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Subsurface Drainage System Design and Management in Irrigated Agriculture:
Best Management Practices for Reducing Drainage Volume and Salt Load

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FOREWORD

The medium to long-term viability of irrigated areas in Australia is closely linked with management of high water tables. Large areas of subsurface drainage have been installed to combat the problems of waterlogging and salinity associated with high watertables. These have generally worked effectively, however there are increasing restrictions on the export of salt from these drainage systems and the availability of funds for new drainage schemes is becoming limited. The existing design and management of subsurface drainage varies widely according to local conditions of cropping, hydrogeology, and administrative framework.

Until this manual, there have been no Best Management Practices for the design and management of subsurface drainage systems that could be applied across varying settings. CSIRO Land and Water led an National Program for Irrigation Research and Development project ‘Best management practices for sub-surface drainage design and management’ which with many collaborators (listed below) reviewed drainage practices across Australia, research in Australia and abroad, and conducted a workshop on likely future restrictions to subsurface drainage.

The biophysical and other technical information obtained was used to define a robust set of principles that define the overall framework for the use of subsurface drainage and to develop a set of generalised Best Management Practices for the design and management of subsurface drainage systems. It is hoped that the information provided in this manual will improve the performance of subsurface drainage and minimise future off site effects.

This manual is divided into two parts, Part 1 includes the background issues, principles and BMP’s, Part 2 provides detailed technical supporting information that can be used by those people requiring more detail for BMP development.

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Introduction

Aim and scope of the BMP’s

Aim
The aim of this study was to provide best management practices (BMP’s) to address the issues that need to be considered for the effective and environmentally safe implementation of subsurface drainage (SSD) in irrigated agriculture in Australia. They do not encompass social, political, or economic issues associated with SSD, as these are generally specific to individual situations and are more appropriately handled by the communities concerned, their land and water management planning groups, and local authorities.

Generalised BMP’s
This manual describes generalised Best Management Practices (BMP’s) for the effective design and management of subsurface drainage (SSD). They are specific only in that they are developed for irrigated conditions rather than for rainfed agriculture. It is envisaged that the detailed BMP’s required at a regional or local level will be developed by local people.

Principles and technical information
The BMP’s are underpinned by a set of principles that provide a general overarching philosophy for the use of SSD and are also supported by technical information from research.

Design and installation procedures
It is not the intention of this manual to provide detailed design and construction guidelines for SSD, nor to document the pros and cons of different types of drainage systems. These issues are highly complex depending upon the soils, geology, land use, and irrigation management. These factors vary widely in areas where SSD is used. For those requiring detailed design and installation procedures the following texts are recommended:
Introduction

- **Agricultural Drainage.** (1999). R.W. Skaggs. and J. Van Schilfgaarde (eds.), Agronomy No. 38, ASA CSSA SSSA, Madison Wisconsin,

Scope
The main areas of focus for the BMP’s are; adequately assessing the drainage objective, proper irrigation and drainage management, and hence minimising salt loads.. This manual should be used to supplement the planning that is required to implement a drainage system design after it has been determined that a drainage system is needed. The guiding principles should be used during the determination of the need for drainage.

For more generalised information regarding drainage water quality and its management the following text is recommended:


These BMP’s were developed by the authors, in consultation with a broad group of stakeholders. It is not intended that these BMP’s be onerous or set specific levels of attainment, rather that a process of improvement be established within a broad framework.

Audience
The audience for these BMP’s is land and water management planning groups, catchment management authorities, resource and technical staff in government organisations and irrigation companies, engineering and planning consultants.
Introduction

Objectives

- Provide guiding principles to be considered when implementing subsurface drainage design and management;
- Provide generalised basic best management practices for the design, operation, and management of subsurface drainage systems;
- Review the literature pertaining to the integrated management of drainage and irrigation systems and determine how this affects best management practices for subsurface drainage design and management.

Using the manual

This manual is intended to supplement the planning required to implement a drainage system design after it is determined that drainage is needed. The manual is divided into two parts:

- Part 1 includes the background issues, principles and BMP’s
- Part 2 provides technical supporting information that can be used by those people requiring more detail for BMP development.

Part 1

- Chapter 1 presents and discusses the issues surrounding subsurface drainage design and management and the disposal of saline drainage water.
- Chapter 2 present the current practices and future requirements
- Chapter 3 provides the Principles for SSD and generalised BMP’s
- Chapter 4 provides some example applications of BMP’s.

Part 2

- Chapters 1-6 provide reference material regarding water management and quality and drainage design. This material is summarised at the end of each chapter to provide information that can be used in developing specific BMP’s.
- Chapter 7 is a detailed analysis of current drainage practices in Australia.
- Chapter 8 is a case study of improved irrigation and drainage management, which compares specific design and management practices and their impact on drainage effectiveness and salt load.
PART 1.
Chapter 1

Subsurface drainage issues

1.1 Development of drainage problems

In Australia, deep percolation from poor irrigation, together with the leakage of water from the associated network of water distribution and drainage channels, has caused watertables to rise under many irrigated areas. The pre-land clearing watertable depth was 10-30m. This was reduced at rates of 0.1 -1m per year, until a new equilibrium position for the ground water became established. This new equilibrium is one where the watertable fluctuates from the soil surface to a depth of about 3 m. A significant part of all irrigation areas in Australia are currently either in this shallow watertable equilibrium condition or approaching it. Irrigation areas in south eastern Australia, particularly in the Murray Darling Basin (MDB), have 60% or more of their land area in this shallow water table regime. It is likely that most other irrigation areas in Australia will develop shallow watertable conditions in the future.

Elevated watertables result in mobilisation of the stored salt and when this saline watertable comes close to the soil surface, soil salinisation and waterlogging result, with detrimental effects on agricultural production. Raised watertable levels can also increase hydraulic gradients between the groundwater and surface water resources, leading to increased movement of salt to drains, streams, rivers and wetlands.

Subsurface drainage systems have been installed in many areas to treat waterlogging and salinization resulting from these shallow watertables. Subsurface drainage is also required where more saline irrigation water is used. With increasing irrigation water salinity the leaching requirement is increased, which often cannot be met by natural drainage. In many areas the irrigation water salinity is gradually increasing as the upstream catchments supplying water become more saline.

For productive irrigated agriculture to continue, adequate leaching and drainage is necessary to
remove salt left in the root zone after crop transpiration of irrigation water (Hoffman, 1985). The natural drainage capacity of the soil and the groundwater system in irrigation areas is often insufficient to remove water in excess of crop requirements and engineered drains are necessary to prevent waterlogging and salinisation of the crop root zone (Tanji, 1990). Subsurface drainage acts to remove water from the soil profile and allow leaching of salts from the crop root zone. Drainage can also be used to alleviate high watertables under urban areas and intercept groundwater flow to surface features to protect valuable infrastructure such as pipes and roads.

Subsurface drainage systems are usually installed on high value crops which are sensitive to waterlogging and salinity, such as perennial horticulture (grapevines, citrus, fruit trees), cotton, sugar cane, and perennial pasture for dairying.

In Australia, often subsurface drainage has been primarily installed for waterlogging control. Many waterlogging problems can be reduced by proper surface drainage. Surface drainage can be applied at the farm scale by laser leveling paddocks to an adequate and even grade to shed water to a system of drains that remove the water from the farm. These require a regional drainage system to remove the water from the area. The provision of a surface drainage network and on farm works have acted to reduce the effects of waterlogging in a number of areas, e.g. Shepparton Irrigation Region, Murray irrigation areas. Surface drainage can also be provided in the paddock by growing the crop on beds or hills. In this case the furrow acts as a surface drain and keeps the top of the root zone aerated. The importance of surface drainage should not be neglected when considering the use of subsurface drainage. In most cases improving surface drainage should be a precursor to subsurface drainage.

Subsurface drainage practices to control waterlogging and salinisation in irrigated areas of Australia vary considerably in design and method. Horizontal pipe drains are often used and where suitable aquifers are present, pumping from tube wells or spearpoints is also undertaken to control watertables and soil salinity.

Overall there are about 35,000 ha of horizontal (tile) drainage and about 64,000 ha protected
Subsurface drainage issues

by vertical drainage (tube wells). It has also been estimated that a further 65,000 ha of all types of drainage may be required in the next 20 years in Australia (Christen, data developed by ANCID for ICID publication on status of world drainage and future needs).

1.2 Drainage disposal

As the salinisation of irrigated areas becomes increasingly serious and widespread, a growing awareness of the link between local, catchment and regional salinity issues has led to a re-evaluation of salinity management strategies. In particular, linkages have been made between the use of engineered works to reduce and manage the impact of salinisation on local irrigated farmland, and the adverse effects of drainage disposal on downstream water resources. Such management concerns highlight the need to account for local catchment and regional salinity issues in any assessment of the costs and benefits of subsurface drainage for irrigated agriculture.

Changing political and community attitudes has increased pressure to minimise the impacts of drainage from irrigation areas on downstream users and the riverine environment. As a consequence, drainage disposal into a river is no longer seen as an overall solution to the problems of waterlogging and salinisation of inland irrigated areas. Where irrigation areas are close to the sea the impact of river disposal is reduced, as there are fewer downstream users and larger flows for dilution of the drainage water. In all cases the costs of rising river salinity in downstream areas need to be balanced against the benefits of upstream irrigation drainage disposal into the river system.

Use of drainage water for irrigation and evaporation basins are two disposal mechanisms being used to help minimise the impact of saline drainage water disposal on river systems. Reuse of drainage water by mixing with good quality water for irrigation is widely practiced, especially in areas where the drainage water salinity is low. However, without disposal this will inevitably increase the salt stored in the soil and groundwater.

Land disposal of drainage water to evaporation basins has recently become more prevalent
Subsurface drainage issues

(Jolly et al. 2000). Regional evaporation basins were commonly used in the past, however, the use of local-scale community and on-farm basins is increasing. Evaporation basins are being used for the disposal of drainage water from 40,000 ha in the Wakool area (into a 2100 ha basin) and the drainage water from perennial horticulture along the lower Murray and in new horticulture areas in the Murrumbidgee Irrigation Area. Other options such as disposal to woodlots and serial biological concentration are being considered and researched (Heath et al. 1993, Blackwell, et al., 2000).

1.3 Aquifer salinisation

Where drainage is undertaken by pumping of aquifers, typically by tubewell or spearpoint systems there is a risk of aquifer salinisation. This is especially the case where small aquifers surrounded by salt laden aquitards (e.g. clays) are over pumped. This causes the migration of salts from the aquitard into the aquifer.

1.4 Reduced irrigation efficiency

This occurs due to watertables being drawn down to a greater depth than is actually required to maintain crop growth production. This removes water from the soil profile that would otherwise have been used by the crop. This effect is often called over drainage. There is an optimum depth to the watertable for most crops, above which the crop is affected by waterlogging and below which the soil is over dry.
Chapter 2

Current practice and future requirements

2.1. Background

This project reviewed current SSD practice in all irrigation areas of Australia, see Christen and Hornbuckle (2001). A detailed analysis of the current practice in terms of drainage design and management is given in Part 2 Chapter 7. The following section provides a brief summary of the findings.

2.2. Drainage problems

Drainage problems were reported as usually being the result of over irrigation leading to shallow watertables and hence waterlogging and secondary salinisation. Subsurface drainage has been a remedy for these conditions both in Australia and throughout the world. It is not clear for any of the regions whether improved irrigation management could have avoided the problem. However, since the 1980’s more emphasis has been placed on improved irrigation practices in Australia by the developing Land and Water Management Plans that focus on sustainable production through the development of land management plans and the improvement of irrigation efficiency.

Subsurface drainage design and management practices across irrigation areas in Australia are highly varied. Subsurface drainage has been used to overcome waterlogging and salinity along with other methods such as surface drainage, improved irrigation practices, and changes in land use management practices. Since these factors are inter-related, it is important to consider them in an integrated manner, when aiming to develop sustainable irrigation systems.
2.3 Irrigation practice and irrigation water salinity

Irrigation water use varies greatly from region to region depending upon the cropping and climate. Most regions report improved water use efficiency in recent times, which is vital to the reduction of drainage problems (waterlogging and salination) and to making subsurface drainage implementation more affordable.

Surface irrigation water salinity is very low (EC < 0.4 dS/m) in most regions. Thus irrigation induced salinity is generally due to shallow saline watertables rather than the application of saline irrigation water. However, the South West Irrigation Area, Sunraysia, Riverland, Boort and Campaspe are areas that can have high salinity irrigation water. There is also a general rising salinity trend in water supplied to most irrigation areas due to gradual salinisation of the upland catchments where water is harvested and due to saline surface and groundwater inflows to rivers.

2.4 Drainage practice and design criteria

In perennial horticulture waterlogging is a significant problem and drainage implemented for watertable control has also controlled soil salinisation. Pasture has also been drained for watertable control and in some cases for salinity control. In the Shepparton region, pasture has not been drained to a specific watertable depth criteria, rather pumped drainage is continued until a volume of water and salt is removed equalling a leaching fraction based on the volume and salinity of applied water. In some areas such as the Burdekin and Macalister it may be worth reconsidering whether the stated aim of watertable depths > 3 m and >2 m respectively are necessary for those cropping systems or whether lower watertable control criteria (water tables depths > 1.2 m) would be adequate to protect these areas.

The drainage design criteria for drainage systems in perennial horticulture, (especially in the Murrumbidgee, Riverland, and Sunraysia areas) is a target watertable depth of 1 m within 7 days after irrigation. This was developed to control very shallow watertables (< 1 m) that resulted mostly after irrigation but also after rainfall. This has resulted in drainage rates of 50-
200 mm/year. However, most regions report declines in drainage water volumes in recent years that may be attributed to climatic conditions and improved irrigation efficiency.

Drainage design criteria also need to be revisited considering the move in perennial horticulture to pressurized irrigation systems and to the improved standards of irrigation management. Very shallow watertables are now much less common in the horticultural areas. Design criteria developed based on today’s improved standards of irrigation design and management should be targeted more towards salinity control rather than waterlogging and should result in lower cost drainage systems with lower drainage discharges. In the extreme situation of well managed drip irrigation, it may be that the natural groundwater system can provide adequate natural drainage. However, it may be useful to still provide some drainage to provide protection during a very wet winter. This would very much depend upon the crop sensitivity to waterlogging and the resulting economic losses.

2.5 Drainage management

Many areas are now reviewing the management of all subsurface drainage systems with a view to reducing drainage volumes due to disposal pressures and balancing groundwater extraction for resource use against the basic aim of long term salinity control. There is virtually no managed operation of horizontal drainage systems. Research by Christen and Skehan (2001) has shown that management of horizontal drains in the Murrumbidgee Irrigation Area can reduce drainage water salinity, making reuse more feasible and disposal easier because of reduced salinity loads and volumes.

Integrating subsurface drainage management with irrigation management at a specific location appears to be in its infancy requiring more research and a change in perspective. However, work in California (as summarised by Ayars et al., 1999) has shown that the integrated management of irrigation and drainage systems will reduce the total drainage volume discharged along with the total salt mass.
2.6 Conclusions and future requirements

Overall it was concluded that:

- New drainage design criteria are required that provide adequate protection for crops (with clear delineation of waterlogging and salinity control objectives) whilst minimising drain water salinity and volume.

- Saline drainage water disposal is now a key issue, which may severely restrict future implementation of subsurface drainage in irrigated agriculture. This may then be the greatest constraint to the sustainability of many irrigated areas.

The key requirements that SSD will have to meet into the future were identified at a national workshop. The participants listed the main requirements for future SSD (applying to existing and new developments) as:

- No disposal of salt off-site, or minimise / eliminate off-site impacts.
- Maintain productivity and land / water resources in a sustainable manner.
- Protection of the environment, infrastructure, surface water quality, and dryland areas.
- Use of drainage for removal of pollutants / filter pollutants.
Chapter 3

Best management practices

3.1 The need for Best Management Practices

The above review has highlighted a need for a change with regard to subsurface drainage design and hence a set of BMP’s to assist with this change. It is clear that subsurface drainage should no longer be used as a sole cure for problems created by inefficient irrigation practices that waste the irrigation water resource and increase downstream salt transport more than is necessary due to mining of salt stored deep in the soil profile. New drainage systems should be managed to treat the watertable as a potential resource, and assist in making irrigation practices more efficient by holding water in the profile for plant use. In the past, subsurface drainage made irrigation less efficient by quickly removing water from the profile before the plant had an opportunity to use any water from the shallow ground water, as the plant root zone dries out after an irrigation or rainfall event.

This requires changes in the way drainage systems are designed and managed. Subsurface drainage designs should be such that the drainage system mobilises as little salt stored below the root zone as possible, which generally means designing and managing the drainage system to drain as little as possible considering of the extent of the root zone and the crop. There should also be structures and feedback mechanisms that allow subsurface drainage systems to be properly managed.

From this review it can be seen that drainage design criteria for many regions should be reassessed in the light of more recent changes in land use and irrigation management. Also the operation of existing subsurface drainage systems needs to be reviewed to establish the management criteria for drainage and to modify operational procedures for minimising salt and water mobilisation.

The review and workshop identified the requirement for the establishment of BMP’s for the design and management of subsurface drainage systems in irrigated areas of Australia. This
The manual is intended to assist in this process by providing generalised principles and BMP’s that can be used to develop more detailed regional and local BMP’s.

3.2 What is a best management practice?

The BMP concept adopted for this manual is to allow development of site-specific approaches, which may be prompted or initiated by legislative or other policy action. The manual outlines alternative methods that can be developed into site specific BMP’s for implementation as funds and other conditions warrant. BMP’s are methods, structures, or practices designed to protect our land, air, and water resources (Phene, et al., 1993).

A BMP may be defined as the use of methods, devices, equipment, or facilities to enhance the sustainability of irrigated agriculture that meet either of the following criteria (Phene et al. 1993):

- Practices that are already established and are generally accepted among agricultural water users as those that might result in one or more of the following: a more efficient use of water, a conservation of water, or a reduction in water pollution; or

- A practice for which sufficient data are available from existing research and demonstration projects to indicate that significant water conservation or water pollution reduction benefits are achievable. Also, the practice is technically and economically reasonable and not environmentally or socially unacceptable, and not otherwise unreasonable for most agricultural water users to carry out.

The aforementioned criteria were developed for water conservation and pollution control related to the implementation of improved irrigation management. However, they also apply to improved drainage system design and management.

The development of best management practices to minimize water quality degradation in irrigated agriculture has been identified as one of the top priorities related to irrigation and drainage system management in the world (Pereira, et al. 1996). This manual proposes
generalised best management practices for subsurface drainage in irrigated agriculture that will be the basis for development of regional or local standards and specifications for site specific drainage system design and implementation. While, the focus is on conditions in irrigated agriculture in Australia, these practices should also be applicable in irrigated areas throughout the world.

3.3 Guiding principles

The following principles have been developed to provide guidance in the decision making process that precedes the implementation of SSD design and construction. The intention is to define desirable objectives for SSD design and management. They are general concepts that provide direction in the investigations associated with and the design and management of a SSD system. They should apply in most situations, however, it is recognized that there are always tradeoffs in design and construction, so consideration will need to be made as to which principles are applicable and most important.

