrigation areas alone was estimated to collectively be worth up to $245 m (in 2000/01 dollars) or 13.5% of the revenue from these cropping systems. While this estimate is a worst case scenario, a clear finding of the analysis is that the more salt sensitive crops should have a higher priority in assessing the likely impact of spatially variable salt dynamics.

Soil-water modelling tools at our disposal for precision irrigation applications include a range of 1-D and 2-D models. True 3-D models are available for the unsaturated zone but are not often required as most situations can be described adequately using a 2-D or radial 2-D model. The analytical or quasi-analytical models are usually written in terms of non-dimensional variables which allow rapid exploration of the parameter space. These models are usually only suitable for specific boundary conditions but provide good insight into axi-symmetric and 2D flow problems. They also provide very good insight into the physical processes involved in irrigation and the non-dimensional variables allow the formulation of the parameter space for the numerical simulations so that redundant simulations are not created.

HYDRUS-2D is increasingly becoming the ‘standard’ tool for modelling variable saturated flow in porous media. It is robust and is the perfect tool for modelling water flow and solute transport under precision irrigation. However, the user requires a high level of modelling expertise in addition to being familiar with the underlying theory that spans across areas ranging from variably saturated water flow to solute transport and root water uptake processes. The current lack of skilled professionals able to parameterise, operate and interpret results from this model is a major barrier to undertaking research in this area and highlights the need for a strategic investment in skills and capacity building.

Modelling of precision irrigation systems should involve several approaches conducted concurrently. There is a mismatch between the data required by complex, process-based simulation models, and the data that is easily available from soil survey and routine soil analysis. Thus, we usually have general soils data available at the broader scale, while input data for modelling are usually measured or derived from detailed site-specific experiments or monitoring. Since the actual modelling exercise can be conducted only by experienced scientists the problem of extending the information obtained to broader scales and to growers and advisors remains a challenge. The major knowledge gaps are the:

- effect of roots, evaporation and transpiration on wetting patterns;
- the accuracy and adequacy of using simple mean values of varying soil salinity levels in the root zone to estimate the effect of salt on the plant;
- fate of solutes during an irrigation cycle and in multiple irrigation cycles; and
- effect of soil heterogeneity on distribution of water and solutes in relation to placement of drippers.

Root zone salt will accumulate in areas where the water flux is less than the evapo-transpirational flux (e.g. edges of wetted zones and middle of beds in furrow systems). Rainfall events will redistribute and/or flush the salt from these storage areas. The one-dimensional analysis conducted in this report (Section 3) confirmed that the build up of salt levels would be greatest in situations of low rainfall and where large irrigations of saline water are applied over shallow water tables. The rate of salt build up in the root zone would be expected to be much slower as rainfall increases.

Recommendations for Research Investment

The aspirational goal for research in this area is: *to ensure that the Australian irrigation community has the tools and capacity to effectively harness the benefits of new precision irrigation technologies and practices to improve productive performance and sustainably manage the catchment wide salt balance without compromising root zone soil health.* Research opportunities have been identified (Section 6.1) across a broad range of areas including (a) requirements for soil characterisation, (b) irrigation management effects, (c) agronomic responses to variable water and salt distributions in the root zone, (d) potential to scale or evaluate impacts at various scales, (e) requirements for simplified modelling tools and (f) the need for skills and capacity building. The priority research investment recommendations (Section 6.2) and indicative project outlines are summarised below. However, it should be noted that these recommendations are solely focused on the research question posed by NPSI (soil-water and solute movement in the root zone and soil profile) and do not deal with precision irrigation adoption issues within a broader catchment or societal context. More detail on each priority area is provided in section 6.2.

1. Development of simple and robust techniques for soil characterisation

Key component	Review and packaging of existing practical methods for characterisation of soil properties influencing soil-water and solute movement at small scales.
Indicative costing:	$75-100k
Suggested timeframe:	12-18 months

2. Building skills and capacity in soil-water and solute management

Key components	(a) Development of an appropriate training package; (b) Development/refinement of application tools/interfaces for soil-water and solute movement that could be used by advisers and farmers; (c) Delivery of training package, engagement with relevant

	technocrats and promotion of soil-water and solute tools to ensure a lasting legacy.
Indicative costing:	(a) \$75-100k (b) \$100-125k (c) \$125-150k
Suggested timeframe:	(a) 6-12 months (b) 6-12 months (could be concurrent with (a)) (c) 12 months

3. Management of soil-water and solutes in precision irrigation systems

Key components	(a) Characterising solute movement and salt storage under precision irrigation (desktop study). (b) Development of irrigation management guidelines (e.g. BMPs) based on agronomic responses. (c) Validation of agronomic responses, sensitivities and management guidelines.
Indicative costing:	(a) \$100-125k (b) \$150-175k (c) \$75-100k
Suggested timeframe:	(a) 6-12 months (b) 12-18 months (c) 6 months

Expansion on Key Points

1. Irrigation as a Precise Activity

The concept of irrigation as an activity requiring some precision in implementation has been around since the introduction of irrigation scheduling and the first improvements in application system efficiencies. However, the specific term "precision irrigation" has only recently been introduced and has not been well defined. It has been variously used to describe efficient application systems (eg. Smith and Raine, 2000) or variable rate irrigation applications controlled by a sensory input (eg. Evans and Harting, 1999). However, neither of these uses adequately conveys that precision is required in both the accurate assessment of the crop water requirements and the precise application of the required volume at the required time. Similarly, the ability to spatially vary the water application within a management unit is not necessarily a requirement for precise irrigation as uniformity of application within a management unit may be preferred. Hence, in this document, precision irrigation is defined as: *the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact.* An important characteristic of a precision irrigation system is that the timing, placement and volume of water applied should match plant water demand resulting in reduced non-transpiration volumetric losses (eg. deep drainage and evaporation) and optimized crop production (ie yield quantity and quality) responses (Figure 1.1).

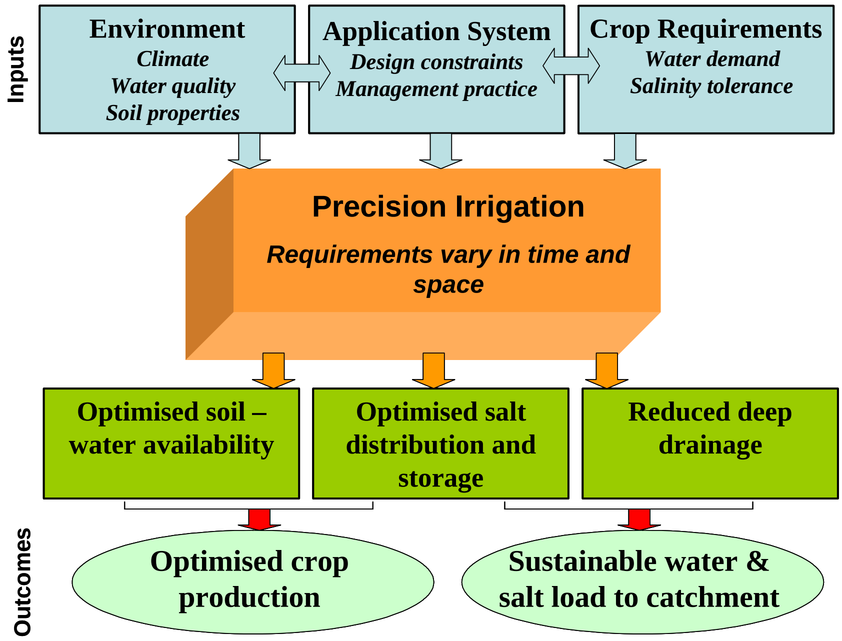

Figure 1.1 Inputs and outcomes associated with a precision irrigation system

The ability of the irrigation system to apply water efficiently and uniformly to the irrigated area is a major factor influencing the agronomic and economic viability of the production system. To achieve this, accuracy is required in irrigation scheduling, and in particular the estimation of how much water to apply, and precision is required in:

- the design of the irrigation system so that each plant or area of the field receives the appropriate amount of water (ie. spatially uniform applications within the management unit if this is the desired objective); and

- the management of the irrigation system that only the amount required is applied.

However, the flexibility in timing of irrigation applications and the volume of application may also affect the ability to utilise in-season rainfall, minimize crop waterlogging and improve management of the root zone salinity. Hence, optimal irrigation requires not only a knowledge of the characteristics of the application system but an understanding of the environment in which it operates.

The evaluation of commercial irrigation application systems of all types (sprinkler, surface and micro-irrigation) suggests that many systems operate with low application uniformities and less than ideal volumetric efficiencies (e.g. Raine and Bakker, 1996; Shannon *et al*., 1996; Dalton *et al*., 2001). Recent data on the performance of Australian irrigation practices suggests that the level of precision currently being achieved in many areas is less than desirable. In-field application efficiencies are commonly less than 70% with the uniformity of application varying by more than ±40% of the target volume. The obvious consequence of this lack of precision is both economic and environmental, manifest through low water use efficiencies and profits, and/or the impact on groundwater and riverine flows. The economic and environmental benefits of improving the volumetric efficiency of irrigation are obvious in both the value of the water saved and the additional production possible with this water. Hence, there is a triple bonus from improving irrigation precision including:

- maximizing yield and quality of production;
- reducing water losses below the root zone; and
- conserving the resource base, by minimising the risk of groundwater salinity and thus enhancing sustainability.

These gains can only be achieved where all elements of precision are operating synergistically within a given environment (Painter and Carren, 1978). Precise volumetric application applied at the wrong time will not achieve all three of the above outcomes nor will complete spatial and temporal precision which does not take into account the impact of rainfall or specific root zone and/or regional ground and surface water environmental conditions.

1.1 Potential for precision irrigation systems

The concept of precision irrigation can be applied to all forms of irrigation application but is exemplified by a well managed and maintained drip irrigation system where the water is placed either on (surface) or in (subsurface) the root zone. Micro-irrigation systems are typically designed to wet only the zone occupied by plant roots and to maintain this zone at or near an optimum moisture level (James, 1988). Obvious advantages of micro-irrigation include a smaller wetted surface area, minimal evaporation from the soil surface, reduced weed growth, and potentially improved water application uniformity within the crop root zone by better control over the location and volume of application (Hoffman and Martin, 1993). The obvious volumetric efficiency and agronomic benefits associated with drip systems has resulted in their widespread usage for high value crops (eg. grapes, horticulture) particularly in areas were water resources are limited.

