Soil-water and solute movement under precision irrigation – knowledge gaps for managing sustainable root zones.

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Abstract

Precision irrigation involves the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact. Under precision irrigation applications, water and associated solute movement will vary spatially within the root zone and excess water application will not necessarily result in deep drainage and leaching of salt below the root zone. This paper estimates that 10% of the irrigated land area (producing as much as 40% of the total annual revenue from irrigated land) could be adversely affected by root zone salinity resulting from the adoption of precision irrigation within Australia. The cost of increases in root zone salinisation due to inappropriate irrigation management in the Murray and Murrumbidgee Irrigation Areas was estimated at AUD245 m (in 2000/01 dollars) or 13.5% of the revenue from these cropping systems. A review of soil-water and solute movement under precision irrigation systems highlights the gaps in current knowledge including the mismatch between the data required by complex, process-based soil-water or solute simulation models and the data that is easily available from soil survey and routine soil analyses. Other major knowledge gaps identified include the (a) effect of root distribution, surface evaporation and plant transpiration on soil wetted patterns, (b) accuracy and adequacy of using simple mean values of root zone soil salinity levels to estimate the effect of salt on the plant, (c) fate of solutes during a single irrigation and during multiple irrigation cycles, and (d) effect of soil heterogeneity on the distribution of water and solutes in relation to placement of water. Opportunities for research investment are identified 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 soil-water and solute modelling tools and (f) the need to build skills and capacity in soil-water and solute modelling.

Additional keywords: salt, salinity, drainage, drip, trickle

Introduction

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 variable rate irrigation applications controlled by a sensory input (e.g. Evans and Harting, 1999) or efficient application systems (e.g. Smith and Raine, 2000). 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, it would seem more appropriate to define precision irrigation as “the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact”. It also follows that 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).

[Insert Figure 1 about here]

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 (a) the design of the irrigation system so that each plant or area of the field receives the appropriate amount of water (i.e. spatially uniform applications within the management unit if this is the desired objective) and (b) the management of the irrigation system such 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. Solomon, 1993; Burt 1995). 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 (e.g. Raine and Bakker, 1996; Shannon *et al*., 1996; Dalton *et al.*, 2001). 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 damaging drainage 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 (a) maximizing yield and quality of production, (b) reducing water losses below the root zone, and (c) 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.

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) and the spatial scale associated with the variability in the crop water requirements. The feasibility of implementing a precision irrigation system 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.

[Insert Table 1 about here]

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, genetic variation or microclimatic influences. In traditional precision agriculture applications (e.g. spatially varied fertilizer addition) it is also assumed that yield (and profit) at the field scale will be maximised if each plant is supplied with the level of inputs required to achieve a uniform (and presumably field optimized) yield output. However, evidence to support this hypothesis is not readily found in the literature and it seems equally plausible that yield at the field scale will be maximized if the yield of individual plants, or some sub-field scale management unit, is maximized by matching inputs to the production potential at this finer scale.

Soil-water and solute movement issues

Effect of water placement

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 either runs off or drains out of the bottom of the root zone and assists in the leaching of salts out of the root zone. However, two dimensional water flow occurs within the soil where only part of the soil surface is wetted (e.g. furrow, low energy precision application by linear move or centre pivot machines, overlapping drip emitters 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. Under these two and three dimensional soil-water movement conditions excess water application does not necessarily translate into deep drainage and leaching of salt below the root zone. 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). Similarly, salt accumulating along the sub-surface lateral margins of drip wetted areas may be mobilized and drawn back into the root zone by the soil-water potential gradient associated with crop extraction.

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 and showed that the soil-water did not move symmetrically 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 (e.g. Reid and Huck, 1990; Li *et al.*, 2002; Fuentes *et al.* 2003).

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 comparatively uniformly 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 period, during which a crop has been drip irrigated, salt patterns are likely to be highly variable. Seasonal 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. This movement of salt can be influenced by the surface soil topographic configuration. For example, ridges and furrows will have different levels of surface accumulation compared with a flat surface and hence, redistribution within the root zone due to rainfall will vary. Also, over a period of time, irrigating with water of high sodium adsorption ratio and high residual sodium carbonate 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) noted that the analysis and measurement of solute movement and distribution becomes complicated due to uncertainty regarding root distribution and functionality within the root zone. The potential for managing root zone salinity and the application of leaching fractions is also 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 of southern Australia. The electrical conductivity of the applied water was generally low (<0.4 dS/m) and irrigation management typically resulted in 15-20% of the applied water contributing to deep drainage which was assumed to be adequate to maintain 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%).