3.2.1 Principles

No. 1 - Resource management

Subsurface drainage should only be used after it has been determined that sustainable production cannot be achieved solely by economically reducing excess deep percolation from irrigation and rainfall through improved irrigation efficiency, agronomic practices and surface drainage.

SSD should not be used as the sole treatment for poor irrigation system design and management. SSD is expensive to construct and operate, that is an additional cost to production. The drainage required should be minimised by improving irrigation efficiency and agronomic practices as much as is economically practical. As such, SSD systems should be designed for a high level of irrigation efficiency. In some areas it might to possible for natural drainage to remove the excess water from irrigation and rainfall when improved irrigation
practices are implemented.

**No. 2 – Site specific design**

Subsurface drainage should be targeted at protecting individual crops and rotations and thus should be based on site specific conditions.

This principle should ensure that the system is adequately designed but not over-designed. The drainage requirement is a function of the total water application (irrigation + rainfall) above the crop water requirement, average water quality, cropping pattern, plant salt tolerance, soil salinity, soil oxygen status with time. These are all highly variable factors and thus the drainage requirement should be based on site specific conditions rather than regional averages or rules of thumb.

An over-designed system will be more expensive to construct and will generate more drainage water requiring disposal. Past drainage systems designs have used regional drainage coefficients that do not account for site specific variations in soils, crops, and irrigation practice. This has generally led to excessive drainage volumes. Where regional designs are used then management to regulate the drainage response to an appropriate level is essential.

Good irrigation practice should minimise irrigation waterlogging and in arid/semiarid environments rainfall induced waterlogging should be infrequent. Other management options can be used to minimize waterlogging e.g. use of beds, cover crops, crop choice, irrigation timing, and improved soil structure. However, the need to protect very waterlogging sensitive crops, e.g. peaches, should not be neglected. Consideration needs to be given to the consequences of extended periods of high rainfall.
No. 3 - Salt mobilisation

In arid areas, subsurface drainage should be designed for long term salinity control in the crop root zone assuming good irrigation practices while reducing mobilization of salt from below the root zone.

Most design practices for subsurface drainage have been based on the need to achieve a specific watertable depth that ensured minimal movement of salt into the crop root zone from shallow ground water, i.e. maintaining a ‘deep’ watertable. As a result, drainage is often from depths well below the root zone, removing salt from deep within the soil profile. Research has shown that reducing the depth of the drainage system installation will significantly reduce the salt load in the drainage water. However, shallower drainage should not be done at the expense of maintaining a well aerated root zone. The optimal removal of salt is when as much salt is removed from the root zone as is added with irrigation water and from upflow of shallow saline groundwater. Removing salt from deep within the soil profile does not directly assist in maintaining a rootzone salt balance.

It may appear that shallower drain system installation will result in higher construction costs due to closer lateral spacings. However, this may not be the case as improved water management with reduced disposal volumes should offset this.

As subsurface drainage will be focused on salinity control, the avoidance of waterlogging by good surface drainage and irrigation management is very important.

No. 4 – Management

Drainage systems should include physical components for monitoring and management, allowing an integrated water management program that includes the irrigation system design and management.

Irrigation and drainage systems should be managed as an integrated water management system and be designed on that basis. To achieve this goal, management and monitoring structures will have to be included in the design and installation of both the irrigation and drainage systems. Monitoring should provide adequate feedback for proper management. Research has
shown that drainage water volumes and irrigation depths can be reduced as a result of integrated management. Monitoring should include depth to the water table at critical locations and applied and discharged water (surface and subsurface).

No. 5 - Drainage Water Disposal

Drainage system design and management must include acceptable means for disposal of drainage water.

Opportunities for re-use of both surface run-off and sub-surface drainage water should be carefully considered, especially if the water is not too saline. Re-use of this water by mixing with groundwater (Bethune et al., 1997) or surface water supplies should be carefully evaluated.

Serial biological concentration schemes could be considered (Heath et al., 1993) prior to basin disposal for water containing higher levels of salt concentration and any other ions that are not suitable for irrigation. Guidelines for the siting, design and management of evaporation basins have been developed for the Riverine plain, (Jolly et al., 2000). These provide information on the technical, environmental and economic aspects of evaporation basins.

No 6. – Responsibility

Subsurface drainage system owners are responsible for the maintenance of the on-farm drainage system and the safe management of the drainage water generated by their system.

Drainage is a necessary part of irrigated agriculture and is needed at some level to sustain agricultural production. However, this should not be at the expense of the environment outside of the enterprise or other agricultural enterprises in the area. Disposal of drainage water to river systems has been and continues to be common practice. This is usually under agreed conditions of salt concentration and loads. Nevertheless efforts should be made to minimise the impact of drainage disposal, principally by reducing drainage volumes and salt loads.
3.4 Best management practices

The following BMP’s were developed based on the principles described in the previous section and are provided to assist in the design of drainage systems for irrigated agriculture that will support:

- Efficient water management
- Irrigation water savings
- Reduced salt discharge

The process of SSD follows a number of sequential steps after the need for drainage has been determined. The type of drainage system is selected and then design parameters determined. This is followed by determination of the management practices to be applied to the system.

BMP’s for each of these steps are outlined below, only those that are applicable to the local conditions should be implemented.

3.4.1 Drainage system selection

Selection of the type of drainage system, e.g. vertical, deep tiles, shallow tiles, mole drains, is important as different types of subsurface drainage systems provide different responses in terms of watertable position, soil salinity control, drainage volumes, and water qualities.

**System selection criteria BMP’s:**

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<td>Determine the objectives of the SSD system.</td>
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This needs to be clearly stated in terms of the primary purpose, either waterlogging control, root zone salinity control or reclamation of saline land. While most systems are suitable to some degree for all these, it is the design and management that will control the effectiveness for a specific purpose.
No. 2
Assess limits of area requiring SSD, regional hydrogeology and land uses.

This determines the likely rate and salinity of drainage induced from outside the specific area of interest by any drainage system and raises issues of regional versus local implementation.

No. 3
For 1 and 2 local or site specific conditions must be used.

These include, water quality (both irrigation and ground water), potential for drainage water reuse, disposal requirements, crops and rotations, regional ground water flow, and soil types and lithology.

3.4.2 Drainage design

The drainage system design should be part of an integrated water management system that includes the irrigation system and its management. The criteria used for drainage design are watertable depth at a specific time or critical crop growth stage, rate of watertable lowering after inundation of the root zone, long term leaching fraction, and/or combinations of the aforementioned.

**Design BMP’s :**

No. 1
Develop drainage design criteria using minimum leaching fractions, minimum rates of watertable draw down, and minimum watertable depths.

This will provide the minimum appropriate design discharges. These design criteria should be based on local or site specific crop rotations, irrigation system type - design and management, irrigation water quality and leaching fraction.
The design of the system should incorporate a temporal analysis of deep percolation from the selected irrigation system for the critical crop, assuming best irrigation management practices.

This is important, as deep percolation losses are not evenly distributed in time. Also for some waterlogging sensitive crops the impact of heavy rainfall periods need to be considered, assuming good surface drainage and using local rainfall data. The effects of regional sources of water to the drainage system also need to be considered.

The system design should include components for controlling the watertable position and drainage system discharge.

This will allow the system to be run for conditions outside the specific design parameters, e.g. changed crop, lower rainfall.

New drainage systems should be designed into management units that relate to the irrigation system layout.

This allows better integration of irrigation and drainage system management.

Drainage system design must include effluent management and monitoring plans based on identified salt, nutrient, and other constituents of concern in the drainage water.

The management and monitoring should include short and long term measures depending on changes in internal/external conditions.

Drainage systems designed for reclamation of saline areas should also consider future management after the initial reclamation period.
3.4.3 Drainage system management

Historically, drainage systems were relatively uncontrolled systems designed to manage waterlogging and root zone salinity for a set of design conditions. Actual conditions vary with time, e.g. change in crop, lower rain, new irrigation system, and this may reduce the drainage requirement and so there is the opportunity to reduce drainage. This can be done by actively managing the drainage system.

**Management BMP’s:**

**No. 1**

Discharge should be managed to prevent flow other than that needed to maintain the desired watertable position or leaching fraction.

This will help to improve irrigation efficiency and reduce nutrient loss.

**No. 2**

Existing drainage systems should be retrofitted to include management structures and be formed into management units.

These structures should not reduce the overall capacity of the system, which may be required during periods of high rainfall.

**No. 3**

The system should be controlled to allow crops to take advantage of the shallow watertable water resource.

Implementation will depend upon the crop rooting depth and salt tolerance, shallow groundwater quality and soil type. Care needs to be taken to avoid root zone waterlogging and salinisation.
Chapter 4

Example applications

The following examples are applications of the Principles and generalised BMP's for drainage designs using both regional and specific conditions.

4.1 Developing regional BMP's for subsurface drainage in the MIA

4.1.1 Aim

To provide improved subsurface drainage system design and management guidelines for the MIA L&WMP, to promote and ensure the sustainability of high value cropping in the area, without causing unacceptable effects to land and water resources as a result of disposal of the drainage water.

4.1.2 Background

The crops requiring drainage protection in the MIA are perennial horticulture, mostly grapevines and citrus. These crops are grown on duplex soils of loams over light to medium clays. The hydraulic conductivity of these soils is in the range of 0.1-0.5 m/day. There are very few transmissive aquifers in these areas. Watertables in the region are generally 1 – 2 m from the surface, the salinity of the shallow ground water ranges from EC of 4-15 dS/m. These horticultural areas interface with broad acre crops that can impact upon watertables in the horticultural areas.

Irrigation has traditionally been flood, moving to controlled furrow over the last 15 years and over the last 5 years many farms have been moving to drip/microspray irrigation. Irrigation water quality has an EC of 0.1-0.3 dS/m. Rainfall of around 400 mm is evenly distributed throughout the year.
Part 1

Example applications

The drainage objective for perennial horticulture in the past has been for waterlogging control due to poor irrigation practice compounded by rainfall. However, with improved water management practices there is less requirement for waterlogging control from drainage and controlling root zone salinisation is now of greater importance. To ensure that waterlogging is minimised the on farm surface drainage should be maintained to a high standard.

Regulations within the MIA prevent any off-farm disposal of subsurface drainage water for new drainage systems. There are at present no opportunities for community level drainage projects or drainage disposal systems.

4.1.3 Design and management guidelines

Drainage system selection

On consideration of the local geology, land use, and farm level drainage water disposal requirements, implementation of horizontal drainage system is most appropriate.

The farm must also have a high standard of surface drainage to minimise waterlogging after irrigation and rainfall.

System design

Example MIA BMP No. 1

Subsurface drainage will be designed on the basis of a high level of irrigation efficiency.

Existing on-farm irrigation systems and practices should be evaluated to determine the opportunities to improve water management. Improvements in water management should be implemented and evaluated prior to completing drainage system design. Future cropping and changes in irrigation systems should be evaluated, i.e. switching from broad acre to horticultural crops, switching from surface to drip systems. Improving irrigation and
agronomic practice will minimise the volume of subsurface drainage required and hence minimise installation cost, disposal cost, and ensure the best use of water as a resource.

**Example MIA BMP No.2**

Subsurface drainage will be targeted primarily at protecting crops from long term salinisation problems.

The drainage requirement should be based upon maintaining a long term salt balance in the root zone. This will be a function of the crop, irrigation water application, rainfall, average water quality, soil salinity, depth to water table, and groundwater salinity. The drainage requirement will be explicitly stated and explained for each farm design. Although the aim is for salinity control only, consideration needs to be given to waterlogging control for sensitive crops such as stonefruit.

Based on past experience in the MIA, the subsurface drainage requirement will result in a drainage coefficient not more than 2.5 mm/day at 0.3m watertable depth. Designs resulting in higher drainage coefficients will need to be justified on the basis of crop susceptibility to waterlogging and salinity. If the proposed drainage system is expected to intercept large drainage volumes from regional sources e.g. surrounding land use, irrigation channels, the management and design will need to describe these outside sources and quantify the potential affects.

The drainage design depth and spacing should be based upon a transient analysis e.g. Glover-Dumm (US Department of Interior, 1993). This type of design uses a specified minimum watertable depth and is based on the intermittent deep percolation from rainfall and irrigation and thus reflects the hydrologic conditions in irrigated agriculture. The watertable depth will vary over the year but should not exceed the minimum depth.

Site investigations should include assessment of soil saturated hydraulic conductivity, depth to impermeable layer, and groundwater quality. Adjacent operating drainage systems are good sources of data at this step.
Example MIA BMP No. 3
Subsurface drainage should primarily be designed for long term salinity control in the crop root zone only. It should minimize mobilization of salt from below root zone.

The optimal removal of salt is when as much salt is removed from the root zone as is added with irrigation water and movement up from shallow saline ground water. The exception to this is a situation where drainage is being used for reclamation prior to production.

Example design factors to reduce salt mobilisation:

- Drainage design must consider salt loads in the drainage water. Where significant salt is stored in the subsoil shallower drainage is less likely to mine the stored salt and so more likely to achieve a balance between applied and drained salt loads. This will increase the total length of drains required. However, costs of pipe and laying and disposal costs will be reduced. Alternatively reducing the salt load may be achieved by vertical drainage or widely spaced horizontal drains being used for targeted salinity control, whilst relying on very shallow drains (e.g. mole drains), beds or hills to provide waterlogging control.

- Drainage systems should be designed, where possible, to operate under the irrigation blocks in order that the drainage system can be managed in an integrated manner with the irrigation system.

- Pipe and pump sizes will be designed according to best practices of drainage design.

- At the junction of drainage management units, sumps will be installed together with valves or weirs so that watertable control is possible.

- Main drains and sumps that are installed at depth should be sealed to prevent entry of saline water.
System Management

Example MIA BMP No. 4
Drainage system design should include components for monitoring and management.

Drainage systems will be accompanied by a management plan that includes target watertable depths, periods when drainage system operation will or will not be permitted.

Examples of management alternatives include:

- Drainage should not usually be allowed to occur during an irrigation event unless the water table is controlled at a fixed depth. This is generally true for fields irrigated with surface irrigation systems that have excessive deep percolation losses, but it might also apply to other systems that are poorly designed and managed.

- Drainage systems should be controlled to restrict flow and still maintain watertables safely below the root zone, not left uncontrolled where water tables may fall much deeper than required.

- The default drainage system management should be drains turned off not on. Drains should normally be kept closed or turned off and then turned on as needed, rather than being left running at all times without considering whether drainage is necessary.

NOTE: When the drains are closed the watertable level at the lowest part of the system should be monitored to ensure that it does not rise to unacceptable levels. This is a problem on sloping land. In this situation the drainage rate may be reduced but drainage not stopped altogether.
Drainage system design must include acceptable means of disposal of drainage water.

In accordance with the MIA L&WMP, the drainage system design needs to include an acceptable means of water disposal. When assessing drainage disposal it is important that the drainage water does not leave the farm either above or below ground as a result of water storage in an engineered structure, and the disposal of the drainage water does not present a risk of soil salinization. In order to be sustainable and minimise risk of salt migrating off farm in the groundwater, the drainage disposal should occur within the drained area. This provides a method of containing the salt.

The MIA L&WMP provides three options for drainage disposal:

a) reuse to the crop on the drained area,

b) reuse on a woodlot/saltbush plantation,

c) disposal to an evaporation basin.

Under NO circumstances will subsurface drainage water be disposed of off farm. In the MIA all subsurface drainage must be kept on farm even during wet weather periods. The disposal options are outlined below:

a) **Reuse to the crop**

   - Reuse of the drainage water onto the drained area will be allowed if this can be shown to be sustainable. This will require an assessment of the groundwater quality including as a minimum salinity, boron, sodium, calcium and magnesium concentrations. In most cases this water will be mixed with fresh irrigation water for distribution. The mechanism by which this can occur will need to be detailed. The management of the drainage water between irrigations and during the non irrigation season needs to be stipulated, e.g. storage in a dam, or drains not to be operated.
• Reuse on the crop will only be allowed where a comprehensive surface water recycling system is in place. Since irrigation water with elevated levels of salt could run off the farm.

• The monitoring and management plan for soil and water salinity will need to be clearly described.

b) Reuse on a woodlot/saltbush plantation

• For such a disposal mechanism to be sustainable, the soil in the area used for the plantation will need to have a high drainage rate to sustain a large leaching fraction. In most cases this will require the provision of subsurface drainage in this area. Measures will need to be taken that will ensure that any groundwater leakage from the area is contained within the drained area.

• The area of plantation required will be based upon the expected drainage volume. Calculation of the area required should be based upon long term analysis of rainfall and evaporation with appropriate estimates of crop water use by the plantation.

• Prevention of saline surface run off leaving the plantation area will be important, so a surface collection and recycling system will need to be provided.

• Measures will need to be taken that will ensure that any lateral groundwater leakage from the plantation is contained within the drained area. In this respect the plantation area will be regarded as similar to an evaporation basin.

• The irrigation management of this plantation will need to be clearly described in the application.
c) Disposal to an evaporation basin

- The MIA L&WMP stipulates the use of ‘on-farm’ evaporation basins only. The use of an evaporation basins depends upon the availability of a suitable site. This site will ensure that there is not excessive leakage from the basin and that any leakage from the basin is contained within the drained area.

- A detailed set of guidelines regarding the design, siting and management of an evaporation basin are provided by Jolly et al., (2000). These should be used for evaporation basins in the MIA.

Example MIA BMP No. 6

A management and monitoring plan must be developed for the disposal of the drainage water.

The MIA L&WMP places responsibility for proper management of subsurface drainage water upon the landholder. The drainage and disposal design and management plan should assist the owner in the safe management of drainage water and ensure accountability.

4.2 Developing drainage system design for vineyard in MIA using BMP’s

4.2.1 Background

The following example is a specific application that demonstrates the concepts being developed. It uses the regional BMP’s for the MIA developed above. It is not the intention of using BMP's to create an onerous situation when considering a new drainage design as can been seen from this example. The generalised description of the MIA in the previous section is taken to apply to this example.
4.2.2 Farm conditions

- Crop - wine grapes on 15 ha, depth of roots about 0.9m.
- Irrigation system - surface irrigation with one siphon per broad based furrow, flooding almost entire area between vine rows. Irrigation set time 24 hrs.
- Water table at 0.9 – 1.2 m depth in Spring.
- Newly constructed 1.5 ha evaporation basin
- Soil investigations determined saturated hydraulic conductivity 0.2 m/day
- Impeding layer 4 m deep
- Lower end of vineyard experiencing patchy salinisation, root zone 5 to 8 dS/m
- Ground water salinity 4 – 20 dS/m
- Soil surface slope 0.2%
- Soil type – clay loam over light clay
- Consideration being given to changing to drip irrigation within next few years
- Sources of deep percolation primarily on-field irrigation with potential lateral flows from rice fields.

4.2.3 Design and BMP Implementation

The design was based in part on previous experience in the region.