While micro-irrigation systems provide the ability for point source application of water, high frequency irrigation events and improved flexibility in managing soil-moisture deficits, the concepts of:

- changing the system design to improve the placement or uniformity of water application, or

- increasing monitoring and control inputs

to improve the timing and/or volume of the application system can be applied to other forms of in-field application system. For example, Raine and Foley (2002) used the term "precision surface irrigation" to describe a furrow system with optimised management practices and/or re-designed fields. One of the major reasons for traditionally low surface irrigation efficiencies is the correspondingly low uniformity of application. However, these uniformities and efficiencies can often be increased by the selection of more appropriate water application methods to reduce potential deep drainage losses. Optimised management of commercial surface irrigation through these simple low cost changes (ie. SIRMOD revised flow rates and times to cut-off) have been found to improve application efficiencies for single irrigations by as much as 30% and to improve seasonal application efficiencies by up to 15% (Dalton *et al.*, 2001; Purcell, *pers. comm.)*.

Low energy precision application (LEPA) attachments (Lyle and Bordovsky, 1981; 1983) are now also in common usage on linear move and centre pivot machines (Figure 1.2). LEPA systems apply water at low pressure either directly onto the soil surface or below the crop canopy to eliminate sprinkler evaporation from the plant canopy and drastically reduce the wetted soil surface and soil surface evaporation. These LEPA applicators only partially wet the soil surface and provide the ability to wet either one or both sides of the crop row. The timing and volume of water application can be regulated by a combination of machine speed and nozzle selection. Spatially varied application within fields is possible using the sensor inputs and existing control units on the machines.

(a) Drag sock (b) Quadspray in bubbler mode

Figure 1.2 Emitter options for low energy precision application on large mobile irrigation machines (From Foley and Raine, 2001)

1.2 Temporal and spatial variability in precision systems

Precision irrigation systems may include either the ability to vary the system spatially or temporally. In particular, there is a need to identify the spatial scales inherent in the irrigation application system used (Table 1.1) and the spatial scale associated with the variability in the crop water requirements. The feasibility further requires an ability to sense in real time the water requirements of the crop at the appropriate scale and hence to be able to apply varying depths of water over a field. The ability to achieve this variable application will depend on the nature of the irrigation system but can be achieved in two ways viz: by varying the application rate or by varying the application time.

Table 1.1. Spatial scales of common irrigation systems
(modified from Smith and Raine, 2000)

System	Spatial Unit	Order of magnitude of spatial scale (m^2)
Surface – furrow	furrow	1000
Surface - border	border	10000
Sprinkler – solid set	wetted area of single sprinkler	100
Centre pivot, lateral move	wetted area of single sprinkler	50
LEPA - bubbler	furrow dyke	1
Travelling irrigator	wetted area of sprinkler	5000
Drip	wetted area of an emitter	0.1 to 1
Micro-spray	wetted area of single spray	50

Irrigation scheduling is commonly employed to counter temporal variations associated with crop water demands. Volumetric inefficiencies in irrigation result largely from irrigating too often or applying too much water at each irrigation. The first step in improving these efficiencies is the accurate assessment of how much water to apply and when to apply it, that is, scheduling the irrigations. Irrigation scheduling has traditionally been seen only in terms of determining when to irrigate. The assumption has been that the crop is fully irrigated and that irrigation is due when the soil moisture falls to some predetermined deficit. However, there is an increasing use of various non-traditional irrigation scheduling strategies including: deficit irrigation, partial root zone drying, and supplemental or strategic irrigation. In each of these cases, the question is not just when to irrigate, but how much to apply. This could be referred to as "temporally varied irrigation" where the objective is to match the time and volume of application to a specific crop and environmental requirement which would be expected to vary over the growing season. However, irrespective of the strategy employed, the benefits of scheduling will only be realised if the irrigation system can be controlled sufficiently well to apply only the exact amount required. Hence, control is a necessary component of any irrigation system aiming to apply water in precise amounts (Hoffman and Martin, 1993).

Spatially varied irrigation is the term used to describe those systems that are able to deliver different amounts of water to different areas of the field. While spatially varied irrigation is not commonly practiced at sub-field scale, irrigation is commonly varied spatially between fields based on differences in crop water use (ie. affected by crop type, planting date, management practice) and environmental factors (eg. rainfall variability, topography, aspect, soil-water holding capacity). The notion of spatially varied irrigation within the field is predicated on the hypothesis that the crop water requirements are non-uniform and probably result from differences in root zone conditions. It is also assumed that yield at the field scale will be maximised if each plant is supplied with water exactly matching its individual requirements. However, evidence to support these hypotheses is not readily found in the literature.

2. Soil-Water and Salt Movement Issues Arising from the Implementation of Precision Irrigation Systems

2.1 Effect of water placement on water and salt distribution

In traditional surface (e.g. bay, border check) irrigation systems, the whole surface of the soil is flooded and water flow through the soil is principally one dimensional. In these systems, water applied in excess of the soil-water holding capacity drains out of the bottom of the root zone and assists in the leaching of salts out of the root zone. However, two (e.g. furrow and overlapping drip emitters) dimensional water flow occurs within the soil where only part of the soil surface is wetted (e.g. furrow, LEPA, micro-irrigation applied to the surface). Similarly, three dimensional water and salt movement occurs where the water is placed at some point below the surface (e.g. sub-surface drip irrigation) within the root zone. Hence, under these conditions excess water application does not necessarily translate into deep drainage and leaching of salt below the root zone (Figure 2.1). For example, some of the water moving from a buried drip irrigation emitter will move laterally or up towards the soil surface. When irrigation water arriving at the soil surface is evaporated, the residual salt accumulates on the surface providing a salt store which may be mobilized back into the root zone by subsequent rainfall events (Figure 2.2).

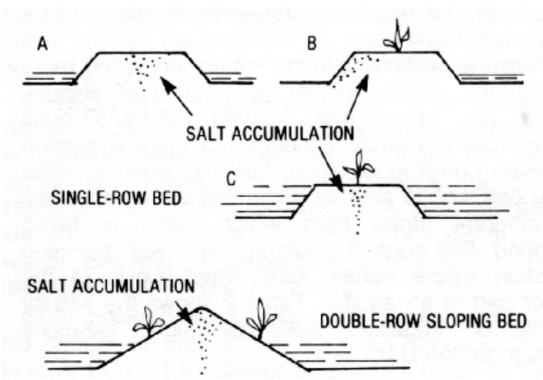

Figure 2.1. Salt accumulation under furrow irrigation depending on bed formation and water placement

Figure 2.2. Salt rings formed on soil surface around drip irrigation of grapes due to evaporation of irrigation water (Courtesy G Schrale)

Drip Irrigation

Skaggs *et al*. (2004) noted that there have been very few, if any, studies showing that numerical simulations of drip irrigation agree with field data, thus bringing into question the value of conclusions drawn from numerical simulations. They then went on to measure wetted patterns from drip irrigation in a sandy clay loam that had been thoroughly homogenized and found a high correlation with soil-water movement simulations conducted using Hydrus 2-D. There are other studies of water flow from axi-symmetric sources where models have been also able to well describe the wetting patterns (Revol *et al*., 1997a & b; Bresler *et al*., 1971; Hachum *et al*., 1976; Cook *et al*., 1986). However, Fuentes *et al.* (2003) measured soil moisture distributions under drip irrigation of grapes under commercial conditions using multiple capacitance probes. The resultant plots (eg. Figures 2.3 and 2.4) showed that the soil-water did not move asymmetrically from the wetted point. In this particular case, Fuentes *et al*. (2003) hypothesized that there were soil structural differences between the along row and inter-row locations associated with compaction induced by field traffic. This resulted in less lateral movement of the wetted pattern between the rows than was found along the rows. One implication is that unless this soil heterogeneity is characterized it would be difficult to adequately account for the water and salt movement. While salt distributions in the soil profile were not studied, it would seem reasonable to expect non-axisymmetric distribution of salt inversely related to the soil-water movement and accumulation around the periphery of the wetted zone.

The non-axisymmetric distribution of water and salt in wetted zones has not been well documented under field conditions and has significant implications for sampling regimes under commercial conditions. Fuentes *et al.* (2003) noted that "*quantitative soil water status measurements are limited by the need to sample adequately to characterise water status of the large volume of soil in the root-zone, leading to uncertainty in the adequate positioning of probes (Li et al., 2002). Quantitative assessment of local and total water uptake responses to soil moisture is essential for optimal irrigation design and management, but non-uniform soil wetting patterns are commonly found in the field (Reid and Huck, 1990), which complicates the assessment.*"

LEPA Irrigation

The application of relatively small volumes (ie. 15-25 mm) of irrigation water to cracking clay soils using LEPA systems has recently been observed to result in deep drainage and potentially impact on leaching efficiencies. Under these systems, water is ponded on the surface of the soil which then enters via the soil cracks. The resultant distribution of the water within the profile is primarily a function of the connectivity and depth of the crack volumes (eg. Figure 2.5). While redistribution of soil-water will undoubtedly occur within the root zone the infiltration has primarily occurred via bypass flow resulting in only a limited potential to flush salts from the upper soil layers out of the root zone. In dry areas where irrigation water quality is poor and leaching rainfall either is not present or at best highly intermittent, the reduced potential to move salt down through the profile may produce root zone salinity issues.