Case study - estimating the production impacts associated with root zone salinity under precision irrigation

The most likely situations where salt accumulation will occur in a horizontally non-uniform way as the result of spatially variable irrigation applications will be those areas that have controlled irrigation, mostly drip and trickle systems. Of the total area irrigated in Australia (about 2.5 million ha), approximately 250,000 ha (10%) currently uses drip and trickle systems. The replacement capital asset value for these application systems and the irrigated crops is approximately AUD6.2 billion. These systems are almost all used on high return horticultural and vegetable crops with 4 to 5 times the value of production per unit area achieved by other irrigation activities. Hence, the annual value of the production systems that could be affected by root zone salinity under precision irrigation could be up to 40% of the total annual revenue from all irrigated agriculture in Australia.

Crop sensitivity to root zone salinity

Estimating the likely impact of spatially variable salt additions on crop production 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, 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) (Robbins *et al*., 1995) and SWAGMAN Destiny (a point scale, one dimensional, salt and water balance model) (Meyer *et al*., 1996; Khan *et al*., 2003). While neither model was specifically 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 (New South Wales) weather data and conditions with fairly standard agronomic management. Cumulative probability distributions of yield were produced to demonstrate the sensitivity of vines, maize and pasture to the equivalent effect of inefficient leaching caused by two and three dimensional flow (Figure 3). This data demonstrates that the build up in salt levels is greatest in situations of low rainfall and large irrigations with saline water over shallow water tables. Where rainfall is higher the rate of salt accumulation is slower and salt levels may even decline if irrigation amounts are also high. Hence, salt levels, like soil-water, are highly dynamic and depend on local conditions. Similarly, responses 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 2). Note that the response of the crop in any one year is dependant on the model run conditions.

[Insert Figure 3 about here]

[Insert Table 2 about here]

Effect of climate on root zone salinity

Scenarios were set up in Whatif to provide an example of the effect of different rainfall and climate on the root zone salt changes over a year. Root zone salinity was found to increase most under dry conditions (Table 3). For example, where grapes are grown in Loxton (South Australia) on a soil with an initial root zone salinity of 1 dS/m, the application of 1100 mm of irrigation water with a salinity of 0.8 dS/m would increase root zone salinity to 2.3 dS/m in a 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.

[Insert table 3 about here]

Where no irrigation is applied to grapes grown in south-eastern Queensland in an average rainfall year, the root zone salinity would be expected to increase to 1.2 dS/m (Table 3). 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 levels in the root zone would increase by 0.1 dS/m.

Scenario analysis case study

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 Irrigation Areas, the decreased revenue would be directly proportional to the yield reduction (Table 4). However, it should be noted that it is highly unlikely that the impact of the increase in root zone salinity would be immediate as salt levels are likely to take a number of years to reach predicted levels and will not affect all irrigated areas equally.

[Insert table 4 about here]

Modelling soil-water and solute movement

Modelling of precision irrigation systems should involve several approaches conducted concurrently. However, there is currently a mismatch between the data required by complex, process-based simulation models, and the data that is readily available from soil surveys and routine soil analyses. Thus, general soils data is often available at the broader scale, while the input data required for modelling are usually measured or derived from detailed site-specific experiments or monitoring.

There is a range of analytical, quasi-analytical and numerical models currently available to evaluate soil-water and solute movement under irrigation. True 3-D models (e.g. Diersch, 1998) are available for the unsaturated zone but these models are often not required as most situations can be described adequately using a 2-D or radial 2-D model. 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) but have provided good insight into axi-symmetric (Philip, 1984; Philip, 1997; Revol *et al.*, 1997a & b; Cook *et al.*, 2003a) and

2D flow problems (Warrick and Lomen, 1981; 1983). The non-dimensional variables also 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 commonly using finite difference or finite element methods. Finite element methods are mostly used in 2D flow problems. More recently, the method-of-lines has also been used (e.g. Matthews *et al.* 2004a & b; Lee *et al.* 2004; Schiesser, 1991) but is still in development. This latter method coupled with scaling techniques offers promise for making layered soils computationally into a homogenous soil problem.