System selection
A horizontal system was selected because of the soil types and the need to restrict the drained area. Potential groundwater flows from outside the vineyard need to be controlled.

System design
- Considering the deep percolation from irrigation, the current irrigation practice and set times are likely to be quite inefficient. This should be improved by using small furrows, improving advance times and reducing set times. The irrigation system should be able to be managed so that deep percolation losses are not greater than 25%. Average irrigation application is expected to be about 80 mm, therefore deep
percolation of 20mm is expected. Irrigation will be about every 10 days at peak periods. Considering that drainage management should allow about half the deep percolation to be stored and used by the crop the drainage requirement is then reduced to about 10mm over the 10 day interval equating to 1mm/day.

Groundwater inflows from surrounding land use will be minimised by drainage management. This will primarily be managing watertables to reduce hydraulic gradients between the vineyard and surrounding areas to a minimum. The drainage coefficient of 1mm/day will be adequate to control likely groundwater inflows.

The coefficient of 1 mm/day is relatively low compared to previous design values (5mm/day for loams and 2.5mm/day for clays) reflecting an increased emphasis on salinity control and less on waterlogging. Waterlogging control should primarily occur by good surface drainage and controlled irrigation practice.

- Drain depth should be such that the crop root zone is protected and the drain spacing is wide enough to be economic. In this type of soil a watertable depth of 1.4 m will minimise capillary upflow during non-irrigated periods. A drain depth of 1.8 m spacing was selected resulting in a calculated 36 m spacing. This is every 10 rows of vines that makes the system affordable. If some areas do not respond adequately to the drainage then it will be possible to install additional drainage laterals at the half spacing. The selected drain depth is likely to mobilise large amounts of salt (groundwater up to 20 dS/m), the drainage management will be critical to minimise this.

- Where the laterals join to the main there will be concrete manhole for access to the junction. In these manholes an overflow riser installed on the lateral will provide drainage control. The riser depth will be set to control the watertable at edge of field at 1.1 m deep during summer. This will conserve irrigation water, allow the vines to access the watertable water and minimise groundwater inflows from the surrounds.
System management

- Drainage control should be implemented as soon as possible after drainage installation is completed. The risers will be used to conserve water during the irrigation season. If watertables are high at the end of the irrigation season then the risers can be removed to allow the watertable to be drawn down. The risers can be left off during Autumn, Winter and early Spring, or set to a slightly deeper level e.g. 1.5m below ground level. This will ensure that salt is leached from the system and waterlogging of the root zone is avoided, especially in the critical period of budburst. Maintaining the control level at 1.5 m will reduce the risk of over draining the profile and reduce salt mobilisation as compared to allowing the drainage to occur to the drainage base, i.e. 1.8m deep.
- Irrigation configuration will need to change to narrower based furrows flooding only the area adjacent to the vine rows. Irrigation will need to be modified to 12 hour sets with 2 siphons per furrow, irrigation scheduling will continue to be based on growers experience.
- Observation wells to be installed at the mid-point between laterals in the middle of the field, watertable depth monitored before and after irrigations and after significant rainfall levels.

Drainage water disposal

Drainage water will be collected to a sump for disposal to a newly constructed evaporation pond on the property. Evaporation basin construction to be based upon best practice guidelines.

4.2.4 Results of implementing BMP’s

The drainage system was installed at the beginning of the 2001 cropping season and performed according to design expectations. Initially there were high flows from stored soil water after the system was installed, this then declined to reflect inputs from irrigation and
rainfall. The drainage water was properly disposed of to the evaporation basin. The changed irrigation practice reduced advance times and the total irrigation set time was reduced from 24 to 12 hours. Drainage management was implemented on only half the vineyard in the first year. This was to enable comparison of the benefits and any possible negative effects of management.

The first year demonstrated that the water table depth could be effectively controlled over a large portion of the field and that often flow was eliminated by use of the drainage control structures (risers). Where the drains were not managed the drain flowed continuously after irrigation until the next irrigation. Even with the drainage management the watertable depth was at least 1 m below the soil surface at all times. There were no signs of plant stress during the irrigation season and crop yields in the managed area were equal to those in the unmanaged area. Yields were maintained and total drainage water volume was reduced in the controlled plots compared to the free flowing plot as a result of the implementation of drainage management. The total drainage from the system was reduced by implementation of these BMP’s.

4.3 Design of drainage system for an individual broad acre farm on heavy soils using BMP’s

4.3.1 Background

This is an example for a broad acre farm growing cotton in California. These conditions are very similar to northern NSW. In this example the opportunity for drainage management to promote crop water use of the shallow watertable is highlighted.

4.3.2 Farm Conditions

- Crop - cotton, wheat rotation
- Irrigation system - basin flood
• Irrigation system flow rate - 850 to 1130 L/s
• Irrigation water quality - 0.4 to 1 dS/m
• Rainfall 150 mm/year
• Water table depth 0.5 to 1 m in Spring
• Disposal - existing evaporation basins
• Soil - Tulare clay, heavy clay (60% clay)
• Irrigation set time - 5 - 6 hrs
• Salinity root zone - 2 - 5 dS/m
• Ground water salinity - 12 to 20 dS/m
• Soil surface slope - 0.03%
• Permeability 0.02 cm/day

**System selection**

The system design was based in part on previous experience in the region. A horizontal system was selected because of the soil type and need to restrict the drained area and the total discharge, due to restricted disposal capacity.

**System design**

• Horizontal drainage system of corrugated plastic tubing at a depth of 1.2 to 1.4 m with sand and gravel envelope. Lateral spacing of 26 to 30 m. with laterals installed perpendicular to surface grade of field
• Lateral pipe diameter 5 to 7.5 cm
• Control on submain by a weir installed in sump.
• Water table to be controlled at 1.1 m on the edge of field with the single control in sump

**System management**

• Implement drainage control during irrigation season. However, during pre-plant
irrigation drainage flow will be allowed for soil salinity management.

- Maintain the current basin flood system, however sprinkler irrigation recommended for first irrigation to minimize deep percolation losses.
- Improve irrigation scheduling by monitoring soil water with capacitance probes and leaf water potential.
- Monitor watertable depth bi-weekly with observation wells.
- Monitor cotton yield with electronic devices

**Drainage water disposal**

- Use existing evaporation basins for disposal
- Surface drainage to be collected and re-used for irrigation.

**4.3.3 Results of implementing BMP’s**

These results are based on comparison with other cotton fields in the farm. One irrigation at the end of the season was eliminated by the improved irrigation scheduling, saving about 100 mm of water. This resulted in a dry profile at the end of the season providing storage for rainfall.

Crop water use from the shallow ground water was encouraged by improved irrigation scheduling combined with the availability of shallow groundwater due to the control structure (weir). This prevented over drainage by the system, so that an estimated 15% of crop water use was supplied by the shallow watertable, about 100 mm of water.

Despite maintaining a higher watertable the root zone salinity was maintained at the pre-season levels and cotton yield maintained.

The total drainage from the system was reduced by implementation of these BMP’s.
PART 2.
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1.1 Need for Drainage

In most areas where irrigation occurs in Australia the soils contain a vast amount of salt that is stored in the soils and groundwater. The use of irrigation, the leakage of water from the associated network of water distribution and drainage channels, and the replacement with shallow-rooted annual crops following clearance of deep-rooted perennial plants, has altered the water balance causing water tables to rise. This has resulted in mobilisation of the stored salt and when the water table comes close to the soil surface, soil salinisation and waterlogging result, with detrimental effects on agricultural production. Raised water table levels can also increase hydraulic gradients between the groundwater and surface water resources, leading to increased movement of salt to drains, streams and rivers.

For productive irrigation farming to continue, adequate leaching and drainage is necessary to remove salt left in the root zone after transpiration of irrigation water (Hoffman, 1985). The natural drainage capacity of the soil and the groundwater system in irrigation areas is usually insufficient to remove water that has infiltrated in excess of crop requirements; and so engineered drains are often necessary to prevent waterlogging and salinisation of the crop root zone (Tanji, 1990). Subsurface drains act to remove water from the soil profile and allow leaching of salts from the crop root zone.

Historically, the water quality concerns in irrigated lands have been focused on management of soil water salinity in the root zone and the irrigation water supply. Civilizations have been destroyed in the Middle East and North and South America due to soil salinization. The failure of Mesopotamia, now Iraq, is one of the most publicized failures of a civilization due to salinization of soils. Indian civilizations in Peru and in the Salt River region of Arizona were also affected by accumulations of salt in the soil profile due to poor drainage or salinization or both (Tanji, 1990).
It was estimated in 1987 that 96,000 ha of irrigated land in the Murray-Darling Basin were visibly affected by soil salinisation and that 560,000 ha had water tables within 2 metres of the surface (MDBMC, 1987). By the year 2015 it was predicted that 869,000 ha of irrigated land would be salinised or waterlogged due to high water tables. This represents about 60% of the land presently irrigated in the Basin (1.47 million ha; MDBC, 1999). However, recent surveys in New South Wales suggest that these predictions may be too high (A. van der Lely, pers. comm.). Most other irrigation areas throughout Australia also face waterlogging and salinisation issues that will require drainage intervention.

1.2 Drainage impacts

Subsurface drainage improves the agronomic conditions in an area by reducing waterlogging and salinisation in the root zone. There will also be wider benefits in reducing surface salinity and hence salt wash off, also generally deeper watertables and hence reduced groundwater discharge to surface features. There are potential negative impacts from subsurface drainage that are outlined in the following sections.

1.2.1 Drainage water salinity

Subsurface drainage water from arid areas always has a higher salinity than the supply water and is usually more sodic. Thus the main off site impact of drainage is in the disposal of the drainage water. The main drainage disposal options which are in use or have been considered are:

- by local or regional re-use - with dilution as required;
- to streams and rivers on an opportunistic basis – used in most irrigation areas;
- to disposal basins - in use in some irrigation areas; and
- by a pipeline to the sea - feasibility studies conducted.

Most drainage water is relatively saline e.g. 2 dS/m for irrigation water that has had the salt concentrated by evapotranspiration, up to 50 dS/m where the drainage water passes through
highly saline soils and groundwater. This increases the salinity of the receiving waters which are usually relatively fresh e.g. 0.1 – 1 dS/m. Some saline water is currently disposed of into river systems and thus exported downstream. However, the salinity of pumped groundwater and drainage effluent is such that continuous unmanaged disposal to rivers and streams may result in unacceptable impacts on the environment and downstream users. The Salinity and Drainage Strategy of the Murray-Darling Basin Commission (MDBC, 1999) imposes constraints on the amount of river disposal possible. Moreover, there appears to be declining political and community tolerance of continued disposal to river systems. Under these circumstances it is obviously useful to minimise saline drainage as much as possible.

It is difficult to assess the total volume of saline drainage produced from water table control measures. As an example, it has been predicted that by the year 2040, between 335 000-608 000 ML/yr of groundwater in the Riverine Plain of the Murray Darling Basin will require disposal (GHD, 1990). The lower value is based on a groundwater extraction rate 0.7-0.9 ML/ha/year (partial water table control), whereas the higher value considers a groundwater extraction rate of 1.4-1.6 ML/ha/year (full water table control – i.e. maintain the water table deeper than 2 m). It was also estimated that if the drainage was concentrated to one eighth of its volume, and no other means of disposal was available, 29 300 ha (partial water table control) to 53 200 ha (full water table control) of disposal basins would be required. These represent between 9 and 16 times the current area of disposal basins in the Riverine Plain. It is important to note that these are probably overestimates as sub-surface drainage is unlikely to proceed in many areas of the Riverine Plain due to the poor viability of drainage (A. van der Lely, pers. comm.).

Some drainage disposal is required, using any of the options outlined above. The option of continuous reuse is not viable. A good example of this is Broadview Water District, an irrigation district in the Central Valley of California. Drainage was installed in the 1960s and 1970s, but a drainage outlet was not obtained until 1983. The district recirculated all the collected subsurface saline drain water, surface runoff, and imported good quality water during the time between installation of the drains and obtaining an outlet. A rising water table and increasing salinity of the applied water led to the reduction in the yield of salt sensitive
crops. Cropping patterns were adjusted to more salt tolerant crops in response to increasing soil and water salinity in the district (Wichelns, 1986). The cropping pattern changed from vegetable crops, safflower and maize to tomatoes and seed lucerne and finally cotton. After several years of disposal of drainage water there has been a shift back to more salt sensitive crops (Wichelns, 1986).

In addition to salts, other pollutants such as fertilisers, pesticides and toxic trace elements can be found in drainage water. For the most part minimisation of saline drainage will also minimise the loads of these other contaminants.

The presence of toxic trace elements, such as selenium (Se), boron (B), arsenic (As) and many others, is one of the major water quality concerns in arid and semi-arid irrigated areas. The bio-accumulation of trace elements in plants and wildlife at Kesterson Reservoir and in the evaporation ponds used for drainage disposal in the Central Valley in California have had significant environmental consequences (San Joaquin Valley Drainage Program, 1990). A reconnaissance survey involving the analysis of water and sediment samples from five evaporation basins in the Murrumbidgee Irrigation Area (MIA) and one in the Shepparton Irrigation Region (SIR) showed that the composition of boron, copper, cadmium, lead and manganese were in some instances, above guideline levels for water and sediments, (Christen et al. 2000). All of the pesticides included in the study (Atrazine, Diuron, Metalochlor, Endosulfan and Chlorpyrifos) were detected at levels above guideline levels for protection of aquatic environments. These pesticides were also found at elevated levels in the sediments.

No longer can agriculture be unconcerned about the off-site effects of the activities that support the industry. It was the potential environmental impact of drainage water from the Central Valley entering the San Francisco Bay delta that was one of the factors responsible for halting the work on the San Luis Drain. Because of the effects of drainage water at Kesterson Reservoir, a large grasslands/wetlands complex in the San Joaquin Valley, known as the Grasslands Area, no longer receives commingled surface runoff and agricultural drainage water.
Aeration, soil profile salinity, trafficability, and removal of excess soil water are all parameters that are currently factored into the design of subsurface drains in arid and semi-arid areas (U.S. Dept. of Interior, 1993). With the need to minimize the effects of drain water on the environment, drain water quality and quantity will have to become design parameters or at least a consideration in the management of drainage systems.

In arid and semi-arid irrigated areas, the groundwater is often more saline than the deep percolation from irrigation and as such there is a potential to mobilise huge quantities of salt by installing drainage systems. In the future, consideration has to be given to the extent of this salt mobilisation and the relationships between where this salt is stored and the actual salinity of the root zone. Often drainage systems remove salt from deep below the root zone, and as such this salt cannot be equated to contributing to the “root zone salt balance”. It has to be considered whether the mobilisation and subsequent disposal difficulties of this salt stored deeper in the profile can be justified in terms of improved root zone salinity status.

1.2.2 Aquifer salinisation

Where drainage is undertaken by pumping of aquifers, typically by tubewell or spearpoint systems there is a risk of aquifer salinisation. This is especially the case where small aquifers surrounded by salt laden aquitards (e.g. clays) are over pumped. This causes the migration of salts from the aquitard into the aquifer. Reported increases in aquifer salinity of about 0.05 dS/m per year have raised concerns as to the sustainability of shallow groundwater pumping in the Shepparton region, (Bethune 2001).

Saline water can also enter fresher aquifers from below or above. Often groundwater pumping occurs from the fresher aquifers that may be underlain or overlain by more saline aquifers. If excessive pumping occurs in the non-saline aquifer, intrusion of the saline water into it can occur. This process is a significant threat where groundwater pumping is used for irrigation or is disposed of into fresh water bodies. For example, analysis of deep pumping in the Shepparton region to assist in salinity control indicated a likely 30% long term increase in
aquifer salinity, (Nolan and Reid, 1989). More recently deep groundwater pumping is proposed in the Coleambally Irrigation Area to assist in long term salinity control. The pumping is proposed from the deepest formation. This formation has low salinity water (0.5 dS/m) that can be used for irrigation. Modelling has shown that if pumping is not carefully managed there is a risk that the saline water in the shallow aquifers, overlying the deep aquifer, will be drawn down into the deep aquifer, (Prasad et al. 2000).

1.2.3 Reduced irrigation efficiency

When subsurface drainage is installed there is often the effect of reduced irrigation efficiency. This occurs due to watertables being drawn down to a greater depth than is actually required to maintain plant production. This removes water from the soil profile that would otherwise have been used by the crop. This effect is often called over drainage. There is an optimum depth to the watertable for most crops, above which the crop is affected by waterlogging and below which the soil is over dry. The effect of water table position on yield and crop water use was studied for sugar, corn, and lucerne (Benz et al, 1978, 1982, 1987; Doering et al, 1982; Reichman et al, 1986). In these studies either the yield was reduced or larger volumes of water had to be applied to sustain yields when the depth to the water table increased. These studies were conducted on lighter textured soils that compounded the problem. As a result, Doering et al (1982) proposed a shallow drainage concept that would limit the water table draw down and allow more uptake from the shallow ground water. The proposal was to install drains at a depth of 1.2 m rather than the 1.8 m normally used.

With shallow horizontal drainage systems and flood irrigation, the application efficiency is also often reduced. This occurs due to water being lost to the drainage system during the irrigation event that slows the rate of advance of the irrigation and hence reduces application uniformity and wastes water. With flood irrigation in a vineyard the irrigation water lost to the tile drainage system can be as much as 30-40% (Christen and Skehan 1998). For the above reasons it is important to understand the interaction between the drainage system and irrigation
method, and to implement some management of the drainage system in order to avoid irrigation application losses and keep watertables at the optimal depth.

1.3 Changes in approach for design and management

Reviewing the performance of subsurface drainage systems for irrigated agriculture has highlighted a need for a change in perspective, (Christen and Hornbuckle 2001). Drainage systems should no longer be used as a cure for problems created by inefficient irrigation practices or as a source of irrigation water of doubtful quality for conjunctive reuse. The inappropriate use of drainage has lead to a waste of irrigation water, salinisation of aquifers faster than necessary and more downstream salt contamination than is necessary. New drainage systems should aim to provide a salt balance in the root zone only whilst treating the watertable as a potential resource and assisting in making irrigation practices more efficient by holding water in the profile for plant use.

This change in perspective requires changes in the way drainage systems are designed and managed. The amount of pumping should be such that the drainage provides only enough leaching to provide a root zone salt balance and such that mobilisation of salt stored below the root zone is minimised. This generally means using shallower pumping systems run for shorter periods to pump smaller volumes. There should also be management and feedback mechanisms that allow subsurface drainage systems to be properly managed, e.g. watertable monitoring devices, soil salinity surveys to ascertain pumping required, aquifer salinity monitoring and even modeling seasonal conditions to ascertain pumping requirements. In the following chapters some ideas for improved design and management of subsurface drainage systems are provided.
1.4 Summary information for BMP’s

- Key beneficial impact is lowering of watertables and reduced salinisation. This improves production conditions, may also reduce negative off site impacts of irrigation such as groundwater discharge to surface drains, surface salt wash off. These benefits only accrue if the drainage disposal is such that it does not have adverse off site impacts.