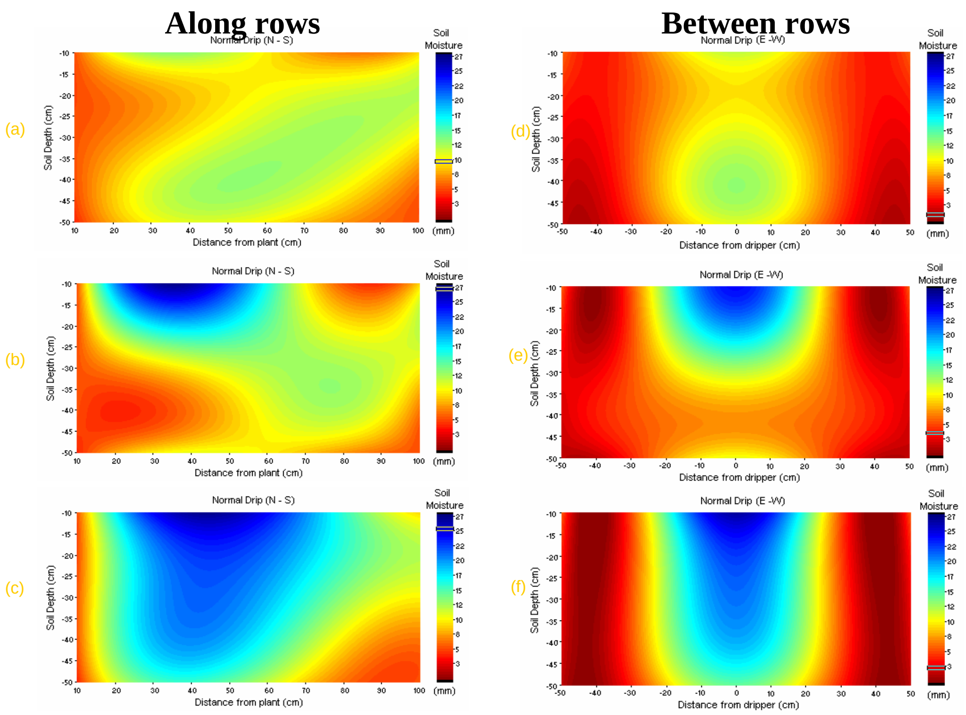

Figure 2.3. Measured soil moisture distributions taken at the beginning (a and d); middle (b and e) and end (c and f) of a 5 hour surface applied drip irrigation event. Distance in a, b and c is from the vine trunk (inter-plant) and for d, e and f is from the emitter (inter-row). ***(from Fuentes et al. 2003)***

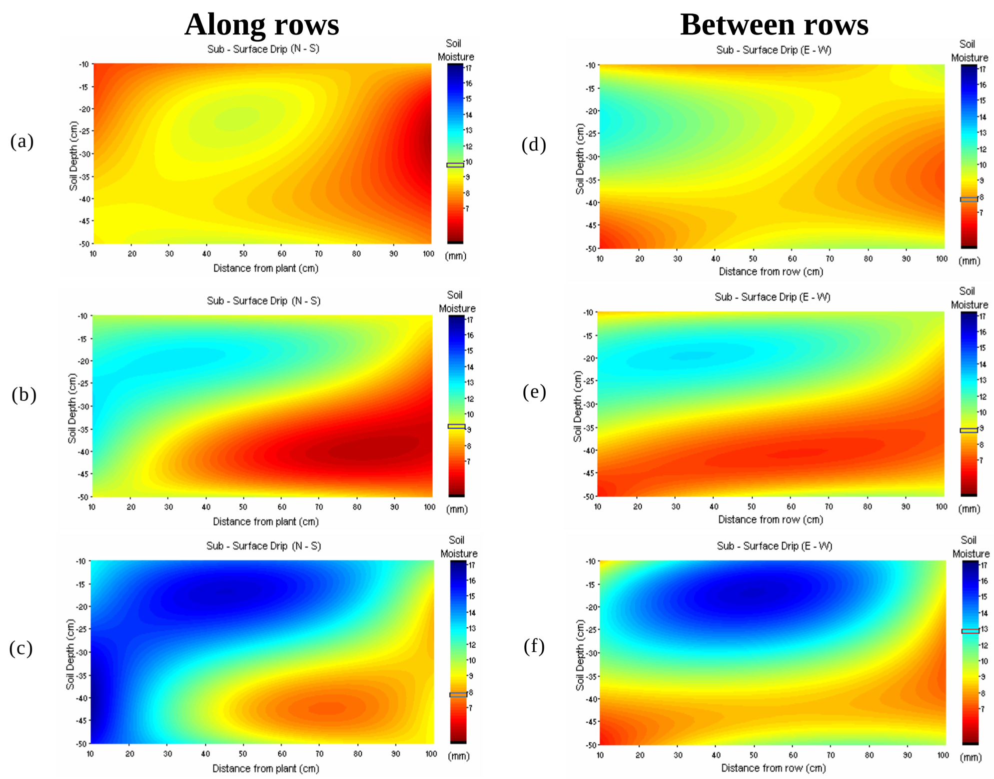

Figure 2.4. Measured soil moisture distributions taken at the beginning (a and d); middle (b and e) and end (c and f) of a 5 hour sub-surface applied drip irrigation event. Figures a, b and c are taken along the sub-surface drip-line and Figures d, e and f are a cross section at 45cm from plant. The subsurface drip-line was running at 30 cm depth and 40 cm from row. ***(from Fuentes et al. 2003)***

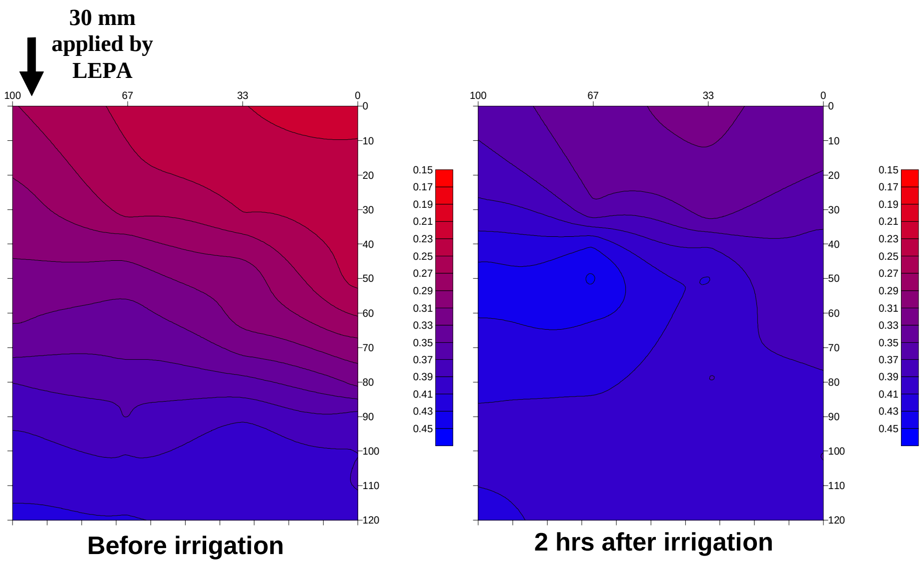

Figure 2.5 Measured soil-water distribution where irrigation is applied using LEPA application to a cracking clay soil (White, *pers comm.*)

2.2 Implications for root zone salinity and leaching efficiency

Precision irrigation implies irrigation systems that deliver water to part of the soil surface only. This means that water will move both vertically and laterally from the point of application. Plant roots will remove water from the moving soil solution, concentrating salts as the distance from the emitter increases. Precision irrigation implies that water sufficient for the plant needs is applied, with little excess for leaching. Any excess water applied through a dripper will leach salts primarily from the zone immediately around the dripper, but will have less impact on salts that have accumulated at greater horizontal distances from the drip line. Rain, on the other hand, falls across the whole soil surface and is the major mechanism through which salts can leach downwards.

Surface evaporation under drip irrigation is spatially variable, as is the net flux of water across the soil surface. At and near the dripper the net water flux will likely be downwards, but further away evaporative fluxes will exceed infiltration, especially during dry periods, leading to an upward flux of water. The use of surface mulches (organic or plastic) which reduce evaporative fluxes can have a large impact of the direction and magnitude of vertical water and salt flux. There have also been anecdotal reports that irrigating during the day produces different soil-water distributions to irrigations conducted at night due to differences in upward flux. Thus at the end of a dry summer, during which a crop has been drip irrigated, salt patterns are likely to be highly variable. Winter rain could leach salt, but may be insufficient to leach salt from areas of high concentration. In some cases, rainfall may mobilise salt previously accumulated on the soil surface back into the root zone creating an adverse impact on root zone osmotic potentials. Also, over a period of time, irrigating with water of high SAR and high RSC, may cause soil structural and permeability deterioration. Stirzaker *et al*. (1999) developed a simple one dimensional approach to determining the frequency needed for flushing events to prevent alleys of trees used for watertable control from being salted out. A similar approach could be developed for drip irrigation systems.

Leaching salts from an irrigated soil root zone is an obligate requirement since all water additions and subsequent evaporation and transpiration will bring about salt concentration. Plant roots exclude most of the salt within the soil solution so a build up around the roots is inevitable. Moving salts away from the roots with diluting, mass flow solution is faster than relying on diffusion to move high concentrations away from the roots. Solute transport will occur by both advection (the solute moves with the water) and by diffusion due to concentration gradients. In soils irrigated by drip irrigation the dominance of these two processes will vary both in space and time during an irrigation cycle. Cote *et al.* (2003) simulated the flow of a pulse of solutes from drip irrigation and showed that solute applied at the end of the irrigation ends up deeper in the soil compared to when it was applied at the start of the irrigation, owing to an increase in the ratio of downward to lateral water flux over time. This is completely different to what would happen for one-dimensional flow. Such studies suggest that much more research is required to understand solute transport in drip systems especially over an irrigation cycle and the interaction with rainfall events.