Comparisons of numerical and analytical models for drip irrigation are not common but recently Cook *et al*. (2003a & b; 2005) did show that they gave similar results apart from where extreme soil properties were 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 (Thorburn *et al*., 2003). 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.

Complex, physically based models are generally data intensive with a high requirement for parameterisation and an increased likelihood of introducing errors. Physically based models may also exhibit numerical instabilities especially with fine-textured soils close to saturation. By comparison, analytical models have less data requirements and are much simpler to implement. However, their applicability is restricted within the underlying assumptions (e.g. use only simple flow domains). The higher demand for data required in physically based models has two compounding adverse impacts. Firstly, there is an increased time and expertise requirement which adds to the cost, and secondly, the increased data requirement adds to uncertainty. The impact on costs is generally well established but the effect of uncertainty is often not well known. 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".

Validation of 2-D simulations of water and salt distributions under drip irrigation may be difficult as 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. For example, 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. Similarly, GIS tools can aid in mapping and classifying the area. Also, land-use and management practices (such as irrigation method and scheduling) 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. However, upscaling from point scale to larger areas require boundary conditions to be described in more detail, which means that outputs from associated surface hydrology, groundwater and crop models needs to be reflected.

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 or parameter optimization so characterisation of soils, crop and management is crucial. 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.

Recommendations for further research

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 could be to ensure that the 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.

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 unit of water and where salt management is seen to be a limiting factor.

There are 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 have been grouped below into (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.
- 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.

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 (a) the application of water at different times of day/night, (b) effect of root extraction, evaporation and transpiration, (c) effect of various cultural practices (eg. mulching) and (d) impact of soil heterogeneity on distribution of water and solutes in relation to placement of drippers.
- 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.
- For any precision irrigation system, what management options does an irrigator actually have? The production and environmental benefits, and economics, of alternative management options need to be evaluated.

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

- What is 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?
- 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.

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:

- Development and extension of existing models 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.

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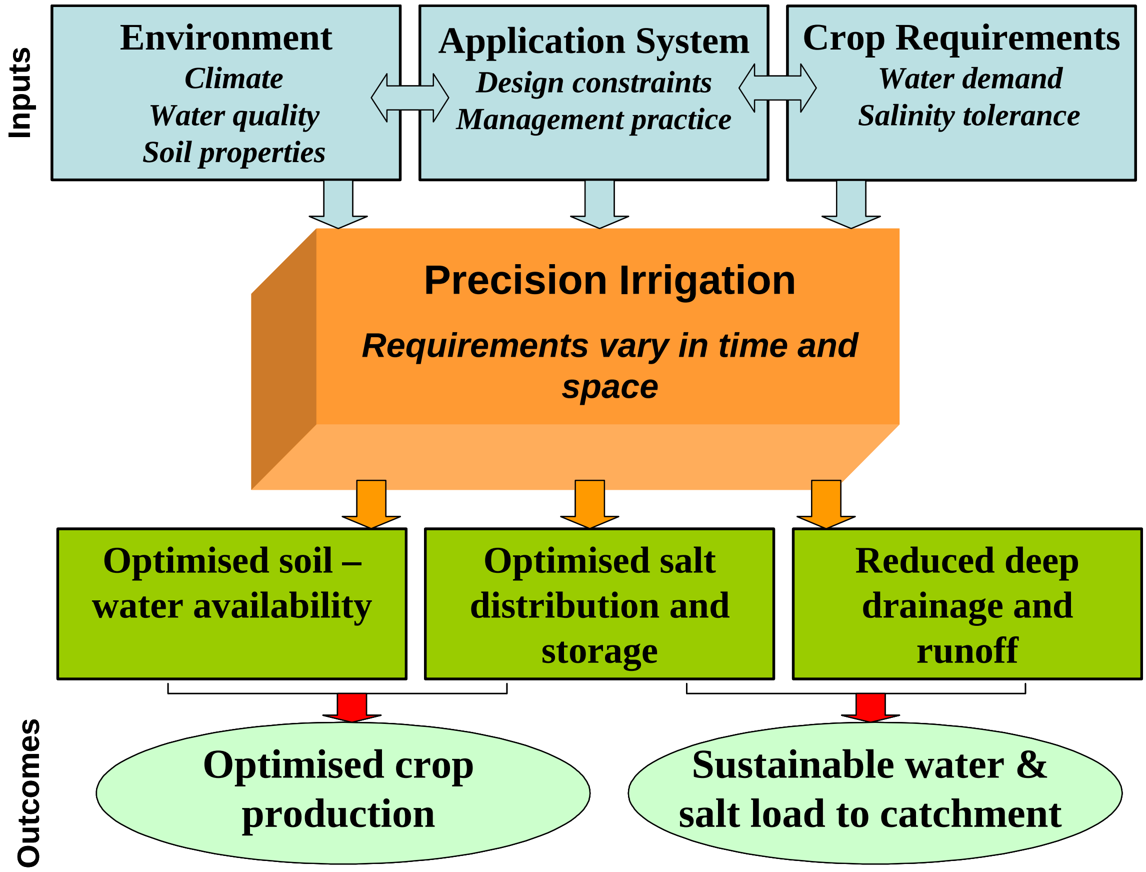