- Drainage disposal is the main negative offsite impact of drainage. Need to consider the potential salt mobilisation and disposal options before installing drainage systems.

- Salinisation of aquifers is a risk with groundwater pumping. Need to ensure that this is a controlled process. It is unwise to degrade the valuable resource of a fresh aquifer for salinity control purposes.

- Reduced irrigation water use efficiency can occur after subsurface drainage is installed. This needs to be addressed at the design stage and management measures introduced to avoid over drainage and poor irrigation application efficiency.

- Land salinisation is a risk if saline drainage water is constantly reused on the drained area.
Chapter 2

Irrigation and drainage interactions

2.1 Irrigation

The irrigation system and its management are critically important as drainage is inextricably linked to the irrigation excess, that portion of irrigation that passes below the root zone and cannot be used by the crop. This is also known as deep percolation. The amount of deep percolation is also related to rainfall, since rainfall and irrigation interact to affect the total deep percolation.

2.1.1 Irrigation systems and uniformity

Irrigation system selection should be done such that the operational characteristics of the system are suited to the soils, and available water supply. The ideal system would apply the same depth of water over the entire area to be irrigated. In reality, the water is spread non-uniformly across the field, as a result of a variety of factors. One of the major factors is the interaction of the irrigation system operational characteristics with respect to the infiltration characteristics of the soil being irrigated. In general, pressurized systems such as sprinklers and drip irrigation can be managed to provide better control of deep percolation than is possible with surface systems.

The application rate of a pressurized system can be controlled such that the infiltration rate of the soil is not exceeded and surface runoff and redistribution are minimized. Because water is distributed uniformly at the same time to all parts of the field by closed conduits prior to application, the total depth of applied water can be effectively controlled with a pressurized system. The infiltration intake opportunity time of pressurized systems is roughly equal for the entire field, while surface systems have greater opportunity times at the head of the field than at the tail end of the field. Application uniformity is affected in sprinkler systems by pressure variations in the system, and wind speed and direction. The pressure variation can be corrected by improved design while wind effects can be minimized by changing lateral move
spacings and operating when the wind velocities are below a threshold value.

Drip systems have a highly non-uniform application pattern on the surface which is smoothed out and becomes quite uniform after water has infiltrated (Wallach, 1990). Poor hydraulic design can also lead to poor distribution uniformity in drip systems and ultimately excessive deep percolation losses.

Another advantage of pressurized systems is the ability to operate the system at a high frequency, i.e., several times a week to several times a day. With this mode of operation, the total water application can be set equal to estimated crop evapotranspiration between the irrigation intervals. If the soil water content in the root zone had been lowered prior to beginning irrigation, then there should be some soil water storage available to reduce the deep percolation resulting from non-uniformity. When the soil water is fully replenished with less frequent irrigation, the soil profile becomes a storage medium for a large volume of applied water and the deep percolation potential is increased due to application non-uniformity.

Surface irrigation systems, such as furrow and level basin systems, can apply water very uniformly if the system is properly designed and operated (Dedrick et al., 1982). These systems work best on soils which contain large percentages of clay and silt. Level basin systems in Arizona have been operated with very high uniformities and low deep percolation losses (Dedrick et al., 1982). Level basin systems require large volumes of water, 2038 m$^3$/h, be available for irrigation, and the careful timing of application cutoff.

Techniques to improve distribution uniformity with furrow irrigation include increased furrow flow rate, reduced run length and cut back flow. Increased flow rates in the furrow decrease the advance time of the furrow stream and thus reduce the difference in intake opportunity time (IOT) between the ends of the field contributing to improved uniformity. The furrow advance time should not exceed 25% of the total set time. Reducing the furrow run length has the same effect on IOT as increasing the furrow flow rate. Surface runoff is reduced by reducing the furrow flow rate after the advance is completed.
2.1.2 Irrigation and resulting drainage volumes

When determining the potential for reducing subsurface drainage water volumes through improved farm level water management it is important to understand the relationship between irrigation volume and the volume of water collected in the subsurface drainage system.

Subsurface drainage systems are designed to remove water that would otherwise lead to high water tables under the crop. These water sources include deep percolation from irrigation and rainfall, seepage from irrigation canals and drainage channels, and lateral subsurface flows.

In a field study of subsurface drainage in the San Joaquin valley California it was found that out of 21 drainage systems 3 of them contributed 39% of the total drainage volume (Wichelns and Nelson, 1989). Their analysis of the 21 systems found that the drainage amount was mainly a function of the irrigation water applied and rainfall. They estimated that 290 mm of drainage resulted from 1000 mm of rainfall. There were also significant differences between crops with melons generating more drainage than cotton, which in turn produced more drainage than sugarbeets. Estimates of the resulting drainage when 1000 mm of irrigation is applied to each crop are shown in Table 1.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Drainage as mm per 1000 mm irrigation applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melons</td>
<td>188</td>
</tr>
<tr>
<td>Cotton</td>
<td>120</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>56</td>
</tr>
</tbody>
</table>

Lateral subsurface flows were found to be significant in some drainage systems, farms in the boundary area of the district adjacent to undrained fields and farms located adjacent to a main drainage channel were found to be most affected. Thus the percentage of drainage due to farm irrigation varied upon the location of the farm, Table 2.
Table 2. **Effect of drainage system location on drainage due to irrigation**

<table>
<thead>
<tr>
<th>Drainage system location</th>
<th>Percent drainage due to farm irrigation (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1986</td>
</tr>
<tr>
<td>Central area</td>
<td>68</td>
</tr>
<tr>
<td>Boundary area</td>
<td>42</td>
</tr>
<tr>
<td>Near main drain</td>
<td>40</td>
</tr>
</tbody>
</table>

after Wichelns and Nelson (1989)

Their study estimated that a 100 mm reduction in irrigation application would result in a 240 mm reduction in drainage at the farm level (IWD) but that a 10% reduction in irrigation across the district would result in only a 15% reduction in total drainage water (BFD).

The conceptual relationship between water drained from a system and the water applied can be described as:

\[
D = f(I, R, C, S, L)
\]  

(Equation 1)

where D is the drained water volume, I is the infiltrated irrigation volume, R is the infiltrated rainfall volume, C is the crop, S is the soil type and L is the lateral inflow volume (including lateral seepage from irrigation canals and drainage channels), (Wichelns and Nelson, 1989).

In this conceptual relationship the irrigation, crop and soil type are the functions controlling the slope/curvature of the relationship between irrigation and drainage volume, this can be termed *Irrigation Water Drainage* (IWD). The rainfall and lateral inflow terms determine the >baseflow= and shift the whole relationship up, this can be termed the *Base Flow Drainage* (BFD). Examples of this relationship are shown in Figure 1, the relationship between water applied and drained (IWD) is the same for both cases, except that B has no lateral inflow.
Figure 1. Example drainage relationships, with and without lateral inflows

![Diagram showing drainage relationships](image)

After Wichelns and Nelson (1989)

When considering this relationship it can be seen that a unit decrease in applied water will result in the same proportional unit decrease in drained water. However, the total change will be less in A than B. Thus analysis of the curvature of the relationship allows comparison of IWD between sites independently of subsurface inflows, Figure 2.

Figure 2. Drainage reduction per unit reduction irrigation water

![Diagram showing drainage reduction per unit reduction irrigation water](image)

After Wichelns and Nelson (1989)
Part 2  
Irrigation and drainage interaction

Analysis of the total change in drainage per unit change of irrigation enables the effect of the curvature and BFD in drainage reduction to be combined, Figure 3. These two measures of drainage water reduction are useful to identify situations with the greatest potential for drainage reduction by irrigation management alone, those with little inflow, and those that require a combination of irrigation management and drainage management measures to reduce inflows.

The IWD is a useful measure of changes to drainage as a result of changes in farm water management whereas the BFD is useful to measure changes in drainage over a whole area.

Figure 3. Drainage reduction expressed as a fraction of the total drainage

![Graph showing drainage reduction expressed as a fraction of the total drainage](image)

after Wichelns and Nelson (1989)

Christen and Skehan (1998) monitored three vineyards with different irrigation systems for an irrigation season; Table 3 shows a summary of water balance for each. With surface irrigation the amount of water applied at each irrigation is generally more than is required to refill the soil resulting in drainage through the tile drainage system. Drip irrigation gave greater control over irrigation as small amounts of water can be applied frequently. This resulted in no run off or tile drainage when properly managed. In comparison, furrow and flood irrigation had large amounts of run off and subsurface drainage, demonstrating the difficulty of getting good control with these irrigation methods.
## Table 3. Summary of irrigation system performance

<table>
<thead>
<tr>
<th>System</th>
<th>Number of irrigations</th>
<th>Applied water per irrigation (mm)</th>
<th>Run off (mm)</th>
<th>Tile drainage per irrigation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood</td>
<td>7</td>
<td>82</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Furrow</td>
<td>6</td>
<td>115</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>Drip</td>
<td>26</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

After Christen and Skehan, (1998)

### 2.1.3 Drainage volumes and climate

The relationship between irrigation and drainage and climate, especially rainfall is important in terms of drainage volumes. This can be investigated by analyzing for ‘wet’, ‘dry’ and ‘average’ years, where wet and dry are taken as one standard deviation above and below average, Figure 4.

![Figure 4. Relationship between irrigation and drainage for citrus in the MIA, modeled](image)


The results show that the relationship between irrigation and drainage for a citrus grove in the MIA is highly influenced by rainfall patterns. In wet years the irrigation is lower and drainage higher than the average. In a wet year where there is only 400mm of irrigation, there can be
about 200mm of drainage, the same level of irrigation in an average year would result in virtually no drainage. The opposite occurs in dry years where for the same irrigation amount there is less drainage than in an average year. For example 700mm of irrigation in an average year may generate about 200mm of drainage compared to virtually no drainage in a dry year.

2.1.4 Summary information for BMP’s

- Improved irrigation management is the first step in reducing deep percolation and hence subsurface drainage flows. Improved irrigation management is important when irrigation management is poor but there are diminishing returns in terms of drainage reduction when irrigation management is of a reasonable standard.

- Pressurized irrigation systems have the greatest potential for improved irrigation uniformity and reduced drainage coefficient.

- Seasonal impacts on drainage are important, irrigation management is significantly more critical to reduce drainage flow during wet seasons than in dry seasons.

- Interaction between irrigation and drainage is critical to reducing drainage flows, therefore need to manage irrigation and drainage in an integrated manner … see next section
Chapter 3

Salinity management

3.1 Managing the root zone soil salinity

In addition to removing excess water and maintaining aeration in soils, drainage also serves as a system to remove salts from the soil profile. There are two main processes of salt accumulation in the root zone, one is due to accumulation of the salt in the irrigation water and the other is due to the presence of a shallow saline watertable which then causes salts to accumulate in the rootzone by capillary upflow.

3.1.1 Managing salts applied by irrigation water

Unlike humid areas that rely on rainfall, which is relatively free of salt, arid and semi-arid areas rely on water that naturally contains some salt. Even the best quality irrigation water will contain salt. For irrigated agriculture to survive a salt balance must be maintained in the active part of the crop root zone. The amount of water required to achieve this control is called the leaching requirement (Hoffman, 1986).

The calculated leaching requirement is the minimum value of the actual leaching fraction needed for a particular crop to prevent a yield reduction. The leaching fraction, the steady-state ratio of water leaving the profile as drainage to the applied water (rain and/or irrigation), can be expressed as

\[ L = \frac{d_d}{d_d + d_i + d_r} = \frac{d_d}{d_a} = \frac{c_a}{c_d} \]  

(Equation 2)

where \(d_d\), \(d_i\), \(d_r\) are depth of flow per unit surface area for drainage, irrigation and rainfall, respectively. The subscript "a" refers to applied water and "c" is salt concentration. Based on Equation 2, the leaching requirement can be expressed as follows
Salinity management

\[ L_r = \frac{d^*_d}{d_a} \]  
(Equation 3)

where the superscript \("^*"\) indicates the required from the actual values (Hoffman, 1986). For systems with perfect distribution uniformity the deep percolation would be equal to the leaching requirement, however, most systems are not perfect and the irrigation efficiencies and distribution uniformities are low enough that the leaching requirement is met and often exceeded. The leaching requirement can also be expressed as:

\[ L_r = \frac{e_a}{e_d} \]  
(Equation 4)

where \("e"\) is the electrical conductivity of the applied (a) and drainage (d) water, respectively. The leaching requirement will be a function of the salinity of the applied water, soil salinity, groundwater salinity, crop salt tolerance, the climate, and the soil and water management. Salt tolerance data is available for a wide range of crops (Maas, 1990).

In some cases there will not be leaching due to excess irrigation water. Research on deep rooted crops such as lucerne on heavy duplex soils has shown that there may be very little or no drainage resulting from irrigation, Noble et al. (1987). In this case the salts accumulated in the profile until being leached out by winter rainfall.

3.1.2 Managing salinisation by upflow

Salinisation by upflow occurs by two basic processes. In the first, a crop uses water from the saline water table and water flows upward due to matric potential gradients established by soil water loss during plant use. The dissolved salt moves with the water and is left behind as the plant uses basically pure water. Evaporation of water from the soil surface also creates matric potential gradients in the soil profile that moves water upward from a saline water table. In this instance most of the salt will be deposited at or close to the soil surface. The rate of movement in either instance will be a function of soil type and the rate of depletion due to either evaporation or crop water use. Soil containing large percentages of silt and clay have large capillary fringes and can move water large distances while sandy soils have small capillary
fringes and lower conductivities when dry and thus less movement of water from the water table.

Regardless of the process used to move the salt upward in the profile, the management is the same as managing salinity deposited during the process of irrigation. The only variation is to determine the additional depth of leaching required. Hoffman (1986) describes a method to determine the leaching requirement based on the crop threshold and the weighted salt concentration of the applied water. The applied water included irrigation and rainfall. The leaching requirement is presented in a graph of salt tolerance threshold vs. salinity of applied water. When salt is added from groundwater the contribution would have to be included in the calculation. This will require knowing the salinity of the groundwater and the percentage of water taken from ground water. The salinity can be determined by analysis but the estimation of the water extraction will be a problem. Very little data exist that describe crop water use from shallow ground water as a function of depth to water table, ground water salinity, and crop salt tolerance. Under most existing conditions of irrigation management it should be safe to assume that less than 10 to 15% of water comes from shallow ground water. If the leaching fraction is determined on that basis, there should not be a problem with salt accumulation. Periodic monitoring will be necessary to verify this assumption.

In all likelihood, managing soil salinity based on the depth of applied water, the salinity of applied water, and crop salt tolerance as described in the previous section should be adequate to control soil salinity. This is true because most irrigation system efficiencies are low enough that the leaching requirement is exceeded during normal operation. If monitoring determined that salt accumulation was occurring an additional irrigation could be applied in a fallow period for leaching. Hoffman (1986) also describes these calculations.

The previous discussion assumed that the water table was a result of deep percolation losses and lateral in-flow from regional sources. However, water tables may also be created by artesian pressure in aquifers underlying the region. Soil salinity management in this instance is more complicated since efforts need to be made to control the additional source of the excess water. The alternatives are pumping the aquifer to reduce pressure or design the subsurface
drainage system to accommodate this continuous flow in addition to the other sources. Once the flow is controlled the salinity in the soil profile may be managed as described in the previous section. It will be essential to maintain a net downward gradient of flow and salt in either case.

3.2 Drainage water salinity

The actual salt concentration in drainage water depends upon the salt stored in the soil profile above and below the drains, the depth and spacing of the drains, aquifer salinity and groundwater flow and the irrigation management affecting rate of watertable recharge. With most drainage systems the drain salinity from newly installed systems is initially high and then declines to a fairly constant level, Johnston (1993). This assumes that the drainage water is disposed of off site. If drainage water is reused on site then the drainage water salinity may increase with time. This can also be the case with vertical groundwater pumping systems where the groundwater is used as an irrigation supply.

3.2.1 Drain water salinity (tile drainage)

Drainage quantity can be reduced but is unlikely to be eliminated, so it is important to investigate the key factors affecting drainage water quality. Monitoring of a farm horizontal drainage system by Christen and Skehan (1998) found that in a furrow irrigated vineyard the drainage water salinity decreased at high watertables levels directly after irrigation or rainfall and then increased as water tables fell. The results of a 21 day monitoring period are shown in Figure 5.

Using this data the direct relationship between water table depth and drain water salinity can be seen in Figure 6. This site had only been drained for about six years and as such is still in a leaching phase. The drainage water salinity was about 10 dS/m when water tables were shallow, 80 cm, and rose to over 13 dS/m when water tables dropped to around 170 cm, a 30%
increase. This trend was not apparent on the flood irrigated vineyard as the drainage system had been installed for 35 years and as such the profile was fully leached, the drainage water reflecting the salt applied in the irrigation water rather than the salt stored in the profile.

Figure 5. Change in drainage water salinity with water table depth

![Figure 5](image)

Figure 6. Drainage water salinity as a function of water table depth

![Figure 6](image)
The increasing drain water salinity with water table depth is due to the changing depth of water flow paths to the drains. As the water table drops the water flow paths to the drains become deeper. The drain flow at deeper water table depths has a greater dominance of deeper water flow paths, which move water through the deeper soil profile, which is more saline. At shallow water table depths the bulk of drainage flow is from shallow flow paths moving through less saline soil. The relationship between soil salinity and drain water salinity is shown in Figure 7.

**Figure 7. Drain water salinity and soil salinity**

The difference in absolute value is due to the higher water content of a saturated paste extract compared to the field water content above the drained upper limit (Field Capacity) and some contribution to the drain flow from flow paths below the drain depth (180cm).

The close correlation between the soil and drainage water salinity, as shown in Figure 8, would indicate that very little of the drain flow in this case is from below drain depth. This is to be expected when drains are installed in a soil of low permeability.
The potential depth of water flow path to a subsurface drain is not only a function of the drain depth itself but is also greatly influenced by the drain spacing. Wider drain spacings create deeper water flow paths. Theoretically, the deepest water flow paths to any subsurface drain can be up to a quarter of the drain spacing below the drain, so drains spaced 40m apart can generate flow paths up to 10m deep. Figure 9 shows the influence of drain spacing, and hence maximum drain water flow paths on the potential for salt removal. This chart uses soil data from a new vineyard compared to a theoretical fully leached profile to arrive at the amount of salt that would potentially be leached.

It is however rare for a soil profile to extend to great depth without a layer of low permeability in the soil profile which limits the depth of flow path. In the MIA the maximum depth of the limiting layer is about 4m below drain depth. This has been included in Figure 9 to give a more realistic representation of the amount of salt that can potentially be removed by subsurface drainage systems.
3.2.1.1 Flow paths to tile drains

Understanding flow paths to drains will assist in design to avoid excessive mobilisation of salts. Solute transport to subsurface drains has been investigated by Fio and Deverel (1991). They analysed flow paths to drains at 1.8 and 2.7 m depth with assumed spacings of 92 and 216 m. Their results are summarised in Table 4.