Plant roots also play a major role in soil-water and solute dynamics by modifying the water and solute uptake patterns in the rooting zone. Mmolawa and Or (2000) observed that "*the analysis and measurement of solute movement and distribution becomes complicated due to uncertainty regarding root distribution and functionality within the root zone. Plant roots, because of their selective uptake of solutes, affect the concentration, movement and distribution of solutes within the root zone. Root uptake patterns of water and solutes are highly dynamic since the root distribution in the soil profile, water content and availability, and aeration status of the soil are in a constant state of change. Under ideal conditions, any attempt to measure root water uptake should consider not only these highly dynamic parameters in detail, but should also consider how they interact as well. Water uptake by plant roots under saline conditions also induces additional osmotic potentials and can raise toxicity levels. This can lead to roots being exposed to very different soil osmotic and matric water potentials from the bulk of the soil during the water depletion period. Hence, in order to improve the understanding of the processes of water supply to crops growing in saline conditions, the effects of decreasing osmotic and matric water potential in the soil surrounding the roots needs to be quantified (Schleiff, 1986).*"

The potential for managing root zone salinity and the application of leaching fractions is increasingly important as precision irrigation is implemented. Stevens *et al.* (2004) reported soil salinity data measured on 20 citrus and grape vine sites located in the Riverland and Sunraysia regions. The electrical conductivity of the applied water was general low (<0.4 dS/m) and irrigation management typically resulted in 15-20% of the applied water contributing to deep drainage which should have been sufficient to main salt levels in the root zone below plant tolerance levels. However, they found that the upper range of average EC_e in Sunraysia sites was above the threshold for salinity damage to vines and in the Riverland above the threshold for both vines and citrus. The calculated mean one dimensional leaching efficiency of 0.63 at these sites was significantly less than unity ($P < 0.01$) and had a large coefficient of variation (77%).

The challenge of managing root zone salinity in precision irrigation systems has significant implications for regulation and/or water use efficiency incentive programs. Stevens (2002) observed that "*the development of regulatory linkages between irrigation and its off-site salinity effects began in the late 1980s with the Murray Darling Basin Commission Salinity and Drainage Strategy. Since this time, there has been a progression to draw more and* *more irrigators under the ambit of legislation that makes them responsible for their salinity impact on the River Murray, for example, water allocation plans or salinity management plans. A rise in irrigation efficiency coupled with the development of linkage between the cost of irrigation's salinity impact and drainage production will probably provide the impetus for increased interest in leaching efficiency*."

Hence, the implementation of precision irrigation practices raises the following issues in relation to soil-water and salt management:

- adoption of precision irrigation technologies and practices can result in root zone salinisation problems which are different to those caused primarily by rising ground water systems;
- leaching calculated using one dimensional equations do not appear to adequately describe leaching under some field conditions.
- given these shortcomings, there is potential for regulatory requirements and management guidelines to be inappropriate for sustainable and/or improved irrigation practice and salinity management; and
- there is a need for better measurement methodology to characterize soil and irrigation practice that can be used in the field to assess salt management practices.

3. Size of Production and Water Losses Associated with Salt Retention in Root zone under Precision Irrigation

3.1 Estimating affected area and value

The most likely situations where salt accumulation will occur in a horizontally non uniform way as the result of spatially variable application rates of irrigation will be those areas that have controlled irrigation, mostly drip and trickle systems. Of the total area irrigated in Australia (about 2,500,000 ha), we estimate that about 250,000 ha (10%) has drip and trickle systems. The replacement capital asset value for these systems and the crops that they are irrigating is about $6.2 billion. The annual value of production from crops irrigated in this way is proportionately higher than the general average from all irrigation because these systems are almost all used on high return horticultural and vegetable crops. There are few reliable survey figures on crop type, revenue return and irrigation type so that only approximate estimates of the likely value of these production systems can be made. The most recent detailed information is from the irrigated areas of the Murray in South Australia. On the basis of revenue generated per unit area from different crops and irrigation systems we expect that the value of production per unit area is 4 to 5 times that on average from other irrigation activities. If this is true then the annual value of the production systems that could be affected by horizontally spatially variable salt retention could be as much as 40% of the total annual revenue from irrigated agriculture.

In summary, spatially variable salt additions resulting from precision application systems could affect about 10% of the current irrigated area, an area that could reasonably be expected to increase in proportion, while the value of the production from these areas could be as high as 40% of annual total revenue.

3.2 Crop sensitivity to root zone salinity

Having established what the likely area and value of the production from possible affected areas is, it is necessary to try to estimate the likely impact of spatially variable salt additions on crop production. This is not straight forward since all of the factors that affect salt balances in a crop root zone will have an influence. Considering the components of the salt balance equation (Appendix 1), it is obvious that rainfall totals as well as irrigation volume and timing are critical, as are the salt loads entering the soil profile through either surface water additions, irrigation or by capillary rise from saturated water table layers. Plant roots within the soil can be affected by salts and nutrients within the soil solution. The physiological mechanisms that cause plant responses to salt are not totally understood with osmotic effects, toxic effects and energy needs for maintenance of cellular integrity all likely to be involved. Models that represent the climate, crop (including root growth and distribution), soil, agronomy and groundwater conditions that affect salt distribution in the root zone and the crop response need to consider all of these components.

Two models of different complexity were used in this analysis to assess the likely impact of horizontally non-uniform salt distributions under different conditions. The models used in this analysis were SWAGMAN Whatif (a multi-crop, single year model designed primarily for educational purposes) and SWAGMAN Destiny (a point scale, one dimensional, salt and water balance model). While neither model has specifically been designed to represent horizontally non-uniform water and salt distributions, both models can be used to evaluate the possible sensitivity of different crops in different locations to conditions that will approximate non-uniform salt distributions

SWAGMAN Destiny was run in strategic mode with 5 different irrigation water salinities (0.1, 1, 2, 3, 5 dS/m) for 10 year periods using Griffith weather data and conditions with fairly standard agronomic management. This produced cumulative probability distributions of yield that demonstrate the sensitivity of vines, maize and pasture to the equivalent effect of inefficient leaching caused by spatially distributed salt. The scenario summary is given in Appendix 1 and the impact on yield shown in Figure 3.1.

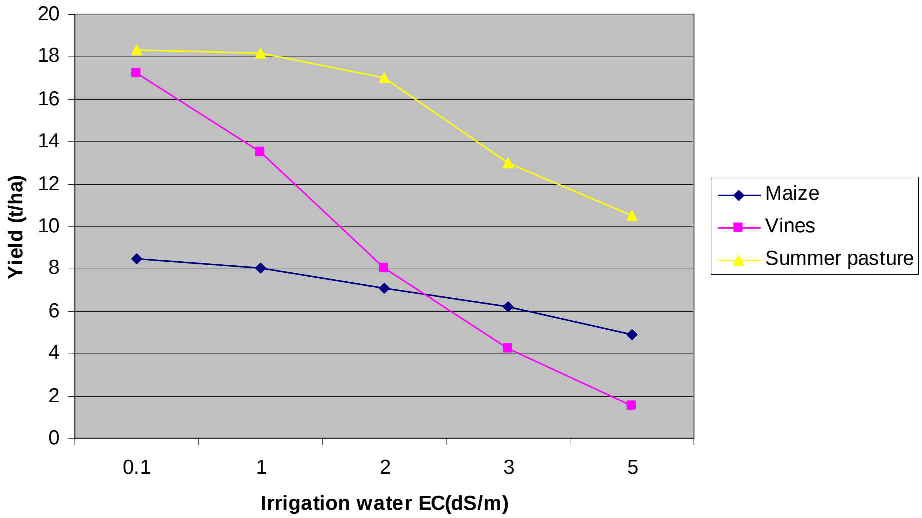

Figure 3.1 Impact of irrigation water salinity (50% probability) on yield of maize, vines and summer pasture

While the timing of changes to soil profile salinity are approximations in the Whatif representation, the extent of change in profile salt levels as the result of interactions with rainfall, irrigation and water tables is nicely illustrated. Clearly the build up in salt levels is greatest in situations of low rainfall and large irrigations with saline water over shallow water tables. If rainfall is higher, rates of salt build up are much slower and may even decline if irrigation amounts are also high. Salt levels, like soil water are highly dynamic and depend on local conditions. Responses, as illustrated in the SWAGMAN Whatif results are not driven by single factors but rather would be best illustrated with multi-dimensional response surfaces.

Not surprisingly the main effect of increasingly saline irrigation water is related to the sensitivity of the crop to salinity and hence, vines are more sensitive than either maize or summer pasture (Table 3.1). Note that the response of the crop in any one year is dependant on the run conditions. In Destiny, this is represented by developing cumulative probability distributions using (in this case) the results from 10 years of weather data. Thus, the output table in Appendix 1 contains both high and low values plus the 50% probability value – as plotted in Figure 3.1 above.

Table 3.1 Sensitivity of grape vines, summer pasture and maize to increasing electrical conductivity (range 1-5 dS/m) of the irrigation water applied (50% percentile rainfall years)

Crop	Yield reduction per unit (dS/m) increase in electrical conductivity of irrigation water
Grapes	3.0 t/ha
Summer pasture	1.9 t/ha
Maize	0.8 t/ha

3.3 Effect of climate on root zone salinity

Scenarios were set up in Whatif to provide an example of projected effects of different rainfall and climate effects on profile salt changes over a year. Root zone salinity was found to increase most under dry conditions (Table 3.2). Where grapes are grown in Loxton on a soil with root zone salinity of 1 dS/m, applying 1100 mm of irrigation water with a salinity of 0.8 dS/m would increase root zone salinity to 2.3 dS/m in wet year and 3.7 dS/m in a dry year. Applying the same strategy in the Riverina would increase root zone salinity to 1.8 dS/m in an average year while if the strategy was applied in the relatively high rainfall area of south-eastern Queensland the root zone salinity would decrease to 0.4 dS/m.

Where no irrigation is applied to grapes grown in south-eastern Queensland it would be expected that root zone salinity would increase to 1.2 dS/m. However, where cotton is grown in the same area without irrigation there would be no significant change in root zone salinity. Adding irrigation with high quality water (0.2 dS/m) effectively results in net leaching of salt and so the root zone salinity will decline. If mildly salty water (0.8 dS/m) is used for irrigation then with the same rainfall and irrigation amounts salinity level in the root zone would increase by 0.1 dS/m.