Figure 1. Inputs and outcomes associated with a precision irrigation system

Figure 2. Salt rings formed on soil surface due to evaporation of saline irrigation water from drip irrigation of grapes (Courtesy G Schrale)

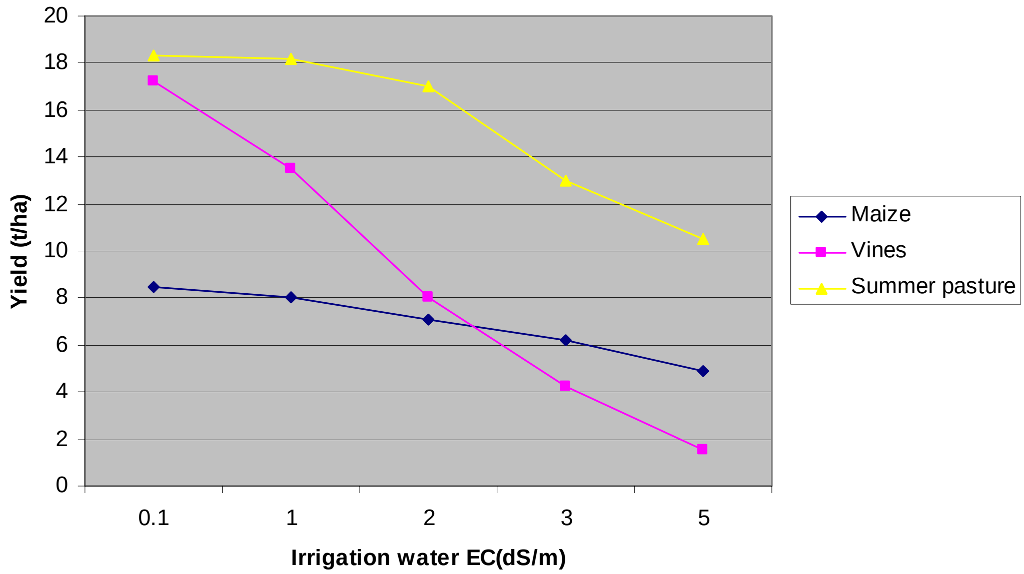

Figure 3. Impact of irrigation water salinity (50% probability) on yield of maize, vines and summer pasture

Table 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

Table 2. 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

Table 3. 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

Table 4. 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 costs)

Enterprise	Value unaffected by salinity impact	Value if affected by salinity impact	Reduction in revenue	Reduction in revenue (%)
Vines	AUD832 m	AUD688 m	AUD144 m	17.4
Summer pastures used for dairy	AUD854 m	AUD765 m	AUD89 m	10.4
Maize	AUD125 m	AUD113 m	AUD12 m	9.4
Total Impact	**AUD1811 m**	**AUD1566 m**	**AUD245 m**	**13.5**