Table 4. Flow conditions to drains at different depths

<table>
<thead>
<tr>
<th>Flow factors</th>
<th>1.8m deep drain</th>
<th>2.7 m deep drain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigated</td>
<td>Non irrigated</td>
</tr>
<tr>
<td>Maximum flow depth (m)</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Maximum travel time (years)</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Flow rate per unit drained area (m3/m/yr)</td>
<td>0.293</td>
<td>0.043</td>
</tr>
</tbody>
</table>

These model results show that flow paths for the 2.7 m drain are twice as deep and five times as long as for the shallow drain under non-irrigated conditions. When irrigations are occurring, the depth and length of the flow lines are reduced. The drain flow for both drains is similar per unit area during irrigations, but when non-irrigated the deeper drains discharge more water. The deeper drains, which had longer and deeper flow paths, resulted in poorer quality drainage water.

Pohl and Guitjens (1994) also used MODFLOW to model flow to subsurface drains in an area with regional flow. The flow to the drains after irrigation was local and then as this diminished the drainage flow was from the regional aquifer with very long flow paths. Fio (1997) again used MODFLOW to investigate drainage flow paths in sloping areas, the upslope areas recharged the water table downslope and water flow paths to the downslope drains were as much as 25 m deep.

This investigation of water flow paths has implications for drainage design and management. It shows that drains that concentrate water flow paths in the shallower less saline part of the soil profile will generate drainage water of lower salinity. This can be achieved in design by having shallower more closely spaced drains and in management by preventing flow from drainage systems when the water flow paths are in the deeper more saline parts of the soil profile.

3.2.1.2 Drainage flow and salt load from tile drains

The salt load from a drainage system is the mass of salt transported by the drainage water. This is a function of the drainage volume and water salinity. In established drainage systems where the leaching of stored salt is past the initial stages then the salinity of the drainage water varies little. Thus the salt load is then linearly related to the drainage volume. In a study of subsurface drainage flows during 1991/92 the Department of Water Resources in Griffith, NSW collected drain water salinities and flows from numerous subsurface drainage systems. From this data a general relationship between flow and load was developed for all the farms.
involved, Figure 10. This relationship may be used as a general indicator of likely changes in the salt load with general changes in drainage volume in response to management or climate variations. However, this relationship is not useful in determining which particular farms or groups of farms contribute the greatest salt loads.

Figure 10. Drainage salt load-flow relationship for all farms monitored, DLWC (1992)

To determine which particular farms are contributing most to salt loads in the drainage system then individual salt load-flow relationships need to be developed for each farm, Figure 11.

The individual farms can be seen to have very different salt load flow relationships with varying slopes, indicating varying water salinity, and varying ranges of flows. These differences are due to physical differences between soil types, hydrogeology, drainage system design and water management. With this information those farms which have high salt loads and steep slopes for the load-flow relationship can be targeted first to reduce drainage flows and get most reduction in salt load.
The linear relationship of these load-flow relationships indicates that these farms are not in the initial leaching phase, where there would be a non-linear relationship between flow and salt load because the drainage water salinity would change markedly between high and low flows. However, the load-flow relationship will change over time as salts are leached from the profile, as this occurs the slope of the load-flow relationship will reduce. Figure 12 shows the decline in salinity of drainage water from four farms in the MIA over time.

The initial decline is quite rapid and then flattens off. Eventually an equilibrium may be reached whereby the salinity of the drainage water reflects only the salt inputs to the system from irrigation, the leaching fraction. In this example, farm 77 drainage salinity has declined to about 2dS/m that would be representative of a 5-10% leaching fraction with irrigation water of 0.1 – 0.2 dS/m. Thus this system has been fully leached and is in equilibrium with irrigation water. There is little scope in this situation for reducing the overall salt load except by attempting to store salt below the rootzone or by encouraging deeper flow past the drains if possible. Farm 513 may still be in a leaching phase, or the latest salinity measurement may be the equilibrium drain water salinity, further significant leaching after 23 years of drainage is unlikely.
In the leaching situation, which is the initial phase for all drainage systems, there is an opportunity to reduce the salt load by preventing removal of salt stored deeper in the profile. Salt leaching from the root zone is necessary but removal of salt from deep in the profile and even below drain depth is unnecessary. This removal can be reduced by improved irrigation water management that reduces water moving past the root zone and also by management of the drainage system to prevent drainage once water tables have fallen to a safe level.

Farms 1380 and 1508 appear to have had relatively stable drain water salinities after only a small initial drop after drain installation. The drain water salinity is around 4 dS/m, if this salinity were due only to irrigation water applied (0.12 dS/m) then this would represent a leaching fraction of only 3%. For farm 1508 this appears feasible from recent drainage records, however for farm 1380 drainage records show a leaching fraction more in the order of 12-20%. This scale of leaching fraction should result in drain water salinity in the order of 1 dS/m if only salt from the applied irrigation water is considered. Since the drainage water salinity is around 4 dS/m the source of salt must be in the soil profile, however the salinity has been relatively static for quite a considerable time indicating that continued leaching of the soil around the drains is not occurring.
The relatively high drain flow and drain water salinity shows that on this farm there must be an outside influence on the drainage system generating these flows and salinities. In this case changes in on-farm irrigation water management may not have a significant effect on the drainage salt load. To reduce the salt load in this situation will require management of the drainage system. The drainage system management needs to try and maintain the water level above the drains at a high enough level to suppress the regional influences. This could be done using a weir structure or by changing the height to which the water table is managed. As the root zone must still be protected there may be a limit in this situation to the level of drainage salt load reduction possible.

3.2.2 Drain water salinity (vertical drainage)

Vertical drainage often results in quite different drainage water salinities than tile drainage systems. This is generally because tile drains are shallow systems (< 3m deep) where the drainage water is generally a mix of irrigation water moving past the rootzone and resident groundwater, whereas vertical systems are often much deeper (6 – 10 m deep) and hence the drainage water salinity is determined purely by the groundwater salinity. With time the aquifer salinity may change and hence the drainage water quality. In some cases the aquifer may freshen as saline water is removed and replaced by fresher irrigation water, in other cases it may become more saline if the leaching irrigation water is more saline than the aquifer salinity or there is intrusion of more saline water into the aquifer.

Often groundwater pumping and conjunctive reuse of the drainage water on the drained area is undertaken. Where there is no salt export this will lead to salinisation of the aquifer, if some water is exported then the aquifer salinity can be maintained or reduced. The relationships between groundwater reuse/export and aquifer salinity have been investigated on the basis of salt and water balances, (Prendergast et al. 1994). Using the conceptual model shown in Figure 13, the rate of salinisation of an aquifer not subjected to pumping can be calculated.
The rate of salinisation is a linear relationship that depends upon the size of the aquifer, the applied water salinity and depth and the rainfall depth and salinity. For example an irrigation application of 0.8 m/year with salinity of 0.2 dS/m, with 0.45m of rainfall at a salinity of 0.008 dS/m will result in a 0.04 dS/m increase per year over the long term, for an aquifer of 10m total depth. This assumes no leakage into or out of the aquifer.

When groundwater pumping is introduced the aquifer salinity can be influenced by salt extraction or salt intrusion. If the pumped groundwater is disposed of, then the salt is exported from the aquifer and salinity can be maintained or even reduced. For the previous example if
the groundwater was 4dS/m then an export of just 0.01 m/year would balance salt input by irrigation and rainfall. More pumping and export than this would reduce the aquifer salinity.

The conjunctive reuse of the groundwater does not affect the aquifer salinity as the salt is recycled. However, often the conjunctive reuse will be concentrated around the point of pumping, as this is where drawdown is greatest. Then conjunctive reuse is not spread over the entire area of the groundwater pumping, and the aquifer in the area where reuse is applied will be salinised. Depending upon the aquifer conditions this can lead to rapid rates of salinisation, with groundwater salinity increasing at 0.1 –0.2 dS/m per year (Prendergast et al 1994).

In some situations an aquifer will be affected by pumping due to intrusion of saline groundwater from surrounding aquicludes (clays) or deeper or shallower aquifers. This is most likely to occur when the piezometric levels in the aquifer are significantly reduced, thus setting up gradients from the aquicludes or other aquifers. This is most likely to occur when the pumped volume is greater than the recharge in the immediate area from irrigation, rainfall and channel seepage. If in the previous example groundwater intrusion of just 0.02 m/year occurs at the same salinity as the aquifer then the rate of aquifer salinisation will be doubled. This depends upon the leakance between the aquifers and may be controlled to some extent by limiting the hydraulic gradient by suitable pump management, (Prendergast and Heuperman, 1997)

Investigations of actual groundwater pumping and reuse over 10 years in Tongala, part of the Shepparton Irrigation Region, have shown an increase in aquifer salinity of 0.35 dS/m in 5 years, (Heuperman, 1986). This increase was 0.07 dS/m per year, which was much quicker than the predicted increase of 0.01 dS/m per year due to addition of salts from irrigation water. The increased rate of salinisation was attributed to periods of heavy pumping causing intrusion of higher salinity water from the deeper aquifer into the shallow aquifer system. In the same area the average increase in aquifer salinity over a 10 year period was found to be an increase of 0.06dS/m per year, (Norman 1991), despite 10 to 25% of pumping being disposed of thus exporting salt out of the aquifer.
3.2.3. Drainage efficiency

Drainage efficiency can be defined as the ratio of deep percolation to drain flow, which means that low drainage efficiency drains are getting a larger percentage of flow from the groundwater than from root zone percolation. Drains which are performing with a low drainage efficiency are typically discharging water with greater salinity and trace element concentrations than found in the deep percolate (Grismer, 1989). It is apparent that the hydrogeologic and hydrochemical setting of the potential drainage system needs to be considered when designing the drains.

3.3 Summary information for BMP’s

- The salt load from most existing drainage systems is linearly related to the drainage flow. So, the first step to reducing drainage loads is to reduce the volume of drainage.

- The volume of drainage can be reduced by:
  - improving on-farm irrigation management
  - reducing regional effects on drain flow by using shallower drains
  - avoiding pumping more water than the minimum level necessary to protect the root zone.
  - Pumping drainage water for conjunctive reuse presents a significant risk of pumping for irrigation supply rather than the salinity control objective, resulting in more pumping than is necessary for salinity control.

- Irrigation system management can also affect the load-flow relationship. Changing from surface irrigation to drip systems with high uniformity and low deep percolation losses, if managed correctly, will:
  - change the flow paths to the drains, resulting in changes to the drain water quality
  - contribute less salt to the soil/aquifer system thus enhancing long term sustainability.
• Drainage water salinity generally increases with the depth of tile drainage. Shallower drainage systems are preferable to avoid highly saline drainage.

• Drainage system management to avoid over draining areas can be used to reduce deep water flow paths to drains that move through the most saline parts of the soil profile and to avoid the intrusion of saline water into aquifers caused by over pumping.

• The likely salt loads and how these can be minimised needs to be assessed before implementing drainage.

• When groundwater is reused it needs to be redistributed over the entire area of influence of the drainage system to avoid soil and aquifer salinisation.

• Reuse of saline drainage water should only be considered if long term salinisation is not a threat. This occurs only when export of salt from the root zone is possible.

• Use of pumped (vertical) drainage is site specific and requires a transmissive aquifer, good quality water, and a disposal plan. Salinisation of the aquifer is a problem if there is no salt disposal and if the pumped aquifer is bounded by systems with higher salinity.
Chapter 4

Regional groundwater impacts on drainage systems

Lateral subsurface flows are due to a hydraulic gradient to the area with subsurface drainage from surrounding areas. Eching et al. (1994) developed a methodology for separating the contribution of regional groundwater from that of deep percolation in total drain flow by studying the drain flow and salinity relationship. They found that with drains 2.5 m deep and 150 m apart on a deep sandy loam soil, 64% of the drain flow was from regional groundwater. They were able to derive this by assuming that the increase in drain flow after irrigation is due to deep percolation. Also assuming that the salinity of the regional groundwater flow was that measured some time after irrigation when all the flow was from groundwater the salt load of the regional groundwater could be established by mass balance. Knowing the flow and salinity at the sump and the salinity and flow of the regional contribution the salt load from deep percolation was estimated.

van der Lely (1993) in assessing new horticultural developments in the MIA, found that in areas where they would be surrounded by undrained land with high water tables there could be large volumes of lateral inflow to the drainage system, Table 5. This would result in much larger potential drainage volumes than where drainage was installed in a farm already surrounded by drained farms.

Table 5. Groundwater flow rates to drained horticultural developments

<table>
<thead>
<tr>
<th>Region</th>
<th>Surrounding WT depth (m)</th>
<th>WT depth in Horticulture (m)</th>
<th>Aquifer Transmissivity (m²/day)</th>
<th>Flow time in clays (days)</th>
<th>Drainage rate* (ML/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilbul</td>
<td>1.3</td>
<td>1.6</td>
<td>&lt;5</td>
<td>1000</td>
<td>&lt;0.11</td>
</tr>
<tr>
<td>Kooba</td>
<td>1.2</td>
<td>1.6</td>
<td>100</td>
<td>500</td>
<td>0.93</td>
</tr>
<tr>
<td>Kooba</td>
<td>1.2</td>
<td>1.6</td>
<td>20</td>
<td>1000</td>
<td>0.32</td>
</tr>
<tr>
<td>Kooba</td>
<td>1.2</td>
<td>1.6</td>
<td>50</td>
<td>1000</td>
<td>0.60</td>
</tr>
<tr>
<td>Hanwood</td>
<td>1.2</td>
<td>1.6</td>
<td>50</td>
<td>250</td>
<td>0.97</td>
</tr>
<tr>
<td>Whutton</td>
<td>2.0</td>
<td>2.0</td>
<td>200</td>
<td>200</td>
<td>0</td>
</tr>
</tbody>
</table>

* Assuming 20 hectares of horticulture, a 1000 metre length of effective perimeter for flow, a buffer area of 50 metres. After van der Lely, (1993)

On-farm monitoring of drainage by Christen and Skehan (1998) found that drain flow
occurred in the periods intervening irrigations, as shown by the flows in Figure 14 where there is zero irrigation. These flows were caused by regional recharge to water tables generating drainage. This may be from general recharge on adjoining farms or recharge due to leaking supply channels.

![Figure 14. Relationship between irrigation and subsurface drainage (furrow irrigation)](image)

Christen and Skehan (1998) when analysing drainage flows from a farm tile drainage system found that most drainage occurred when water tables were high on the farm after irrigation or rainfall. The relatively small amounts of drainage, about 0.5 mm/day, that occurred between irrigations occurred when water tables had declined to a deep level, below the level of most of the drainage system, Figure 15. In this situation the small amount of drainage generated must occur from the deepest part of the tile drainage system, in this case below 180cm, which is generally the main lines into which the shallower laterals drain. In this situation some kind of control that restricts drainage from the system once the water table has dropped adequately on the main part of the farm would be useful in reducing drainage volumes.
Drain flow from other regional sources may be significant. This was found by Christen and Skehan (1998) when monitoring the perimeter tile drainage line around a drip irrigated vineyard. Adjacent to the vineyard was a rice crop, which was slightly higher in elevation and located on soils with some prior stream activity. Figure 16 shows the drain flow whilst the rice crop was ponded with water and the decline once the rice crop was drained. In the following season when no rice was grown on the neighbouring paddock the flow from the drains fell to a negligible level.

When considering regional water flow the effect of drain depth is an important factor. The deeper drains are installed the more drainage they are likely to generate due to regional effects. Figure 17 shows the drain flows that could occur if drains are installed below the regional water table level. For horticultural soils in the MIA, at a typical drain spacing of 40m, if drains are 0.5m below the regional water table, then up to 1ML/ha/yr (100mm/yr) of drainage could occur.

These results show the importance of site selection together with drainage design and management with regard to regional effects.
Figure 16. Perimeter drain receiving inflow from outside the vineyard

During ponding of rice crop

After rice crop drained

Figure 17. Effect of drain depth on flow due to regional influences

- Drains 1m below regional wt
- Drains 0.5m below regional wt
- Drains 0.1m below regional wt

Drainage (ML/ha/yr) vs. Drain spacing (m)
4.1 Summary information for BMP's

- Regional effects can contribute significantly to drainage flow. When possible site selection should avoid areas where there is likely to be significant outside influences on the drainage system.

- The impact of regional influences can be reduced by system design and management that keeps drains above regional water table levels or controls drain flow. With new developments installing subsurface drainage there should be an aim to continue this general trend of not intercepting large flows from the regional groundwater by careful site selection and drainage design. This will enable the farmer to have control over the volume and quality of the subsurface drainage, which would not be possible if there were large inputs of regional flow to the drainage system.
Chapter 5

Integrating irrigation and drainage management

5.1 Shallow ground water use by crops

To minimise the amount of water requiring drainage we can encourage crops to ‘reuse’ excess deep percolation from irrigation by accessing the shallow water that builds up after irrigation.

There is extensive literature quantifying crop water use from shallow ground water from both humid and irrigated areas throughout the world. The Maas-Hoffman (Maas and Hoffman, 1977) threshold for plant salt tolerance has generally been used to establish the potential for plant use of saline water without any adverse effects on yield. It was theorized by van Schilfgaarde et al. (1974) that plants could use higher salinity water than previously thought possible without any deleterious effects on yield. Hutmacher et al. (1996) demonstrated that cotton and tomatoes used ground water with an electrical conductivity approximately equal to twice the Maas-Hoffman threshold at the same rate as low-salinity water (< 0.4 dS/m).

Field and lysimeter studies have quantified crop use from shallow ground water for a wide range of crops. In a semi-arid area with low salinity ground water, Benz et al. (1978) found lucerne, sugar beet, and maize all used significant amounts of water from a shallow (< 1m) watertable.

Using column lysimeters Namken (1969) determined that cotton could get up to 60% of its water requirement from a saline watertable (1.6 dS/m) at a depth of 0.9 m. This is consistent with the data of Wallender et al. (1979), who found similar ground water use by cotton from saline water (5-7 dS/m) at a depth of up to 2 m. Hutmacher et al. (1996) found that cotton water uptake from a depth of 1.1 m was not affected by ground water salinity until the salinity was in excess of 15 dS/m. Grimes and Henderson (1984) determined in field studies that crop water use for cotton and lucerne from shallow saline ground water was a function of both depth to ground water and salinity of ground water. They determined that percentage uptake
by lucerne was in the range of 14 to 45% of the crop water use depending on the equation used to calculate reference crop evapotranspiration (ET$_{0}$). Water use from shallow ground water by cotton ranged from 27 to 60% again depending on the calculation of ET$_{0}$.

Kruse et al. (1985) using lysimeters determined that maize grown in the presence of saline ground water (6 dS/m) obtained approximately 55% of its water requirement when that watertable was within 0.6 m of the ground surface. They found that increasing the depth to ground water had a larger effect on reducing crop uptake than did the increase in ground water salinity. The maize was irrigated with a low salinity water typical of the Colorado River at Grand Junction, Colorado.

Using lysimeters, Meyer et al. (1996) determined that lucerne would use from 13 to 55% of its crop requirement from shallow ground water depending on soil type and ground water salinity when the watertable was maintained at a depth of 0.6 m. The percentage contribution was lower for finer textured soil and higher ground water salinity. With an EC of 1.6 dS/m in the ground water the contribution was in the range of 22 to 55%. When the ground water salinity was increased to 16 dS/m the contribution reduced to 13 to 25%.