Table 3.2 Effect of climate on root zone salinity of a fast infiltration loam with a starting root zone salinity of 1 dS/m [a]

Crop	Location	Rainfall during season (mm)	Total annual rainfall (mm)	Irrigation water applied (mm)	Change in root zone salinity after one year (dS/m)
Grapes	Loxton (dry year)	88	93	1100 [b]	2.7
	Loxton (wet year)	79	198	1100 [b]	1.3
	Riverina	223	418	1100 [b]	0.8
	S.E. Qld	523	719	1100 [b]	-0.6
	S.E. Qld	523	719	0	0.2
Cotton	S.E. Qld	491	777	0	0 [d]
	S.E. Qld	491	777	300 [c]	-0.4
	S.E. Qld	491	777	300 [b]	0.1

[a] Watertable depth = 2.2 m below surface with water quality = 5.0 dS/m
[b] Irrigation water quality = 0.8 dS/m
[c] Irrigation water quality = 0.2 dS/m; note 300 mm of irrigation required to achieve fully irrigated yield
[d] note yield is estimated to be 28% lower than a fully irrigated yield

3.4 Scenario analysis to assess impact

If the effect of spatially non-uniform distribution of salt which was poorly managed was the equivalent of increasing the effective salinity level within the soil root zone by 1 dS/m, then in the Murray and Murrumbidgee Basins irrigated areas, the decreased revenue would be directly proportional to the yield reduction (Table 3.3). It should be noted that it is highly unlikely that the impact of the increase in root zone salinity would be immediate as increases are likely to take a number of years to reach predicted levels and will not affect all irrigated areas equally. Hence, these estimates are likely to be the worst case scenario. What is clear is that the more sensitive crops should have higher priority in assessing the likely impact of spatially variable salt dynamics.

Table 3.3 Effect on revenue of precision irrigation induced root zone salinity for enterprise options in the Murray and Murrumbidgee Basins irrigated areas (based on 2000/01)

Enterprise	Value unaffected by salinity impact	Value if affected by salinity impact	Reduction in revenue	Reduction in revenue (%)
Vines	$832 m	$688 m	$144 m	17.4
Summer pastures used for dairy	$854 m	$765 m	$89 m	10.4
Maize	$125 m	$113 m	$12 m	9.4
Total Impact	**$1811 m**	**$1566 m**	**$245 m**	**13.5**

The effect of variable effectiveness of leaching can be handled more explicitly in SWAGMAN Destiny by invoking the variable mixing that will come from preferential flow and matrix flow. While it is relatively straight forward to account for this effect in the simulation model (see Appendix for the way that this can be represented), being able to assign the right values to different soils is harder and needs some measures or robust surrogates to be developed. Nonetheless, some moderate adjustment of the SWAGMAN models could be very helpful in exploring and better defining those conditions and management regimes when spatially variable salt distribution and variably efficient leaching will be a problem. Further, such models would assist in directing attention to those management strategies that could or should be employed in different regions to minimise these salinity effects.

4. Modelling Soil-Water and Salt Movement Associated with Precision Irrigation

Modelling tools at our disposal include a range of 1-D and 2-D models. True 3-D models are available for the unsaturated zone but not often required as most situations can be described adequately using a 2-D or radial 2-D model. These models consist of analytical, quasi-analytical and numerical models.

The analytical (direct solution of the differential equations) or quasi-analytical (these contain some functions or integrals that have to be analysed using numerical methods) are usually written in terms of non-dimensional variables which allow rapid exploration of the parameter space. These models are usually only suitable for specific boundary conditions i.e. the drip source is considered to occur at a point (this is physically impossible) but have provided good insight into axi-symmetric (Raats, 1971; Philip, 1984; Philip, 1997; Revol *et al.*, 1997a & b; Cook *et al*., 2003a) and 2D flow problems (Warrick and Lomen, 1981; 1983). These models have given a very good insight into the physical process involved in irrigation and the non-dimensional variables allow the formulation of the parameter space for the numerical simulations so that redundant simulations are not created.

Numerical models solve the differential equations by discretisation of the spatial and temporal domains (this is covered in more detail below. Commonly used methods that exist are finite difference and finite element. Finite element methods are now mostly used in 2D flow problems. More recently the method-of-lines has also been used and is a promising new method but is still in development (Matthews *et al.* 2004a & b; Lee *et al.* 2004; Schiesser, 1991). This latter method coupled with some new scaling techniques offers promise for making layered soils computationally into a homogenous soil problem.

Comparison of numerical and analytical models for drip irrigation are not common but recently Cook *et al*. (2003a & b; 2005) did show that they give similar results apart from when extreme soil properties are used. The analytical solution used by Cook *et al.* was that of Philip (1984) and has been incorporated into a software tool for predicting wetting patterns from drip irrigation (http://www.clw.csiro.au/products/wetup/). Such simplified tools could be developed from a properly designed modelling project.

While the assumptions regarding process (Richards equation and CDE) and soil uniformity may reduce the applicability of these models to structured and layered soils, they play an important role in simulating rigorous validation scenarios for numerical models.

4.1 Flow domains

In numerical modelling, we need to discretise the flow domain (flow region) into smaller units called ‘elements’ where each element has a number of nodes; we then write flow and transport equations for each node and solve them at each time step. This implicitly means that the more nodes we have, the harder the problem becomes thus requiring more computer time. Common sense suggests that we should solve the flow problem only along axes where change is anticipated (otherwise we get duplicate results). There are three independent spatial axes, the z-axis (depth), the x-axis (width), and the y-axis (3rd dimension orthogonal to the z-x plane). Therefore we can solve any flow problem using a three-dimensional flow domain but do we always need to? No, not every time; rather, we can use symmetry to eliminate axes along which there is no change. Therefore, we define one- and two-dimensional flow problems. The primary task that a modeller undertakes is to correctly conceptualise the problem in order to identify those axes along which flow is similar (i.e., identify the question and judge which model is capable of providing the answer).

4.1.1 One-dimensional flow

If we have uniform rainfall (or uniform spray irrigation) on a flat paddock similar to that shown in Figure 4.1, then we expect that flow along axes z_1, z_2, z_3, and z_4 (and all vertical axes parallel to them) will be identical; therefore, it is sufficient to solve the flow problem along one axis and by symmetry have the solution everywhere. If we want to know what is happening every 10-cm along a 2-m deep soil profile, then we need 20 elements to solve the problem; remember that fewer elements means less computations.

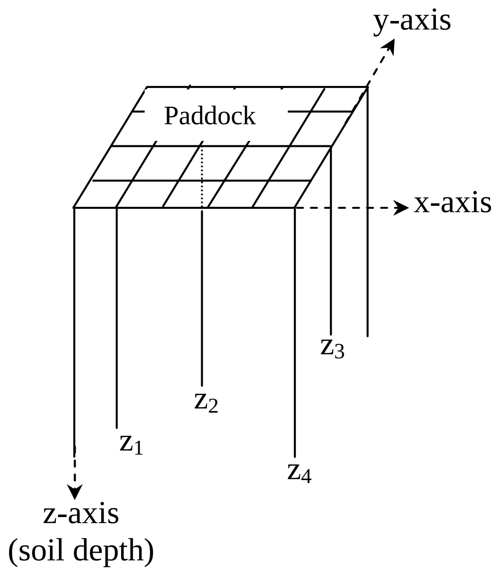

Figure 4.1 One-dimensional flow

4.1.2 Two-dimensional flow

In the case of furrow irrigation (shown in Figure 4.2), we expect things to be different along axes z_1 and z_2 since the former is closer to the furrow; however, since the furrow extends along the y-axis, we expect things to be similar across any plane parallel to that defined by axes z_1 and z_2 (i.e., flow along z_2 and $z_3$is identical). If we want to know what is happening every 10-cm along a 2-m deep soil profile across a width spanning 2 m in the x-direction, then we need 20×20 elements to solve the problem; this is 20 folds more computationally intense than the 1-dimensional problem.

Note that the flow problem arising from a drip source placed at the surface of a flat paddock can also be solved using a two-dimensional flow domain since there is symmetry along any radius of a circle whose centre is the drip itself (it is called an axi-symmetric flow problem); it is an implicit assumption here that the wetting fronts from adjacent drippers do not interfere with each other.

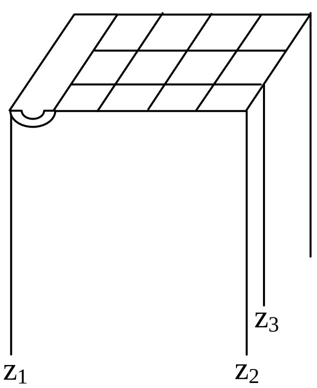

Figure 4.2 Two-dimensional flow

4.1.3 Three-dimensional flow

If we add a drip source to the furrow system shown in Figure 4.2, then we no longer have symmetry in any direction, which means we have to model the entire volume along the three orthogonal axes. One practical application for full three dimensional flow is when we want to investigate how the wetting fronts from multiple drippers interfere with each other at a great soil depth and how that impacts deep drainage.

If we want to know what is happening every 10-cm along a 2-m deep soil profile across a width spanning 2 m in both the x- and y-directions, then we need 20×20×20 elements to solve the problem, this is 400 folds more computationally intense than the 1-dimensional problem.

4.2 Tools for modelling water flow and solute transport under precision irrigation

4.3.1 HYDRUS-1D (1-dimensional model)

HYDRUS-1D is a one-dimensional numerical model that can simulate water flow, mass transport, heat flow, water and solute root uptake, and plant growth. The latter is the only extra feature that is not present in HYDRUS-2D; the other advantage with HYDRUS-1D is that it is freely available; the technical capabilities of the program are similar to those of HYDRUS-2D and are covered in the following section.

4.3.2 HYDRUS-2D (2-dimensional model)

This software package is increasingly becoming the ‘Standard’ tool for modelling variable saturated (coupled saturated and unsaturated) flow in porous media; it is being used world wide by government agencies, consultants, and universities. The software is robust and its reliability has been proven during the past decade. It is the perfect tool for modelling water flow and solute transport under precision irrigation as its time-marching scheme allows modelling of the flow problem in real time (e.g. can investigate the spatial and temporal distribution of drippers). Hence, users of Hydrus-2D require a high level of modelling expertise in addition to being familiar with the underlying theory that spans across area ranging from variably saturated water flow to solute transport and root water uptake processes. This implicitly means that there is a need for investment in terms of capability building. The main features of HYDRUS-2D are as follows:

- Main processes: it is possible to model water flow, solute transport, and root uptake (and any combination); there is a very useful feature to model transport under steady state water flow conditions. The inverse option is extremely useful for parameter estimation (will be discussed in more detail in Section 4.3).
- It is possible to model conventional two-dimensional flow (in Cartesian x-y coordinates) as well as axi-symmetric flow, which ideal to model flow under drip irrigation. The mesh generator can model two-dimensional domains of any shape.
- The software handles heterogenous soil profiles (up to 10 material types) and provides full mass balance calculations in selected regions (which may be similar or different to the material regions).
- Heterogeneity may also be statistically represented using the stochastic option; the concept of scaling factors may be adopted to scale the relevant soil properties.
- A range of soil hydraulic models is available to choose from with a hysteresis option (where wetting cycles are different from drying cycles). There is a built-in library and an advanced neural network application that helps the user to select the proper soil hydraulic properties (which may not always be readily available.
- There is a range of boundary conditions that can model a variety of situations such as:

- Atmospheric boundary (e.g., model evaporation, infiltration, and volatilisation).
- Constant head boundary (e.g., model flood irrigation).
- Flux boundary (e.g., model spray irrigation; surface or buried drippers).
- Free and deep drainage boundaries (e.g., model deep drainage and salt movement below the root zone).

- Though most of the precision irrigation applications involve mainly unsaturated flow, the capacity to model coupled saturated/unsaturated flow is essential (e.g., formation of a shallow perched water table).
- Root water uptake may be modelled using two alternative models; there is a library that contains recommends parameters for various plants. There is an option to include solute stress (account for osmotic pressures).
- Solute transport is modelled in either a conservative or a reactive manner. The reactive option may involve adsorption (linear or non-linear) and/or degradation/production processes. Physical or chemical non-equilibrium may also be modelled; the former option models two phases (open pores and dead-end pores) and the latter option allows adsorption on some sites to be time-dependent. The ability to simulate reactive non-equilibrium solute transport is extremely useful in modelling chemical transformations that could potentially change soil structure.

It is possible to investigate the effects of preferential flow using Hydrus-2D by incorporating stochastic soil properties (Figures 4.3 & 4.4). However, it is necessary to characterise the flow system statistically if this option is used. It is also possible to use the modified van Genuchten functions to allow for more rapid flow near saturation conditions. In addition to the stochastic option, there is also a proper dual porosity model that handles preferential paths. This add on model is not publicly available with Hydrus but it can be obtained from the software developer. The real task is then applying the model and calibrating it using field data. Field lysimetry experiments may be useful in this context (eg. NRM in Toowoomba have collected such data but have not modelled it yet). Preliminary modelling of this type of experiment has been conducted (Foley *et al*., 2003) but there is a need for field trials which include both flux and head controlled experiments to investigate for example, the role of preferential paths in cracking clay soils.

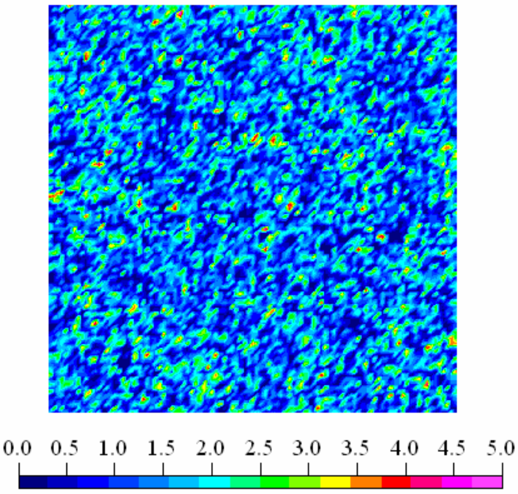

Figure 4.3 Stochastic distribution of hydraulic conductivity (1 cm/day, coefficient of variance ~ 30%) in a 100 cm x 100 cm domain

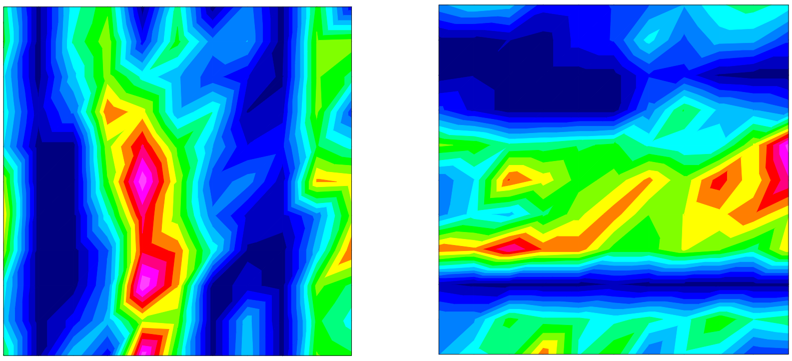

Figure 4.4 Visualisation of (a) vertical and (b) horizontal oriented preferential flow paths that can be applied within Hydrus-2D. The colours represent different values of hydraulic conductivities based on a statistical distribution of scaling factors.

4.3.3 FEFLOW (3-dimensional model)

FEFLOW models full 3-dimensional flow and transport problems; however it has limitations in terms of essential capabilities relating to root uptake processes and modelling evaporation but has the advantage of accepting custom built models into it. It is very expensive (in the order of thousands compared to HYDRUS 2D, which is about $1,500). This package is more oriented toward modelling groundwater systems with the capability to explicitly model the unsaturated zone whereas HYDRUS is the opposite, which makes it more suitable for the current task.

4.3 Data requirements

It is common knowledge that complex, physically based models are data hungry; the more processes we model the more parameters we need (and the higher the likelihood of getting them wrong!). Unsaturated flow parameters (that feed the hydraulic models, e.g., van Genuchten model) can be estimated via laboratory as well as field methods. Estimating solute transport parameters is a more complex task; they can be evaluated in the laboratory using leaching column experiments and in the field using tracer experiments; analysing the results also involves sophisticated analytical or numerical modelling.

The 'inverse' option in HYDRUS allows indirect model parameters to be estimated; the model compares the simulation results with observed experimental data (like water contents, pressure heads, or concentrations), and then re-runs a number of times until a close fit to the observed experimental data is obtained. This process is alternatively referred to as "Model calibration", or "Inverse parameter estimation".

The higher demand for data has two compounding adverse impacts; firstly, it requires more energy/expertise and hence adds to cost, and secondly, it adds to uncertainty. The former points are well known but unfortunately the latter is not. Uncertainty manifests itself very clearly in inverse parameter estimation where more than one set of parameters can produce good fits to the observed data. The inevitable consequence of this phenomenon is "predictive uncertainty"; for example, if we want the model to predict deep drainage, two parameter sets (that produced good fit to the observed data) will result in different deep drainage results. This means that we should experience extreme caution when using such complex models that have such advanced features (we stress again on the importance of capacity building).

4.4 Limitations and research gaps

The main limitations of complex numerical models are:

- high data requirements (as outlined in Section 4.3);
- numerical instabilities especially with fine-textured soils close to saturation; and
- the user needs to know the underlying theory, have a high modelling expertise (e.g., familiar with boundary conditions, spatial discretisation, and time marching schemes), and requires the ability to correctly interpret the results (and more crucially identify situations where a model has produced faulty results).

Analytical models on the other hand have less data requirements and much simpler to implement. However, their applicability is restricted within the underlying assumptions (e.g. use only simple flow domains). There is a great potential for the implementation of analytical solutions especially if they are presented in a simple user-friendly environment (such as a spreadsheet).

Modelling of precision irrigation systems should involve several approaches conducted concurrently. There is a mismatch between the data required by complex, process-based simulation models, and the data that is easily available from soil survey and routine soil analysis. Thus, we usually have general soils data available at the broader scale, while input data for modelling are usually measured or derived from detailed site-specific experiments or monitoring. Thorburn *et al.* (2003) use general and site specific soil data to estimate soil wetting patterns using an analytical model. These results show that wetting patterns fall into two broad classes for the general soils and is less well defined for the site-specific soils. The actual modelling exercise can be conducted only by experienced scientists. However the problem of extending the information obtained to broader scales and to growers and advisors although a challenge can be accomplished by such approaches as those shown by Thorburn *et al*. (2002; 2003).

Validation of 2-D simulations of water and salt distributions under drip irrigation has been raised. Observed wetting and salinity patterns in the soil and on the soil surface are usually highly irregular. However, a 2-D model often describes general aspects such as depth of wetting and temporal patterns of soil water content from the surface to a depth of 1.5 m fairly realistically. Simulating such a system in a way which produces results which reflect the range of field spatial variability will be difficult. Similarly, interpreting simulations (or measurements) in terms of impact on plants or for assessing leaching efficiency would be equally daunting if the model does not include plant growth and the factors that limit it, or preferential flow. These problems could be reduced by taking advantage of the unique contribution of each of several different modelling tools and approaches as well as some simple field characterization studies:

- Soil survey, either manual grid-based, or using geophysical aids, can provide an indication of the range of soil properties, depths and underlying materials in an irrigated area.
- GIS tools can aid in mapping and classifying the area. Also, land-use and management practices (such as irrigation method, scheduling, etc) can be mapped and overlaid, producing areas of land that can be treated similarly for modelling

purposes. The recognition of spatial variability has led to increased efforts to combine GIS and simulation models in order to describe solute transport on a farm and catchment scale, accounting for soil, land management, vegetation and terrain differences. Upscaling from point scale to larger areas require boundary conditions to be described in more detail, which means that output from associated surface hydrology, groundwater and crop models need to be reflected.