Crop age influences potential ground water use in two ways. First, it has been demonstrated that plants tend to be more salt sensitive during early growth stages than in later growth stages (Maas, 1986). This suggests that as a plant matures it would have the potential to extract poorer quality from ground water than might be indicated by the salt tolerance classification. Roots have to be in the vicinity of the watertable to maximize the uptake potential, and the extent of rooting is the second factor affected by crop age. The potential for crop water use increases as the root system develops in volume and length during growth. Borg and Grimes (1986) characterized the development of the root system based on the plant growth in relation to days to maturity. In arid areas, plant and root development can be estimated reasonably well and used to characterize the changes in volume of stored soil water and the position of the root system in relation to the watertable. This information is needed to develop an irrigation scheduling methodology that includes crop water use from shallow ground water.
Dugas et al. (1990) determined the effect of soil type on soybean crop water use from ground water at a depth of 1.0 m. They demonstrated that use of water from shallow ground water was reduced in a soil with a high percentage of clay and a compacted layer compared to a less dense soil without a compacted layer. The reduced hydraulic conductivity in the compacted soil and the reduced root length density in the zone above the watertable were responsible for the reduction in water use.

They (Dugas et al., 1990) also determined that the extraction from the ground water was increased as the soil water content was reduced in the upper portion on the root zone. This increased hydraulic gradients and increased the potential for water to move into the root zone. The majority of the crop water use came late in the season as a result of the reduction in soil water. This was also demonstrated by Wallender et al. (1979) in a field study on cotton.

5.2 Managing irrigation for crop use from shallow ground water

Water quality and irrigation management will have a significant effect on the potential for crop water use from shallow ground water. Plants will selectively extract water from the portion of the root zone having the highest potential either due to low salinity or high water content. As long as these conditions are maintained, there will be little extraction from the ground water. Water uptake from shallow ground water has to be induced by reducing the stored water in the root zone and then irrigating in a fashion that requires extraction from the watertable to meet the crop water requirement. By extending the irrigation interval it is possible to achieve this effect. Using an indicator such as leaf water potential for scheduling has successfully extended the irrigation interval and increased shallow ground water contributions (Kite and Hanson, 1984).

Irrigation method also affects the potential extraction. Surface irrigation methods are limited in the minimum possible application depth and depths of application fall in the range of 50 to 100 mm. Maximum ground water use occurs at the end of the irrigation interval just prior to the next irrigation. This is particularly true in the early growth stage when the root system is
still small. The most effective method to increase shallow ground water use with surface irrigation will be to extend the irrigation interval with alternative scheduling methods and to eliminate the final irrigation.

Pressurized systems such as sprinkler and drip allow automated operation of the system with good control on the depth of application. With drip irrigation the irrigation interval is set for daily or near daily applications. When this is the case the application depth has to be determined by underestimating the previous days crop water use. By routinely deficit irrigating it is possible to induce extraction from the stored soil water and then from the ground water. If water is applied to meet the previous days Et, no potential is established for water extraction from other sources, such as stored soil water and ground water. Irrigation should begin only after the root zone soil water has been lowered. Sprinkler systems are ideally suited for use in maximizing potential crop water use from ground water because the depth of application can be controlled with greater precision than surface systems such as furrow and flood.

Use of shallow ground water as a supplemental water supply in irrigated agriculture is sustainable if several conditions can be met. The source of water supplying the ground water will be a major factor in determining the sustainability as will the ground water quality. If the ground water is the result of poor irrigation practices, the volume available is limited if irrigation is improved and deep percolation reduced. Lateral inflows are potential sources of water but these need to be quantified to determine the volume and extent of the supply and whether it is a result of poor irrigation practices or rainfall.

The salinity of the ground water will determine whether, and how much, water will be extracted by the plant, and the effect on soil salinity. Crop use transports both salt and water up into the profile but the salt remains after the water is extracted. This leads to a gradual salinization of the soil that eventually eliminates production if not properly managed. Leaching of salts is the required management and requires application of water (irrigation or rainfall) in excess of water demand and disposal as drainage water. If disposal of drainage water is not possible then lateral flow from the area or deeper percolation will be required to
remove the salt. There is little incentive to implement management systems that increase shallow ground water use if yields are not maintained.

Maximizing the potential water use will require the integrated management of the irrigation and drainage system. The crop has to be well established and growing vigorously for the system to work. At germination and early growth there is essentially no water use from the ground water by the crop. After the plant is established the irrigation management is directed to extending the root system and drying down the upper part of the root zone. This is accomplished through extending the irrigation interval and reducing the applied water. By under-irrigating the crop, the plant will seek alternate water sources and begin to use more water from deeper in the soil profile and from shallow ground water in preference to reducing soil water in the upper portions of the root zone.

Leaf water potential (LWP) has been used effectively to schedule the irrigation timing in cotton. This technique integrates both the osmotic and matric potentials being experienced by the plant. Grimes and Yamada (1982) established threshold values to initiate irrigation of cotton based on plant development. Similar values are not available for other crops, limiting the utility of this technique.

The depth of application needs to be determined after the time of irrigation is established. This is done by methods such as soil sampling or measurement with neutron probe, or another soil water sensing device. Water balance calculations to determine both the timing and depth of application are generally not possible in shallow ground water systems since the ground water contribution to crop water use is not known. Ayars and Hutmacher (1994) modified a cotton crop coefficient to account for the ground water contribution to evapotranspiration as a function of ground water salinity and depth to ground water. Application of this technique permits water balance determination of a cotton irrigation schedule that includes both depth and timing.
5.3 Managing drainage systems for crop use from shallow ground water

Part of the integrated management requires maintaining the watertable at a depth that is readily available to the plant later in the growing season. This is accomplished by restricting the flow in the drains or checking the outlet of the system to maintain the watertable at a higher depth than was used in the design. This is similar to the technique used for sub-irrigation in humid areas (Fouss et al, 1990). It is difficult in arid areas because the drain configuration is such that the laterals run parallel the surface slope and raising the watertable depth at the tail end of the field will have little impact on the head end of the field. In these situations, in-field control is needed to distribute the ground water over a larger area. For new systems, the drainage laterals and mains should be installed such that the laterals are placed approximately perpendicular to the field surface slope and the collector submain is installed such that the flow and depth can be controlled at several points along its length. Placing control structures at the edge of the field will minimize obstructions in the field.

Ayars and McWhorter (1985) demonstrated that when crop water use from shallow groundwater was included in the drain design that the total flow from the drainage system was reduced by nearly 60%. Incorporating crop water use in the design also resulted in wider lateral spacing than would otherwise have been calculated. The crop water use effectively reduced the drainage coefficient.

Based on his research, Doering et al. (1982) proposed a shallow drainage installation concept to increase crop water use from shallow ground water for semi-arid areas with good quality ground water. Implementation of this concept would reduce drainage discharge and applied irrigation water and result in improved irrigation efficiency thus saving water and energy (Benz et al, 1987). Maximum effect is achieved when the new system design is coupled with outlet control. Reducing depth of installation and drain spacing results in the watertable being closer to the soil surface throughout the growing season. Also, the shallower depth of drains means the volume of water stored between 1.5 and 2.1 m is available for plant use. When drains are placed at a depth of 2.1 m the watertable is drawn down quickly and the water is not available for plant use. Shalhevet (1994) stated that the critical design aspect of drainage
design was maintenance of aeration status plus providing adequate leaching. Both of these criteria can be met with the proposed modifications in design and management of subsurface drainage systems.

An alternative technique for reducing drainage discharge has been proposed by Manguerra and Garcia (1997) using drains installed at a depth of 2.1 m. They proposed a series of alternating drainage and no drainage cycles. In this proposal, after a leaching event the drains are closed and no drainage is permitted until the watertable rises to a predetermined depth or until soil salinity levels are reached which damage yields. At this time the drains are opened and drainage and leaching occur and then process begins again. For this procedure to be effective the drainage system layout will need to be configured to distribute the watertable as uniformly as possible under the field.

Together with these investigations into alternative drainage design the integration of drainage management into irrigation practice has recently been investigated for arid areas, Table 6. Unlike the management of drainage systems for irrigation in humid areas, which has long been in use (Fouss et al. 1990) the management of water tables in arid areas is relatively untested. However, the incorporation of a shallow groundwater component to crop water use has been investigated by Ayars & Hutmacher (1994), Wallender et al. (1979), Meyer et al. (1996). These workers have shown that crops can use water from shallow water tables but have not specifically managed the water table to achieve this.

Table 6. Crop water use on shallow watertables

<table>
<thead>
<tr>
<th>Crop</th>
<th>Watertable salinity (dS/m)</th>
<th>Watertable depth (m)</th>
<th>Water use from watertable (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomatoes</td>
<td>3 – 8</td>
<td>1 – 2</td>
<td>17</td>
<td>Ayars (1996)</td>
</tr>
<tr>
<td>Cotton</td>
<td>4 – 5</td>
<td>1.5 – 2.5</td>
<td>35</td>
<td>Ayars (1996)</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>5</td>
<td>1.2</td>
<td>45</td>
<td>Hutmacher et al (1989)</td>
</tr>
</tbody>
</table>

In a field experiment Ayars (1996) showed that by combining irrigation management to take advantage of a shallow water table and actively managing the subsurface drainage system to
create a shallow water table significant savings in irrigation water and decreased drainage volumes could be achieved. To maintain shallow water tables Ayars (1996) put valves on the drain laterals and weirs on the main. To force the crops to use the shallow groundwater he adapted the crop factors for the depth and salinity of the water table resulting in a deficit irrigation schedule. A cotton crop was grown with a water table at 1.5 m with a salinity of 4 - 5 dS/m. The calculated crop water requirement was 510 mm fully irrigated but only 330 mm was applied in the deficit irrigation schedule. Despite this deficit irrigation the crop was not found to be stressed and the cotton yield was 1500 - 2300 kg/ha that compared well with the district average of 1500 kg/ha. In the following season the field was divided into three water table areas; shallow, medium and deep for comparison in a tomato crop. The shallow area started at 1.5m deep and finished at 2.2 m, the medium area went from 1.8 to 2.6 m whilst the deep area went from 2.2 to 2.6 m. The highest tomato yields, 114 t/ha were measured in the shallow and medium areas, whilst the yield in the deep area was only 63 t/ha. Maintaining the shallow water table reduced the tomato crop irrigation requirement by 141 mm.

5.4 Summary information for BMP’s

- Plants use significant quantities of water from shallow water tables and hence improving overall water use efficiency and reducing drainage coefficient.

- Depth to water table criteria should be based upon avoiding waterlogging of the plant root zone only.

- Plants have higher salt tolerance limits than previously considered.

- Over drainage that draws down water tables beyond where plants can access and use the water should be avoided.

- Water table depth should be a function of the plants ability to use water from shallow ground water, root depth, crop growth stage, and water table salinity.
- Drainage is required to manage soil salinity in the crop root zone.

- Irrigation management needs to be modified to induce shallow ground water use by crops.

- Drainage system design should include aeration, water logging and salinity control on a seasonal basis.
Chapter 6

Drainage of heavy clay soils

6.1 Water flow to drains

Water table response to tile drains in clay soils behave differently to that expected by drainage theory due to the low hydraulic conductivities and a high degree of anisotropy (marked difference between hydraulic conductivity in horizontal and vertical directions). Grismer and Todd (1991) studied a clay soil where the vertical conductivity was about 10 times lower than the horizontal in the topsoil layers and about 5 times lower in the deeper layers, Table 7. This results in preferential horizontal water movement in these types of soils, Figure 18.

<table>
<thead>
<tr>
<th>Depth below ground level (m)</th>
<th>Vertical hydraulic conductivity (mm/d)</th>
<th>Horizontal hydraulic conductivity (mm/d)</th>
<th>Ratio Kh/Kv</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13 - 0.7</td>
<td>149</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>0.61</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.38 - 1.7</td>
<td>22</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>0.91</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.22</td>
<td>3.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


The anisotropy in clay soils results in relatively flat water tables between drains with sharp draw down occurring very close to the drain. A typical series of watertable draw down curves with time after an irrigation is shown in Figure 19. When water tables are high the water table is drawn down sharply above the drain but remains flat between the drains. At this time water flow is mostly horizontal. As the water tables decline and the anisotropy in hydraulic conductivity becomes less marked the water table shape becomes more curved.
Figure 18. Sources of drainage flows,

![Diagram of Drainage Flows](image)

Todd and Grismer, (1991)

Figure 19. Watertable profiles with time after irrigation in a clay soil

![Watertable Profiles Diagram](image)

Todd and Grismer, (1991)

It can be seen that the water table recession rate decreases with time as the water table moves through deeper, lower conductivity soil. The water level decline in close proximity to the drain
is due to the greater permeability of the backfill material in the trench over the drain. In this system the drainage flows increased to a maximum 5 - 10 hours after irrigation and the drain water salinity dropped sharply by about 2 dS/m during this time. After about 40 hours the drain flow was back to pre irrigation rates, the water table in the backfilled trench was at drain level. At this time the soil between the drains remained largely saturated, thus the drains were ineffective at drawing down the mid drain water table, further water table decline is by vertical leakage past the drains and upflow to the root zone. The drain flow rates were largely a result of flow down the backfilled trench.

Trench flow occurs because the permeability of the backfilled material is significantly higher than that of the undisturbed surrounding soil. This results in large amounts of water flowing directly to the drain. Irrigation water becoming trench flow is not subsequently available for crop water use; neither does it leach salts from the soil profile outside the trench. Todd and Grismer (1991) found that in heavy clay soil, trench flow accounted for almost all of the drain flow for 40 hours after an irrigation. The drainage water from trench flow is less saline than later flows and thus is more suitable for reuse. Alternatively the drains maybe prevented from discharging during an irrigation to reduce this trench flow.

As can be seen from the above discussion the challenge is are to provide cheap and effective drainage for areas of heavy clay soils. To effectively drain clay soils, traditional pipe (tile) drains at about 1.8m depth would need to be 5 - 10 m apart. This is very expensive at about $5000/ha. Further to the problem of draining these soils the disposal of saline drain water is problematic. Drainage disposal to surface water courses is becoming highly restricted as downstream users demand improved water quality and the protection of the riverine environment.

6.2 Mole drainage

Mole drains offer a potential solution to the dual problems of effectively draining heavy clay soils whilst producing the least amount of saline drainage effluent.
6.2.1 Installation and costs

A mole drain is a tunnel 75-100 mm in diameter formed in clay soil by a mole plough. This unlined tunnel acts as a conduit to remove water from the soil, Figure 20. Mole drains are generally spaced about 2 m apart and are 0.5 – 0.8 m deep. This provides an intensive drainage system suitable for heavy clay soils that quickly removes excess water from the root zone and intercepts less saline groundwater than deeper traditional pipe drains.

Mole drainage is a cost effective option for clay soils, where existing surface drains can be used. The cost is ~ A$130/ha, about the same as for deep ripping. Where surface drains have to be dug, then a 20 ha field can be drained for about A$300/ha, (Moll 1995). This is the initial cost, remoling every 3 or 4 years will then cost A$130/ha.

In most cases a pump and sump are used with drainage pipe to collect the water from mole channels. The costs are about A$1500/ha with collector mains every 200 m running back to a sump and pump. If the same amount of money per hectare were spent on pipe drains the drains would have to be 80 m apart. For drains 30 m apart, which would still not give as intensive
drainage as moles, the cost would be about $3000/ha, (Moll 1995).

The potential for mole drainage is clear, however there are significant difficulties in ensuring that mole drainage can function effectively in the Riverine plain. The greatest problem is that of mole stability; most heavy clay soils are slightly to severely sodic and thus ensuring that the mole drains remain stable for a reasonable length of time (3 – 5 years) is essential. Also affecting mole stability is the problem of preferential flow of surface irrigation water into the mole drains causing dispersion, erosion and collapse. However, this can be reduced greatly by preventing flow from the drains during irrigation events and also placing the mole drains away from where irrigation water is ponded, (Christen and Spoor, 1999). A further factor limiting mole stability and their cost effectiveness is the low slope in most irrigation areas, about 1:2000, 0.05%. This restricts the length of mole runs and also requires accurate grade control to prevent back grades. Associated with the flat landscape is the absence of widespread opportunities to use gravity outfalls for subsurface drainage. Thus most systems will need to be reticulated back to a sump and pump.

6.2.2 Waterlogging control and yield

Trials with mole drains in the Murrumbidgee Irrigation Area (MIA) have consistently shown that the soil in moled areas is less waterlogged than in areas with no subsurface drainage, waterlogging was taken as when the watertable was within 400 mm of the soil surface and yields increased, Table 8.

Despite the reduction in watertables it was found that the soil air filled porosity was low (<10%) below 300 mm depth. This indicates that on heavy clays the soil porosity is so low that drainage alone has a limited effect. For increased yields drainage must be in conjunction with soil management that increases the soil porosity.
Table 8. Reduction in waterlogging and yield improvement with mole drainage

<table>
<thead>
<tr>
<th>Crop</th>
<th>Number of days watertable in rootzone (&lt;400 mm)</th>
<th>Reduction in waterlogging</th>
<th>Yield increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moled soil</td>
<td>Unmoled soil</td>
<td></td>
</tr>
<tr>
<td>Onions (1991)</td>
<td>17</td>
<td>47</td>
<td>64%</td>
</tr>
<tr>
<td>Tomatoes (1992)</td>
<td>12</td>
<td>18</td>
<td>33%</td>
</tr>
<tr>
<td>Wheat– red clay (1993)</td>
<td>9</td>
<td>12</td>
<td>25%</td>
</tr>
<tr>
<td>Wheat– grey clay (1993)</td>
<td>29</td>
<td>35</td>
<td>17%</td>
</tr>
<tr>
<td>Tomatoes (1995)</td>
<td>7</td>
<td>11</td>
<td>36%</td>
</tr>
</tbody>
</table>

Data from Christen (1994) and Muirhead et al (1995)

6.2.3 Mole drainage salinity and salt loads

The trials with mole drainage also showed that salt is removed from the soil profile. Over a 3 year period the mole drains in one trial removed 1.9 tonnes/ha of salt, about the same amount as was applied in the irrigation water (Muirhead et al. 1995). In another 2 year trial the mole drains removed 1.5 tonnes/ha of salt in rainfall events alone (Christen 1994). These results suggest that using mole drainage can also help to prevent soil salinisation. Muirhead et al. (1995) found that the discharge from mole drains had much lower salinity than that from deeper pipe drains. The mole drain salinity from these trials was 1 - 2 dS/m making the disposal of the water more acceptable than the very saline usually associated with subsurface drainage in this region. Another trial compared mole drains 0.7 m deep and 3.6 m apart with pipe drains 1.8 m deep and 20 m apart in a vineyard situation, (Christen and Skehan, 2001). The trial was established to compare drain water quality and drain performance. The mole drain water was around 2 dS/m whereas the pipe drainage was 11 dS/m. Also it was found that the moles flowed only infrequently, after irrigation and rainfall events, and thus drained much less water than the deeper pipe drains, that flowed continuously, due to regional groundwater effects. This resulted in much reduced salt loads from the mole drains, Table 9.
Table 9. Drainage and salt load over two seasons

<table>
<thead>
<tr>
<th>Factor</th>
<th>Pipe Drains</th>
<th>Mole Drains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage (mm)</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Mean salinity (dS/m)</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Total salt load (t/ha)</td>
<td>5.9</td>
<td>0.3</td>
</tr>
</tbody>
</table>


6.3 Summary information for BMP’s

- Effective drainage of clay soil requires narrow drain spacing, which is expensive.
- Reclamation of clay soils difficult because of low hydraulic conductivity and potential high degree of anisotropy and macro pore flow.
- In heavy clay soils shallower drains tend to have lower drainage water salinity
- Mole drainage offers the potential to drain heavy clay soils, but it has not been widely adopted in irrigated areas.
Chapter 7

Review of current performance of subsurface drainage systems in Australia

This chapter provides a review of current irrigation design and management in Australia and the drainage performance. This is based on a Journal paper by Christen et al., (2001).