- Detailed 2-D modelling could indicate the likely behaviour of water and salt in the root zone of each area. These simulations could, for example, encompass long-term weather patterns, likely variations in water application efficiency, soil surface options and perhaps some soil heterogeneity. These simulations could be used to generate a spatial distribution of salt concentrations which reflect irrigation management, but not necessarily leaching.
- 1-D multi-region models may be useful is assessing the spatial efficiency of leaching, especially if much of the leaching is by rain falling uniformly across the surface.
- There is a big difference between applying models to explain what has been measured, and using models to predict likely behaviour. For the latter there cannot be any calibration, parameter optimization, etc, so characterization of soils, crop and management is crucial. I see this as one of the largest gaps. Managing salt in the unsaturated zone hinges first on a conceptual understanding of process, formulating management strategies that may lead to improved irrigation, water and salt management, followed by assessment of these options through simulation, and finally testing in the field. The process may be repeated as we learn more about specific soils and situations.
- In many respects, leaching in structured soils is analogous to surface runoff. Preferential flow is triggered by antecedent soil conditions and water application rates. Understanding runoff was increased through the use of a standard runoff measurement using rainfall simulators. Perhaps there would be benefit in developing an analogous technique to assess preferential flow and rank soils?

The major knowledge gaps are the:

- effect of roots, evaporation and transpiration on wetting patterns;
- the accuracy and adequacy of using simple mean values of varying soil salinity levels in the root zone to estimate the effect of salt on the plant;
- fate of solutes during an irrigation cycle and in multiple irrigation cycles; and
- effect of soil heterogeneity on distribution of water and solutes in relation to placement of drippers.

There has been some discussion in the irrigation literature about pulsing, but this is mainly a furphy, as similar results can be produced using a reduced flux (see Cote *et al*. 2003).

The research needs to be done in a collaborative way between both private and public entities. Most of the modelling and certainly mathematical skills are within the public sector. However, the experimental opportunities are mainly within the private sector. Thus there is a need for collaboration between the two sectors.

5. Salt Management under Precision Irrigation Systems

5.1 Salt storage in the unsaturated zone

The application of water to soil whether in the form of rainfall or irrigation carries with it salts. When the soil is in equilibrium the rate of addition of salt is equal to the rate of loss. With precision irrigation systems the desire is to minimise the amount of water added to the soil to maximise the crop production. This is likely to lead to salt storage in areas where the water flux is less than the evapotranspirational flux (edges of drip zones and middle of beds in furrow systems). These areas will then either continue to accumulate salt over time up until a maximum concentration. Rainfall events will redistribute and/or flushed the salt from these storage areas. The rainfall amount frequency will need to be considered when determining the amount of irrigation that can be applied without salinity adversely affecting crops. For each combination of irrigation, salt concentration and groundwater conditions there would be a minimum amount of rain that could leach salt – assuming there is somewhere for which the leachate to drain. Using non-dimensional analysis will reduce the number of combinations that need to be tested. This analysis needs to consider:

(a) How salt added to the system can be minimized by efficient water applications.
(b) Patterns of accumulation of salt and the effect on plant growth and yields
(c) Soil property changes (chemical and physical) consequent on concentration and precipitation of salt must be understood.
(d) Removal of salt by leaching needs to be efficient and evaluated over a period of time which encompasses the range of likely weather patterns.
(e) The longer term fate of leached salt needs to be assessed in relation to possible extended storage in the vadose zone, groundwater levels and flows, and also the impact of salt added through irrigation in comparison to other sources or background levels of salt in the larger system.

5.2 Mobilisation of salt from the unsaturated zone to groundwater system

Continual leaching from an irrigated area will inevitably cause the downward movement of salt. Increased recharge rates under irrigation means that the recharge volume and mobile salt mass are higher. Increased recharge rates under irrigation also means that the time required for a water parcel to reach the groundwater table becomes shorter. Continuous irrigation (of any magnitude) causes a rise in the groundwater table; this rise is a function of aquifer conductivity and specific yield; if irrigation water is applied at certain areas, the increased recharge will result in a groundwater mound under that area.

Effective aquifer transmissivity in the mound area is increased as a result of a higher saturated aquifer thickness, meaning a shorter lateral travel time (of recharge water that met the groundwater level) to the neighbouring river system (due to the increased aquifer transmissivity). The extent of water table rise is a function of aquifer storage and conductivity; i.e., if the catchment is able to drain the applied recharge (due to a high conductivity), we have a small water table rise and vice versa. A rising water table also shortens the unsaturated flow path, which implies that the new irrigation recharge (and accompanying salts) needs to travel a shorter distance to the water table. The spatial variability of unsaturated zone processes may be accounted for by using a variable recharge that varies with the hydraulic parameters of the soil. This variation may be represented using a statistical distribution (e.g. log-normal as used by Cook *et al*., 1989).

5.3 Lateral movement through the aquifer and discharge into the river system

The adverse effects of irrigation are manifested as an increased discharge (and potentially increased salinity) to the neighbouring river system. The salinity of the discharge water is a function of aquifer salinity and the amount of salts that are mobilised from the unsaturated zone of the irrigated area. The temporal variation of discharge (best represented by a unique dimensionless unit response function) varies linearly with aquifer diffusivity and non-linearly with the distance between the irrigated area and the river (varies with the square of the distance). Pressure head gradients as well geological features do have a significant effect on the discharge response.

Understanding and representing processes at this broader scale requires modelling tools very different to those employed in describing wetting patterns around a dripper, for example. A research task is to develop protocols that can use the key output data from a model applied at a detailed scale as input to a broader scale model of regional impacts. There is also potential to enhance capability of SIMRAT (URS, 2005) to predict deep drainage under different irrigation schemes.

6. Recommendations for Research Investment

Improving the precision of irrigation has implications for the management of soil-water and salt within both a production and environmental context. A suitable aspirational goal for research in this area would be: *to ensure that the Australian irrigation community has the tools and capacity to effectively harness the benefits of new precision irrigation technologies and practices to improve productive performance and sustainably manage the catchment wide salt balance without compromising root zone soil health.* Hence, research investment into factors influencing the adoption and management of precision irrigation systems will have an impact on policy development both at a regional and national scale and provide both public and private good benefits.

Precision irrigation is inherently a complex concept and encouraging adoption will require significant changes in both the industry knowledge and capacity base. Part of this capacity building will require improved cross-discipline linkages to encourage the development of outcomes which provide a tangible impact on both the production and environmental drivers for investment. While the potential benefit from improved irrigation practices is significant, the successful implementation of appropriate on-farm practices will require significant investment from farmers. Hence, it seems likely that adoption will occur first in those industries with the greatest returns per ML and where salt management is seen to be a limiting factor and hence, research and development opportunities should be focused on these industries.

6.1 Goals and further research opportunities

This study has identified a wide range of research issues associated with spatially variable water and salt distributions in the root zone due to the introduction of precision irrigation systems. These issues can be grouped into categories of: (a) requirements for soil characterisation, (b) irrigation management effects, (c) agronomic responses to variable water and salt distributions in the root zone, (d) potential to scale or evaluate impacts at various scales (e) requirements for simplified modelling tools and (f) the need for skills and capacity building.

Requirements for soil characterisation

- There is a need to develop quick, simple and robust techniques to characterise soil infiltration and leaching efficiencies to enable evaluation of in-field soil heterogeneity and potential impacts on irrigation and salt leaching performance.
- As much emphasis should be placed on characterising soils to define model inputs and provide general applicability as is put into modelling these processes.
- Soil structural problems associated with changes in soil chemistry need better description, greater identification of current and potential problems and better collation of management options.
- Preferential flow can be measured by using saturated/unsaturated disc permeameters. Publications on providing methods for rapid determination of hydraulic properties using the initial infiltration process (transient methods) are currently in prep (Cook and Dawes, 2005a & b). Training in both the analysis and use of these instruments will be required.

Irrigation management effects

- There is potential to better evaluate the impact of transient flux gradients on soil-water movement and salt accumulation under commercial conditions particularly with respect to how (a) the application of water at different times of day/night and (b) under various management practices (eg. mulching) will affect salt distribution.
- There is sufficient evidence to suggest that in situations of point water applications and associated salt distribution that rainfall could be used to advantage in displacing salt and moving it below the root zone. This dynamic situation needs to be explored further and the limits and management options determined. This will involve better characterisation and modelling of solute transport in relation to climate and soil properties.
- The issue of leaching efficiency is mostly separate from that of spatially different distributions of salt from point and line irrigation sources and these should be studied as separate processes.
- For any precision irrigation system, what management options does an irrigator actually have? The production and environmental benefits, and economics, of the feasible management options need to be evaluated.

Agronomic responses to variable water and salt distributions in the root zone

- There is currently little understanding of the physiological responses of crops to various salt distributions within the root zone. Priority investigations should be undertaken on the most salt sensitive crops where precision irrigation is being currently or likely to be implemented.

Potential to scale or evaluate impacts at various scales

- Point scale modelling of any kind will need to be complemented by models that account for the dynamics of weather, crops, irrigation practice, salt loading, and groundwater interactions to assist general applicability i.e. extend beyond the immediate study area.
- There is a need for some form of Scenario Analysis capacity for regions – examining the changed salt management infrastructure required under a range of precision

irrigation adoption scenarios – e.g. what would be the national impact on salt management of the "Drip Australia" concept?

Requirements for simplified modelling tools

It should also be noted that the existing soil-water modelling tools were regarded as appropriate and adequate to simulate the majority of spatially variable solute issues arising under precision irrigation. While there are issues associated with the parameterisation, operation and interpretation of these models there does not appear to be any need at this point in time to develop further models. What is needed is packaging of existing knowledge, which often includes difficult mathematical concepts, in ways that make this knowledge available to a wide range of users. Opportunities include:

- Extension of existing models such as WetUp to any combination of soil properties, flow rates and application times. This can be done by replacing the present dimensional databases with non-dimensional databases.
- Packaging of existing analytical models into user friendly front ends for calculation of wetting patterns and salt distributions.
- Verification of analytical models by comparison with numerical models in case where the underlying assumptions are violated.
- Use existing numerical models to determine the effects of heterogeneity on water and salt distribution patterns and the interaction with climate. From these studies develop simple non-dimensional rule-based knowledge systems.
- The models should be used to develop and evaluate any experimental work, so that redundant data sets are not produced (note some replication is required).
- The analytical and rule-based models can be included in GIS models to assist with interpretation of wider landscape issues.

Skills and capacity building

- There is a significant lack of appropriate mathematical skills and capacity in relation to soil-water modelling within the Australian research community
- There are currently a range of tools (both sensory and modelling) available to understand the plant-soil-water interactions. However, these tools are currently poorly linked and the skill sets and capacity to operate these tools effectively are rarely available with single projects. Hence, there is a need to:
  - (a) build capacity in the operation and interpretation of the constituent components;
  - (b) develop cross-disciplinary studies which take a whole-of-system view; and
  - (c) investigate the development of integrating frameworks between existing tools and models.

  However, there would also be a need to investigate error propagation and validation within such a framework.

6.2 Key recommendations for investment

It is recognised that it is not possible for NPSI to invest across all of the potential gaps and opportunities identified in section 6.1. Hence, there is a need to prioritise the opportunities for investment. The general principles adopted in this process were:

- It is more efficient to use and improve that which already exists rather than encouraging re-inventing and re-interpretation of previous work without any improved conceptual or representational construct;

- Any additional modelling and measurement work should improve the capability to assess, for a whole range of climates and agronomic practices, the options for management of salt and especially the possibility of combining small irrigation events with the occurrence of rainfall; and
- Targeted measurement and selective modelling using existing tools will have the greatest value if combined with some training and capacity building within the industry.
- The funds should be sufficient for the research to not only be carried out but published in internationally regarded journals, so that (i) the learnings are readily and widely available and (ii) the quality of the research is fully assessed and evaluated.

On this basis, the key recommendations for research investment and indicative project outlines are identified below.

1. Development of simple and robust techniques for soil characterisation

Key components	Review and packaging of existing practical methods for characterisation of soil properties influencing soil-water and solute movement at small scales. This project would provide the basis for improving the level of knowledge and skills available at the operational field level. It would also lead into the identification of specific methodologies requiring further development and field evaluation. For example a simple method for measuring infiltration rates of soils has been developed by Cook (unpublished) but requires some further testing with numerical models and field tests.
Indicative costing:	$75-100k
Suggested timeframe:	12-18 months

2. Building skills and capacity in soil-water and solute management

Key components	(a) Using existing knowledge and expertise to develop a training package which includes the principles, techniques and tools for evaluating soil-water and solute movement under precision irrigation systems. (b) Development/refinement of application tools/interfaces for soil-water and solute movement that could be used by advisers and farmers (eg. refined Wet-up could include evaporation/transpiration/solutes). This component would utilise existing analytical solutions within user friendly environments (e.g. spreadsheets or GIS), and explore their applicability by comparing their results to those arising from more complex and versatile numerical models. This process would also identify knowledge gaps and provide guidance on future research direction (i.e., develop new solutions for situations where the existing solutions break down). The recent development, implementation, and accreditation process of the SIMRAT model (URS, 2005)

	demonstrates this process. SIMRAT is a rapid assessment tool that uses simple and basic concepts to model the movement of salts under irrigated land through the unsaturated zone then estimates the time lags for their discharge to the river using the simple analytical solution presented by Knight *et al*. (2004). It accounts for the spatial variability of recharge by using statistical functions. The model is built into a user-friendly GIS framework where the cumulative effects of (spatially explicit) individual irrigation developments can be quantified. As part of the accreditation process required by the MDBC, a study was conducted by Rassam *et al.* (2004) to further enhance the credibility of the model (e.g. by comparing results to more known models such as MODFLOW and addressing numerous concerns raised by model users and peer reviewers). There is also potential to enhance the capability of SIMRAT to predict deep drainage under different irrigation schemes. (c) Delivery of the training package, promotion of the soil-water and solute tools, and engagement with relevant technocrats to ensure a lasting legacy.
Indicative costing:	(a) $75-100k (b) $100-125k (c) $125-150k
Suggested timeframe:	(a) 6-12 months (b) 6-12 months (could be concurrent with (a)) (c) 12 months

3. Management of soil-water and solutes in precision irrigation systems

Summary	The key components of this project are: (a) Characterising solute movement and salt storage under precision irrigation. Will involve an evaluation of the factors influencing the time frames and patterns of salt movement under precision irrigation. This would be a desktop (modelling) study using a small number of case study sites representing the range of soil, water quality, irrigation practices and rainfall conditions encountered. Some soil characterisation data may be available for case study sites but additional data collection will be required. This stage will provide input data (root zone scale) on solute concentration gradients, potential for salt storage and impact of rainfall on solute distribution necessary for the next stage of the project. (b) Development of irrigation management guidelines based on agronomic responses. This stage will involve the evaluation of agronomic responses to the soil solute distribution created under a range water quality, irrigation management and rainfall conditions. This stage will use

	existing agronomic models and soil-water and solute data inputs from the earlier stage to identify appropriate thresholds and management practices for a range of conditions. (c) Validation of agronomic responses and management guidelines. This stage involves validating the modelled agronomic responses against expert knowledge and field observations under the various irrigation management and rainfall conditions. Differences between the predicted and observed agronomic responses will provide the basis for targeting follow-on experimental research into the various components (ie. investigating specific crop responses or inaccuracies in salt storage/distribution prediction)
Indicative costing:	(a) \$100-125k (b) \$150-175k (c) \$75-100k
Suggested timeframe:	(a) 6-12 months (b) 12-18 months (c) 6 months

It should be noted that there are also some opportunities to leverage funding towards work that has already been initiated or is being partly funded by other research organisations. For example, ACIAR will provide funding to CSIRO Land and Water to analyse raised bed furrow irrigated systems. Opportunities for additional investment include the:

- development of a user friendly front end developed for the mathematics produced from the ACIAR project (would fit with project 2, component b as outlined above) and
- to further instrument existing raised bed projects ACIAR has in India, Australia and China to obtain better data sets (would fit with project 3, component a as outline above).

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Appendix 1. Scenario Analysis to Evaluate the Impact of Root Zone Salinity on Production

The salt balance equation below contains all of the components that interact to describe the salt mass within a given soil profile, assuming spatial uniformity and 1-D flow processes:

$$C_s^i = [C_s^{i-1} W_i + Ra\,C_{Ra} + I\,C_I + (U - D)\,C_{WT} - R_o C_{Ro}] / W_f$$

where:
C_s^i is the current salt concentration in the soil element at time *i* (dS/m).
C_s^{i-1} is the initial soil salt concentration and W_i is the initial total water content of the soil element (mm).
R_a is rain (mm) over the time duration being considered (i to i-1) with C_{Ra} being the salt concentration in the rain water (dS/m).
I is irrigation (mm) over the time duration being considered with C_I being the salt concentration in the irrigation water (dS/m).
U is the upflow from a water table (mm) into the soil volume of interest.
D is the drainage downwards to the water table (mm) which has a salt concentration C_{WT} (dS/m).
R_o is the runoff (mm) from the soil element with C_{Ro} being the salt concentration of the runoff (dS/m).
W_f is the final total water content of the soil element (mm).

The SWAGMAN Destiny model was set up with the following characteristics to indicate the yield outcomes that could result from different irrigation water salinity levels. From this it is possible to see the effects of different weather sequences and to identify the species sensitivity to changing salinity.

SWAGMAN Destiny: Strategic mode with 5 levels of irrigation water EC Griffith weather data, 1965 onwards for 10 years Hanwood loam soil Fluctuating water table with initial EC of 0.6 dS/m Irrigation – critical ET (50mm) driven with 100% effectiveness					
Irrigation water EC (dS/m)	**0.1**	**1**	**2**	**3**	**5**
Maize					
50% probability	8.5	8.0	7.1	6.2	4.9
Range: low	7.6	6.6	5.2	4.4	0
high	9.1	8.8	8.1	7.1	5.1
Vines					
50% probability	17.2	13.5	8.0	4.2	1.5
Range: low	14.8	11.5	6.8	2.7	0
high	20.0	15.1	11.8	8.5	3.0
Summer pasture					
50% probability	18.3	18.2	17.0	13.0	10.5
Range: low	18.2	18.0	14.0	12.0	5.4
high	21.0	18.5	17.5	16.5	12.0

Method used in SWAGMAN Destiny model to represent the variable leaching effectiveness of water additions because of by pass and soil matrix water flow.

Salt movement in the soil profile is dependent upon water movement. In this treatment, salt is assumed to move only by mass flow and effects of diffusion are ignored.

The water balance routine calculates the volume of water moving through each layer in the profile as *Flowd(L)*. The volume of water present in each layer before flow occurs is:

$$Wvol = sw(L) \times Dlayr(L) \quad (1)$$

A critical drainage rate (*Dmax*) from a soil layer is estimated. This critical drainage rate is used to partition drainage water into slow and fast flow components in an approximation of the notion of leaching efficiency.

$$Dmax = (Sat(l) - Dul(L)) \times 0.5 \times Dlayr(L) \quad (2)$$

Flow in excess of *Dmax* is deemed to be *Fast* flow and carry less solute than flow less than *Dmax*. Flow is thus partitioned into *Fast* and *Slow* components. If all flow is less than *Dmax* it is all considered as *Slow*.

$$\begin{aligned} Fast &= Flowd(L) - Dmax \\ Slow &= Flowd(L) - Fast \end{aligned} \quad (3)$$

The solute leached from the layer with slow draining water (*Leach1*) is calculated from the proportion of water that moves from the layer (*Slow/Wvol)*

$$Leach1 = Slow/(Wvol + Flowd(L)) \times Solute(L) \quad (4)$$

For fast draining water the number of volume equivalents (*Voleq*) of water passing through the layer is calculated.

$$Voleq = Fast/Wvol \quad (5)$$

A volume equivalent factor (*Voleq*) is determined which slows relative leaching rates when large volumes of water are passing. A term (*Eqcoeff*) is introduced to account for a reduced rate of equilibration of solute with the fast moving water. Currently we have assigned a value of 1.0 to this term, but acknowledge appropriate values for a range of soils has yet to be determined.

$$Voleq = 1.0/(Voleq + Eqcoeff) \quad (6)$$

The solute leached with fast moving water (*Leach2*) is then calculated and the total leachate from the layer (*Leach*) determined as the sum of *Leach2* and *Leach1*.

$$Leach2 = Fast/(Wvol + Flowd(L)) \times Voleq \times Solute(L) \quad (7)$$

Leachate moved from one layer is added to solute in the layer below in a simple cascading system.