7.1 Introduction

Use of subsurface drainage has been the historical remedy for poor irrigation practice both in Australia and throughout the world. However, since the 1980’s more emphasis has been placed on improved irrigation practices in Australia. Most irrigated areas in Australia have Land and Water Management Plans that focus on sustainable land management and irrigation in their area, through the development of land management plans and by improving irrigation efficiency.

Waterlogging and salinisation are the result of shallow watertables, and subsurface drainage systems are installed to treat these conditions. These systems are usually associated with high value crops such as perennial horticulture, cotton, sugar cane, and perennial pasture for dairying. Horizontal pipe drains are often used for perennial horticulture and pumping from tubewells or spearpoints are often used to control the water table in perennial pasture.

It is demonstrable that most existing irrigation development throughout the world has resulted in deep percolation past the root zone, recharging both shallow and deep groundwater. It has often been found in Australia that watertables rise under irrigation projects at around 0.5 m per year due to losses from flood irrigation. This continues until a new water table position is established with the watertable fluctuating from the soil surface to a depth of approximately 3 m in response to laterals flows, evaporation, and deep percolation losses. A significant part of all irrigation areas in Australia have water tables currently either in this equilibrium condition or approaching it. Irrigation areas in southeastern Australia, particularly in the Murray Darling
Basin (MDB), have 75% or more of their land area in this shallow watertable regime. Environmental quality considerations have significantly limited the option of irrigated agriculture discharging saline drainage water into a surface water body. Water quality standards that set the salinity levels in streams and rivers have resulted in the establishment of salt load limits for each irrigation area discharging into a stream or river. These limits are calculated based on the total drainage discharge from the area and the salinity of the drainage water.

In the MDB the salt load limit is a major constraint to the expansion of subsurface drainage. The salt load limit is imposed upon irrigation areas in terms of their disposal of saline water into the river systems. This has led to the conjunctive reuse of drainage water and evaporation basins as alternative saline drainage water disposal mechanisms. Conjunctive reuse of drainage water with fresh irrigation water is widely practised in areas using groundwater pumping for water table control. Evaporation basins have allowed the drainage of 40,000 ha in the Wakool area (into a 2100 ha basin) and continued drainage from perennial horticulture along the lower Murray and in new horticulture in the Murrumbidgee Irrigation Area. Other options such as disposal to woodlots and serial biological concentration (Heath, et al., 1993) are being considered and researched (Blackwell, et al., 2000). This paper analyses the current state of subsurface drainage in irrigated agriculture in Australia, in terms of drainage design and management practices, and possibilities for improved design and management that might allow drainage to continue and expand in the future.

7.2 Methodology

This paper uses data from a review of irrigation and drainage practices in Australia edited by Christen and Hornbuckle (2001). In the review, local experts provided the biophysical conditions and practices in ten major irrigation region. The regions had varied types of subsurface drainage systems covering areas from 100’s to 10,000’s hectares.

The review provided data for each area that included; description of cropping and annual irrigation volume (also irrigation water quality), description of the drainage problem,
description of the drainage methods and design criteria used and values for the annual volume and salinity of drainage waters. For the irrigation and drainage data average annual values were provided based upon data collected by State agencies in each area. The data was given as a range representing the different cropping systems in each region. The data represent area averages and long term (> 10 years) values, rather than experimental data. These were the best area wide estimates from the most credible sources.

The information on irrigation and drainage water volumes and salinity were taken from the review and used in this paper to assess the performance of the drainage systems in each region. The factors considered were a) the design drainage volume, b) required leaching fractions for sustainable crop production, c) salt input/output ratios, and d) salt mobilisation and drainage disposal. These analyses include an assessment of individual case studies highlighting areas where design or management may be improved. A general description of each region and the drainage method in the region is provided in the following section to assist in understanding the data and analyses. All regions are dominated by surface/flood irrigation and have similar heavy soils (clay to clay loams).

7.3 Comparison of regions

7.3.1 Crops and irrigation

The major cropping systems in the irrigation regions are given in Table 10 along with data on the irrigation and drainage water quantity and leaching fractions. The irrigation amount is given as a range where there are diverse irrigation practices in a region.

The method of irrigation is important in understanding the problem with high water tables. Surface irrigation methods are typically the least efficient in terms of distribution uniformity and application efficiency and as a result there are significant losses of water to deep percolation. Most field crops (pasture, rice, sugarcane, cotton) are surface irrigated using either flood or furrow irrigation. Horticulture is moving away from flood irrigation to furrow
irrigation with some regions having converted the entire perennial horticulture to microspray or drip irrigation. The development of drainage problems and the current status of drainage varies from region to region. Most problems are related to the watertable rise caused by deep percolation losses from irrigation, with the severity of the problem depending upon the local hydrogeology, history of high watertables and type of irrigation used.

### Table 10. Major crops, irrigation and drainage quantities and leaching fraction

<table>
<thead>
<tr>
<th>Region</th>
<th>Major Crop</th>
<th>Average Annual Irrigation (m)</th>
<th>Average Annual Drainage (m)</th>
<th>Leaching fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdekin</td>
<td>Sugarcane</td>
<td>0.9</td>
<td>0.15</td>
<td>17</td>
</tr>
<tr>
<td>Emerald</td>
<td>Cotton</td>
<td>0.34</td>
<td>N.A.</td>
<td>-</td>
</tr>
<tr>
<td>Kerang</td>
<td>Perennial pasture</td>
<td>0.6 – 1.0</td>
<td>0.1 – 0.4</td>
<td>31</td>
</tr>
<tr>
<td>Macalister</td>
<td>Perennial pasture</td>
<td>0.5</td>
<td>0.05</td>
<td>10</td>
</tr>
<tr>
<td>Mid Murray</td>
<td>Rice and pastures</td>
<td>0.8 – 1.6</td>
<td>0.3 – 0.6</td>
<td>37</td>
</tr>
<tr>
<td>Murrumbidgee/</td>
<td>Perennial/annual horticultural crops</td>
<td>0.4 – 0.8</td>
<td>0.05 – 0.2</td>
<td>20</td>
</tr>
<tr>
<td>Coleambally</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riverland</td>
<td>Perennial horticulture</td>
<td>0.6 – 1.2</td>
<td>0.1 – 0.2</td>
<td>17</td>
</tr>
<tr>
<td>Shepparton</td>
<td>Perennial pasture</td>
<td>1.0</td>
<td>0.1 – 0.3</td>
<td>20</td>
</tr>
<tr>
<td>Sunraysia</td>
<td>Perennial horticulture</td>
<td>0.6 – 1.2</td>
<td>0.1 – 0.15</td>
<td>14</td>
</tr>
<tr>
<td>SWIA</td>
<td>Perennial pasture</td>
<td>0.7 – 1.4</td>
<td>0.5</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 7.3.2 Drainage methods and design criteria

Drainage objectives will vary depending upon the drainage problem and crop type, as will the drainage method. Table 11 outlines the drainage objectives and methods for the irrigated regions of Australia where subsurface drainage is present.
## Table 11. Drainage objectives and methods

<table>
<thead>
<tr>
<th>Region</th>
<th>Drainage objective</th>
<th>Drainage method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdekin</td>
<td>WT control and subsequent prevention of soil salinisation</td>
<td>Vertical 30 m deep, protecting about 40 ha each</td>
</tr>
<tr>
<td>Emerald</td>
<td>WT control and subsequent prevention of soil salinisation</td>
<td>Cross slope interceptor pipe drains. One drain 2.5 - 4m deep, additional drains 150 – 200 m apart if required</td>
</tr>
<tr>
<td>Kerang</td>
<td>Salinity control</td>
<td>Vertical, 5-15 m deep, protecting perennial pasture and experimental horizontal drains 70m apart, also relief of artesian pressures</td>
</tr>
<tr>
<td>Mid Murray</td>
<td>WT control and subsequent prevention of soil salinisation</td>
<td>Shallow vertical with evaporation basin</td>
</tr>
<tr>
<td>Macalister</td>
<td>Salinity control - protection of low-lying areas from salinisation, where WTs are less than 2m. Partially pumping/reclamation in the low lying areas and partially interception of groundwater recharge/flows to the low lying areas</td>
<td>Vertical, 5-15 m deep, protecting 200 - 2000 ha each</td>
</tr>
<tr>
<td>Murrumbidge/Coleambally</td>
<td>WT control and subsequent prevention of soil salinisation for perennial horticulture, salinity control for other crops.</td>
<td>Horizontal drains or vertical spearpoints for perennial horticulture, Vertical for other crops.</td>
</tr>
<tr>
<td>Riverland</td>
<td>WT control and subsequent prevention of soil salinisation</td>
<td>Horizontal drainage, grid pattern, 10-30m apart</td>
</tr>
<tr>
<td>Shepparton</td>
<td>Salinity control for pasture, WT and salinity control for horticulture</td>
<td>Vertical 5-20 m deep protecting 100-200 ha each for perennial pasture and horizontal drains or spearpoints (~25 ha each) for perennial horticulture</td>
</tr>
<tr>
<td>Sunraysia</td>
<td>WT control and subsequent prevention of soil salinisation</td>
<td>Horizontal drainage, interceptor drains on slopes, grid 13-40m apart</td>
</tr>
<tr>
<td>SWIA</td>
<td>Watertable and salinity control</td>
<td>Horizontal drainage in horticulture, composite tile (40-60m apart)+ mole (1-2m apart) systems in perennial pasture</td>
</tr>
</tbody>
</table>
7.4 Results

7.4.1 Drainage volumes

Drainage design criteria include the target watertable depth after irrigation or rainfall and a drainage coefficient. The criteria vary depending upon the drainage objective and method. These design criteria together with the actual long term drainage rate are given in Table 12, ranges of values are shown due to different crops and varying hydrogeological conditions.

The table shows a considerable disparity between the design drainage coefficient and the actual measured long term drainage rate. Where the design rate is given as a watertable depth subsequent to irrigation an average annual design drainage rate has been calculated using the drainage rate for that depth for each irrigation event multiplied by an average eight irrigation events per year.

The data from Table 12 of actual and design drainage rates for the different regional drainage were plotted as Figure 21, where data was available. The data was taken as the average of the ranges given.

The results show that in many cases the drainage systems are removing more water than the design criteria. This ‘extra‘ drainage is most often a result of a poor irrigation management, in terms of excessive application depth and poor uniformity, coupled with a lack of management of the drainage. For example, those systems that are operated using a target watertable depth that is measured at the "mid-drain" position in the field. In each case, the drainage system is installed considerably deeper than the target watertable depth for practical (draw down effect) and economic reasons. Thus, if the drains are not managed, the water table will inevitably be drawn below the target depth.
### Table 12  Design criteria and actual drainage for subsurface drainage systems

<table>
<thead>
<tr>
<th>Region</th>
<th>Drainage type</th>
<th>Target watertable depth</th>
<th>Design drainage coefficient (m/year)</th>
<th>Actual long term drainage rate (m/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdekin</td>
<td>Vertical</td>
<td>3 m</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>Emerald</td>
<td>Vertical</td>
<td>&gt; 1.2 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kerang</td>
<td>Vertical</td>
<td>&gt; 1.2 m</td>
<td>0.025 - 0.05</td>
<td>0.3 – 0.4</td>
</tr>
<tr>
<td>Kerang (Horizontal)</td>
<td>&gt; 1.2 m</td>
<td>0.29</td>
<td>0.1 – 0.2</td>
<td></td>
</tr>
<tr>
<td>MacAlister</td>
<td>Vertical</td>
<td></td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>Mid Murray</td>
<td>Vertical</td>
<td>&gt; 1.5 - 2.0 m</td>
<td>0.06 – 0.1</td>
<td>0.03 – 0.06</td>
</tr>
<tr>
<td>Murrumbidgee/</td>
<td>Vertical</td>
<td></td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Coleambally</td>
<td>Horizontal</td>
<td>0.45 - 0.75 m</td>
<td>0.05* - 0.12*</td>
<td>0.05 – 0.2</td>
</tr>
<tr>
<td>Riverland</td>
<td>Horizontal</td>
<td>0.9 - 1.1 m</td>
<td>0.12* - 0.21*</td>
<td>0.1 – 0.2</td>
</tr>
<tr>
<td>Riverland (1 week)</td>
<td>Horizontal</td>
<td>0.9 - 1.1 m</td>
<td>0.12* - 0.21*</td>
<td>0.1 – 0.2</td>
</tr>
<tr>
<td>Shepparton</td>
<td>Vertical</td>
<td>None</td>
<td>Private – 0.1 Public - 0.05</td>
<td>Private – 0.3 Public - 0.05</td>
</tr>
<tr>
<td>Sunraysia</td>
<td>Vertical</td>
<td>0.9 - 1.1 m</td>
<td>0.12* - 0.21*</td>
<td>0.1 – 0.15</td>
</tr>
<tr>
<td>Sunraysia (1 week)</td>
<td>Horizontal</td>
<td>0.9 - 1.1 m</td>
<td>0.12* - 0.21*</td>
<td>0.1 – 0.15</td>
</tr>
<tr>
<td>SWIA</td>
<td>Horizontal/</td>
<td>Watertable &lt; 0.3 m</td>
<td>10 mm/day**</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>mole</td>
<td>for less than 3 days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Converted from the target watertable depth,  ** Conversion not possible as designed for winter rainfall

This is especially true of horizontal drains which if unmanaged will draw down watertables to close to the drain depth. Most horizontal drainage systems are installed at around 1.2 to 1.8 m with some being 2 to 3 m deep, which is well below the target watertable depth for the reasons stated above. Prolonged pumping after the critical depth is reached "mid-drain" leads to extra water being drained.
There is a cone of depression with spearpoint systems and the greatest drawdown occurs next to the spearpoint. If a target watertable depth is to be maintained at some distance from the spearpoint then inevitably the watertable near the spearpoint will be drawn down to a greater depth than needed. In some cases the increased drainage from spearpoint systems above the design rate is due to institutional decisions. These mainly occur where the drainage water is of reasonable salinity and is reused on farm to supplement the water supply. In these cases higher drainage rates than strictly required have been allowed by management authorities to encourage investment in these systems. The tendency is for farmers to pump a lot in dry years when there is a shortage of surface water (periods when a lot of drainage is not actually required) and then use surface water in preference to groundwater in wet years when surface supplies are not limited. When farmers use the system purely as an irrigation resource, it is potentially in conflict with the objective of drainage for salinity control. For salinity control some pumping might be required every year including wet years. This will depend on the water table position and the previous years irrigation history. This is an institutional issue that needs to be addressed by incentives to manage spearpoint systems in a manner that meets both waterlogging and salinity control objectives.
The drainage system efficiency for the various regions was characterized by comparing the drainage volume with the irrigation applied for each drainage method. The drainage volumes are shown with the irrigation volumes in Table 10. Irrigation is in the range of 0.3 to 1.4 m/year and drainage 0.05 to 0.6 m/year. These are long term average values and it is expected that rainfall should be a relatively minor component of drainage.

Since the irrigation water salinity is very good for all regions (0.05 to 0.8 dS/m), we would expect a leaching requirement of 5 to 10% to maintain a salt free root zone using the method of Hoffman and Durnford (1999). Using the data for applied water and drainage in Table 10 and Table 12 the leaching fractions were determined to be in the range of 10 to 47%, with most being 15% or more. This is higher than is necessary to maintain a salt balance and is probably due to poor irrigation management and drainage management. The SWIA is the exception within this category as the rainfall there is close to 1000 mm, almost all falling in the winter.

The rainfall contribution to the drainage volumes is unknown. However, these results are mostly confined to arid areas (<500 mm rainfall) so it is unlikely that rainfall constitutes a large proportion, except SWIA. If rainfall is a large proportion of these drainage volumes, it can still be inferred that irrigation and drainage management is inadequate. Irrigation management should allow for rainfall, primarily by trying to maintain a relatively deep unsaturated zone to store rainfall for subsequent use by the crop. This will require the use of an irrigation system that has good control on the depth of application, i.e. sprinklers, micro-irrigation.

Drainage management should also be adaptive to rainfall events. It may be beneficial to allow watertables to rise after rainfall, so that water from the saturated zone may be accessed by plants. During some seasons, allowing watertables to rise will not affect crop performance because there may be no crop or it may be dormant. These considerations are directed at treating the unsaturated zone as a soil water store that if managed correctly can be a resource and indeed reduce irrigation requirements. With appropriate irrigation and drainage management rainfall should be used as the primary leaching mechanism in non-irrigation
Review of current performance of subsurface drainage systems

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periods conserving irrigation water for crop use.

7.4.2 Drainage salinity

Drainage water salinity is affected by groundwater salinity and drainage system design and management. Table 4 shows typical groundwater and irrigation water salinity and the resulting drainage water salinity which is a mix of the two. In broad terms for all the cropping systems represented in this study a drainage water salinity at the bottom of the root zone of 2 dS/m, representing, about a 10% leaching fraction will allow a sustained high level of crop production, (Hoffman and Durnford, 1999). As can be seen from Table 13, the drainage water salinity is often 5 to 10 times greater than this. This indicates that these systems are removing more salt than is applied with the irrigation water.

Table 13. Groundwater, irrigation water and subsurface drainage salinity (dS/m)

<table>
<thead>
<tr>
<th>Region</th>
<th>Groundwater</th>
<th>Irrigation Water</th>
<th>Subsurface drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdekin</td>
<td>0.1 - 21</td>
<td>0.3</td>
<td>6</td>
</tr>
<tr>
<td>Emerald</td>
<td></td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Kerang</td>
<td>30 - 50</td>
<td>&lt; 0.4</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Macalister</td>
<td>0.6 - 20</td>
<td></td>
<td>0.5 - 2</td>
</tr>
<tr>
<td>Mid Murray</td>
<td>0.5 - 66</td>
<td>0.06</td>
<td>Public 23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Private 0.5 - 3</td>
</tr>
<tr>
<td>Murrumbidgee /Coleambally</td>
<td>1 - 20</td>
<td>0.05 - 0.15</td>
<td>Horizontal 2 – 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vertical 5 - 20</td>
</tr>
<tr>
<td>Riverland</td>
<td>1.6 - 3.9</td>
<td>0.3 - 0.8</td>
<td>1.6 - 47</td>
</tr>
<tr>
<td>Shepparton</td>
<td>1 – 10</td>
<td>0.05 - 0.15</td>
<td>Private up to 3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public up to 10</td>
</tr>
<tr>
<td>Sunraysia</td>
<td>2 - 4</td>
<td>0.3 - 0.6</td>
<td>2 - 5</td>
</tr>
<tr>
<td>SWIA</td>
<td>5 - 40</td>
<td>0.25 - 2</td>
<td>2 - 10</td>
</tr>
</tbody>
</table>

Whether these drainage systems are draining the salt applied in irrigation water or are mining the salts in the groundwater can be further assessed by analysing the salt applied per ha in the
irrigation water to the mass that was drained. The range of irrigation applications, irrigation salinities, drainage volumes, and drainage salinities in each region were used in combination to make assessments for various mixes of crops, irrigation waters, drainage volumes, and salinity. The resulting data are presented in Figure 22.

**Figure 22. Salt loads in irrigation and drainage water**

The results of this analysis show that in many situations the salt drained is far in excess of that applied in the irrigation water. Commonly there is 5 to 10 times more salt drained than applied, and in extreme cases 25 to 45 times more salt drained than applied. These results indicate that a great deal of salt stored below the root zone is being mobilised by these drainage systems. Typical of arid environments, soil salinities increase rapidly with depth reaching very high salinity groundwater within 1 to 2 m. The depth of the flow path to a drainage system is related to both the depth of installation of the drain line and the spacing of the drain laterals. Typically, as the drain lateral installation depth increases the lateral spacing will also increase. This results in deeper flow lines that passes through more saline areas of the soil profile. Reducing either the depth of installation or the drain spacing will reduce the depth of the flow path and the salt load in the drainage water (Grismer, 1989).

In the Australian environment most shallow groundwater in arid areas is highly saline. Thus
when subsurface drainage systems are installed using the existing criteria they tend to drain the saline groundwater as well as deep percolation past the root zone. The level of salinity depends upon how much irrigation water is mixed with the groundwater, the depth and management of the drainage system, and how long the drainage system has been operating. The problem with mobilising this stored salt is that it makes disposal of the drainage water more difficult because of existing load restrictions in receiving waters and reuse improbable.

In Australia the salinity of surface waters is increasing which is negatively impacting users, thus the disposal of saline drainage to river systems is becoming very restricted. In this type of limited disposal to river environment it is very important that drainage water salt load be minimised. This analysis shows that present drainage systems could benefit from improved design and management to reduce the drainage salinity. It has been shown in the Murrumbidgee Irrigation Area that managing horizontal drains to avoid drawdown of watertables to the full depth of the drains e.g. drain to 1.2 m rather than 2 m will reduce salt loads significantly, (Christen and Skehan 2001) Many of the regions had stated watertable depths as their design objective. These depths are probably conservative in that they provide the greatest protection to the crop from salinity effects, but as a result are likely to have more saline drainage water discharge than if a shallower watertable control depth was used.

7.5 Discussion

It can be seen that practices relating to subsurface drainage design and management across irrigation areas in Australia are highly varied. Subsurface drainage has been used to good effect to overcome waterlogging and salinity along with other methods such as surface drainage, improved irrigation practices, and changes in land use management practices. Since these factors are inter-related, it is important to consider them in an integrated manner, when aiming to develop sustainable irrigation systems.

Irrigation water use varies greatly from region to region depending upon the cropping and climate. Most regions report improved water use efficiency in recent times, which is vital to
the reduction of drainage problems and to making subsurface drainage implementation more affordable. The surface irrigation water salinity is very low (EC < 0.4 dS/m) in most regions. Thus irrigation induced salinity is generally due to shallow saline watertables rather than the application of high salinity irrigation water. Only the South West Irrigation Area, Sunraysia and Riverland have occasional high salinity irrigation water.

Drainage problems have been reported as usually the result of over irrigation leading to shallow watertables and hence waterlogging and secondary salinisation. It is not clear for any of the regions whether improved irrigation management could have avoided the problem. In perennial horticulture waterlogging is a significant problem and drainage implemented for watertable control has also controlled soil salinisation. Pasture which is not sensitive to waterlogging has also been drained for watertable control and in some cases for salinity control. In the Shepparton region, pasture has not been drained to a watertable criteria, rather a leaching fraction is extracted annually. In some areas such as the Burdekin and Macalister it may be worth reconsidering whether the stated aim of watertable depths > 3 m and >2 m respectively are necessary for those cropping systems or whether a reduced salinity and watertable control criteria may be more appropriate.

The drainage criteria that have been applied to perennial horticulture, especially in the Murrumbidgee, Riverland, and Sunraysia areas is a target watertable depth of 0.75 – 1.1 m within 3 - 7 days after irrigation. This was developed to control very shallow watertables (< 1 m) that resulted mostly after irrigation but also after rainfall. This has resulted in drainage design coefficients of 2 - 5 mm/day and high drainage rates from these areas. However, most regions report declines in drainage in recent years that may be attributed to climatic conditions and improved irrigation efficiency. These design criteria need to be revisited considering the move in perennial horticulture to pressurized irrigation systems and to the much improved standards of irrigation management. Very shallow watertables are now much less common in the horticultural areas. Design criteria developed based on today’s standards of irrigation design and management should be targeted more towards salinity control rather than waterlogging and should thus result in lower cost drainage systems with lower drainage discharges.
Many areas are now reviewing the management of all subsurface drainage systems with a view to reducing drainage volumes due to disposal pressures and balancing groundwater extraction for resource use against the basic aim of long term salinity control. There is virtually no managed operation of horizontal drainage systems. Research by Christen and Skehan (2001) has shown that management of horizontal drains in the Murrumbidgee Irrigation Area can reduce drainage water salinity, making reuse more feasible and disposal easier because of reduced salinity loads and volumes. Integrating subsurface drainage management with irrigation management at a specific location appears to be in its infancy requiring more research and a change in perspective. However, work in California as summarised by Ayars, et al., (1999) has shown that the integrated management of irrigation and drainage systems will reduce the total drainage volume discharged along with the total salt mass.

7.5 Conclusions

This review of the performance of subsurface drainage systems for irrigated agriculture in Australia has highlighted a need for a change in perspective with regard to subsurface drainage. It is clear that subsurface drainage should no longer be used as a cure for problems created by inefficient irrigation practices. This leads to a waste of the irrigation water resource and a great deal more downstream salt contamination than is necessary. New drainage systems should be managed to treat the watertable as a potential resource, and assist in making irrigation practices more efficient by holding water in the profile for plant use later. In the past excessive subsurface drainage made irrigation less efficient by quickly removing water from the profile before the plant had any opportunity to use that water.

This change in perspective requires changes in the way drainage systems are designed and managed. Subsurface drainage designs should be such that the drainage mobilises as little salt stored below the root zone as possible, which generally means making drainage as shallow as possible. There should also be structures and feedback mechanisms that allow subsurface
drainage systems to be properly managed.

From this study it is concluded that:

- New drainage design criteria are required that provide adequate protection for crops (with clear delineation of waterlogging and salinity control objectives) whilst minimising drain water salinity and volume.

- Saline drainage water disposal is now a key issue in Australia and in most parts of the world, which may severely restrict future implementation of subsurface drainage in irrigated agriculture. This may then be the greatest constraint to the sustainability of many irrigated areas, and requires further research to explore other novel disposal options.

- Reassessment of drainage design criteria for many regions of Australia is required in light of more recent changes in land use and irrigation management.

- Management of the operation of subsurface drainage systems needs to be understood, expanded, and implemented. Integrated subsurface drainage and irrigation management for improved overall water use efficiency is in its infancy.
Part 2

Review of current performance of subsurface drainage systems
Chapter 8

Case study of improved subsurface drainage design and management in the MIA

This chapter is a summary of a paper by Christen and Skehan (2001) on improved subsurface drainage design and management techniques to reduce salt loads.

8.1 Methods

Improved drainage design and management strategies were tested in a replicated field trial in a vineyard in the MIA. The new design and management strategies were tested against current design and management practice, and a no drainage scenario, summarised in Table 14.

Measurements were taken over three years from 1996 to the end of the 1998 season, this period included three irrigation seasons. Measurement on individual drainage treatments involved; irrigation and rainfall, run-off, drain flow, drainage salinity, water table depth, and soil salinity.

<table>
<thead>
<tr>
<th>Table 14</th>
<th>Drainage treatment summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drain type</strong></td>
<td><strong>Deep Drains</strong></td>
</tr>
<tr>
<td><strong>Depth (m)</strong></td>
<td>slotted PVC pipe</td>
</tr>
<tr>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Diameter (mm)</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Spacing (m)</strong></td>
<td>20</td>
</tr>
<tr>
<td><strong>Length (m)</strong></td>
<td>70</td>
</tr>
<tr>
<td><strong>Management</strong></td>
<td>unrestricted flow</td>
</tr>
</tbody>
</table>
8.2 Results and discussion

The different drainage treatments resulted in markedly different drainage volumes and salinities, and hence salt loads, Table 15. The differences in flow resulted from the drain position in the soil profile and the management of the drains. The Deep Drains flowed continuously for the irrigation seasons, a small saline flow being sustained between irrigations and a large flow during and just after irrigation, Figure 23. The Deep Drains continued to flow long after an irrigation had ceased because they were draining a larger soil volume, down to 1.6-1.8 m, and they were influenced by regional groundwater pressures. This was despite the area having no significant shallow aquifer systems and being in a fairly flat area so that hydraulic gradients from neighbouring farms and channels were small. That there were some regional effects was demonstrated by the rise in piezometric levels at the beginning of the irrigation season in the experimental area before any irrigations had been applied. The Managed Deep Drains were less influenced by these regional effects and the Shallow Drains were completely isolated from them.

Figure 23. Drainage treatment hydrographs during and after an irrigation

The Deep Drains removed the most water and at the highest salinity, about 11 dS/m, and hence had the highest salt load, Table 15. The Managed Deep Drains had 33% less flow than the
Deep Drains at a lower salinity, 7-8 dS/m, resulting in a 49% reduction in salt load. The Shallow Drains removed 78% less water than the Deep Drains at a significantly lower salinity, about 2 dS/m, resulting in a 95% reduction in salt load. The large amounts of water removed by the Deep Drains leads to reduced overall water use efficiency and increased farm costs in terms of increased pumping and nutrient loss. The extra salt removed by the Deep Drains compared to the Shallow Drains and even the Managed Deep Drains doesn’t have a negative impact on the drained area but will adversely affect the receiving waters. If in the future farmers are charged for the amount of salt they export off farm then this extra salt export will have a negative effect upon farm income. Where farms are denied the option of off farm disposal of drainage water, then the use of shallower drains will be advantageous in reducing the overall volume requiring disposal and also the lower salinity of the drainage water will leave more options open for reuse.

<table>
<thead>
<tr>
<th>Drainage Treatment</th>
<th>Total drainage volume (mm)</th>
<th>Average drainage salinity (dS/m)</th>
<th>Total salt load (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep drains</td>
<td>70</td>
<td>11</td>
<td>5867</td>
</tr>
<tr>
<td>Managed deep drains</td>
<td>47</td>
<td>7 - 8</td>
<td>2978</td>
</tr>
<tr>
<td>Shallow drains</td>
<td>15</td>
<td>2</td>
<td>319</td>
</tr>
</tbody>
</table>

Of the three drainage treatments tested only the Shallow Drains came close to a salt balance with the irrigation water, removing 0.7 of the salt applied in the irrigation water. This is actually a small accumulation of salt, but this was in absolute terms a very small amount 170 kg/ha, and was not accumulated in the root zone. The Deep Drains removed 11 times more salt than was applied, a large net leaching of salt. This leaching was not reflected in a large relation in soil salinity in the top 2 m, thus this salt was from below drain depth. This was somewhat reduced by the managed treatment which exported 5 times more than the salt applied, still a large net export. This shows that drains placed deep in the soil profile will export large quantities of salt over and above that applied in the irrigation water. Assessment of the drainage water salinity with depth of water table confirms this. When the water table was at one metre below the surface the drainage water salinity from the Deep Drains was
around 8 dS/m; as the water table fell to 1.6 m below the surface the salinity increased to around 11 dS/m, Figure 24. This is consistent with the suggestion that deeper drainage intercepts deeper water flow paths that move through much more saline portions of the soil profile.

**Figure 24.** Drainage water salinity and watertable depth between drains

![Figure 24](image)

In terms of water table and waterlogging control the Deep Drains were adequate in reducing the periods of high water tables and waterlogging to a negligible amount, Table 16. The management changes used to control water flow from deep drains had only a small effect on waterlogging, about an extra day of waterlogging during the irrigation event itself. This minimal increase in waterlogging is a small trade off for the benefits of less water drained resulting in greater water use efficiency, lower operating costs and improved downstream water quality. At this stage in the development of the vineyard this small increase in waterlogging had no effect on vine leaf chlorides or yield. The Shallow Drains as expected gave the best control of root zone waterlogging, the watertable did build up beneath this treatment but was controlled at mole depth.
Table 16. Duration of water tables above specified depths

<table>
<thead>
<tr>
<th>Treatment</th>
<th>300</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep Drains</td>
<td>70</td>
<td>86</td>
<td>156</td>
</tr>
<tr>
<td>Managed Deep Drains</td>
<td>26</td>
<td>60</td>
<td>207</td>
</tr>
<tr>
<td>Shallow Drains</td>
<td>13</td>
<td>27</td>
<td>64</td>
</tr>
<tr>
<td>Undrained</td>
<td>70</td>
<td>168</td>
<td>859</td>
</tr>
</tbody>
</table>

These varying water table regimes resulted in some differences in the root zone soil salinity trends over the two seasons monitored, Figure 25 and Figure 26. The Undrained treatment soil salinity remained static, whereas all the drained treatments showed a decrease in salinity after the first season. In both the Shallow Drains and Managed Deep Drains there was a rise after the second season resulting in no net change. For the average salinity down to two metres this picture was similar except the Deep Drains showed a fall in salinity after both the first and second seasons. These results are somewhat unclear in terms of the possible effects of the different treatments on long-term soil salinities especially since the undrained treatment did not show any change in salinity over the experimental period. However, there is an important outcome from this analysis in that, the drainage treatments had only small effects on the root zone salinity, no measurable effect on vine health over the experimental period, but still drained water and salt from the area. So over this particular time the water drained, salt removed, costs incurred and downstream impacts of drainage water resulted in little benefit to the farm. Under these circumstances of small benefit from a drainage system, which can occur due to site factors, dry climatic conditions and plants not highly susceptible to waterlogging, it is even more important that the drainage system incurs the least downstream impacts and least costs to the farmer.
Figure 25. Change in salinity in the top 600 mm of soil

Figure 26. Change in salinity in the top 2000 mm of soil
8.3 Discussion

This field trial was conducted in a dryer than average year, the relatively low drainage flows and static soil salinities reflect this. During wetter conditions it is likely that the drainage water reduction would be greater than measured here and that there would be more soil leaching due to rainfall, both of which are positive. However, there may be negative effects due to the design and management suggested, such as increased waterlogging. These negative effects are unlikely to be great and with good management could be monitored and controlled. For instance if the water table was remaining high for too long on the Managed Deep Drains then the drainage depth could be increased to provide a greater soil buffer to store rainfall. The main negative effect of a prolonged wet period on the Shallow Drains would be an increased rate of collapse in the mole drains. At this site, the soil was quite stable and as such it is unlikely that the moles would collapse to the point of being ineffective within a single season. Obviously if a shallow pipe system was installed this would not be a concern.

Predicting the effects of wetter periods on the results of drainage design and management tested here is possible. The likely drain flow under wet conditions can be considered by analysing single high input irrigation events. Figure 27 and Figure 28 show the proportion of water applied that drained through the different drainage treatments at a particular event.

During wet periods when the soil has a small storage a lot of the water applied that does not run off will be drained out, similar to irrigations 3 and 4 in Figure 27 and the highest ranked drainage events in Figure 28. This gives an indication that under wet conditions it is likely that up to 25% of water applied may be drained by a deep pipe drainage system, whether managed or not.
Figure 27. Drainage as a proportion of water applied at each event

Figure 28. Water application and the proportion of water drained (individual plots)

The rate of drainage can be predicted by considering the drain hydrographs such as in Figure
23. The peak flow rates shown here are unlikely to be greatly exceeded, but the duration of the peak flows will be prolonged under wet conditions with high inputs of water. The effect of wetter conditions on drain water salinity can be considered using the drainage water salinity as a function of water table depth results. Since water tables are likely to be high during wet conditions the drain water salinity will be lower than dry periods when the water tables are deeper. The height and duration of water tables during wetter periods is harder to predict. Water table depth is a function of the time from the last recharge event, the drainage rate of the system and the combination of deep leakage and plant water use. If recharge events are larger, and at shorter intervals, then water tables will remain higher. Analysis of water table responses under a particular set of weather conditions can be undertaken using water balance models such as SWAGMAN Destiny (1996) and BASINMAN, Wu et al. (1999).

An indication of the impact of a drainage system on water use efficiency and hence total water costs is shown by the Deep Drains that drained 20% or more of the water applied in 23% of plot drainage events and drained 10% or more in 65% of plot drainage events. This is a considerable proportion of the water applied that was intended for use by the plant. Management of deep drains cut the proportion of plot drainage events draining more than 10% of water applied to 37% and events draining more than 20% to 6%. This is a significant improvement but does not match the Shallow Drains, which drained less than 5% of the water applied in 90% of plot drainage events.

8.4 Conclusions

Drainage systems for irrigated areas on clay soils in south eastern Australia can be designed and managed better than the currently accepted practices, so that detrimental downstream environmental effects due to excessive salt export are reduced, without affecting the productivity of the farm.
Changing drainage design from deep widely spaced drains to shallow closely spaced drains:

- Shallow drains remove less irrigation water than deep drains, thus reducing irrigation losses.

- Shallow drains have low drainage water salinity and remove smaller drainage volumes, thus reducing the salt load, with up to 95% reduction compared to deep drains in this trial.

- Shallow drains control waterlogging better than deep drains.

Managing deep drains by preventing discharge during irrigation and whenever the water table was below 1.2 m deep:

- Managed deep drains reduce irrigation water losses compared to unmanaged deep drains.

- Managing drains reduces flow and drainage water salinity compared to unmanaged drainage, resulting in a reduction in drainage salt load of 50% in this trial.

- A more rapid decline in drainage water salinity can be achieved by managing deep drains.

- A deep pipe irrigation system, without major groundwater inflow from surrounding areas, only needs to be run for 2 to 7 days after an irrigation to control the water table below the root zone and then can be switched off.
References


Environmental Hydrology and Hydrogeology. Water Environment Federation, Alexandria, VA.


