Review of deep drains to manage salinity in Western Australia

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Neil A. Coles
University of Leeds

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Chandler, K.L. and Coles, N.A.

Engineering Water Management Group
Department of Agriculture Western Australia

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For more information, contact
Dr Neil Coles
Resource Water Management Manager
Department of Agriculture Western Australia
Locked Bag 4
Bentley Delivery Centre WA 6953
Telephone (08) 9368 3333

Cover photography:
Deep drains near Watheroo (2001)
Deep drains near Wylkatchem (2001)
Kristy Chandler

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1 Introduction

The impact of salinity and other associated degradation processes on the land and water resources of Australia is a major ecological and economic problem that is expected to increase substantially in the next 50 to 100 years. Under the Salinity Strategy (2000), the Western Australian State Government made a commitment to evaluate the effectiveness of engineering options for salinity management and develop a best practice information and decision support package for landholders.

In 2002, the Western Australian State Government allocated funds ($4M) to an Engineering Evaluation Initiative to evaluate existing engineering practices and their effectiveness in managing salinity and associated problems. A review of specific engineering applications (i.e. drainage, pumps, earthworks) was recommended. The review would collate available data, identify knowledge gaps and potential research directions. The recommendations will be used to identify potential engineering projects that will enhance the States' knowledge on the use of engineering options for managing salinity in the dryland agricultural areas of Western Australia.

This review focuses on the use of deep drains as a salinity and water management tool. Deep drains have been used in the development of agriculture and intensive irrigation areas in Western Australia (WA) since the 1860's. The early use of drainage was aimed at managing waterlogging and flooding on the coastal sandplain where high value crops, mainly horticulture, and dairy were established. As the mallee belt, (later to become the Wheatbelt), areas were cleared and problems associated with water management and salinity became more apparent, deep drainage was employed as a salinity management strategy in the 1960's (some 100 years later).

The evaluation of engineering options is timely, as it coincides with a recently released national literature review of engineering options to manage salinity, conducted by National Dryland Salinity Program (NDSP 2002). The review revealed lack of effective documentation of drainage case studies across Australia. In recent times, a number of drainage reviews have been conducted (Coles *et al.* 1999, Taskforce 2000, Chandler 2002). This review is expected to build on the recommendations stemming from these previous reviews, evaluate other information that has been collated concerning the effectiveness of drainage, and highlight technical issues associated with the placement, construction and maintenance of deep drains.

1.1 Objectives

The broad objective of this review is to evaluate the use of deep drains as a tool to manage salinity in WA. The more specific objectives of this report are to:

- summarise previous and current deep drainage research undertaken in WA and elsewhere in Australia;
- identify gaps in technical information; and
- recommend potential research projects.

1.2 Definitions and scope

In the context of this review, a "deep drain", and the shortened version a "drain" is used to describe any man-made horizontal channel or pipe constructed into the soil to intercept and convey groundwater. For drainage purposes, groundwater is defined as water that is found below the soil surface, and will flow into a well or drain (Houghton 1986). Whilst groundwater can occur within many different formations and aquifer conditions, drainage water is usually limited to that which is local, unconfined and may express at or near the land surface.

A drain may or may not be lined, be back-filled with a more permeable substrate, or left open. The NDSP (2002) definitions have been slightly modified and deep drains have been separated into closed drains (French, pipe and mole) and open drains (e.g. leveed and non-leveed). *Closed* drains in the context of this report consist of some form of buried conduit that is not visible or 'open' to the land surface. *Open* drains in the context of this report, are defined as trenches, with a base and sides that are visible, and the drains are either leveed to exclude surface water flows or un-leveed to allow surface flows to enter the drain.

The dimensions of a deep open drain can be similar to that of drains used for other purposes (such as surface water management). This makes their description and identification more complex. Deep drains are commonly defined by at least one of the following features:

- a base width less than five times the depth (Keen 1999);
- the drain floor consistently intersects the groundwater table; and
- the drain floor and batters are not lined, or are pervious to allow the inflow of groundwater from the adjacent soil.

Deep drains may be used to intercept lateral flow (interceptor drains) or lower watertables (relief drains). All other forms of banks and channels, including seepage interceptor banks are not considered as deep drains and have not been included in this review.

Drainage is divided into three broad types: dryland, irrigation and urban. This report focuses on dryland drainage, however similar design principles can be applied.

Deep drains are constructed in WA at the sub-catchment, catchment and sub-regional scale. This review focuses on deep drains constructed on a sub-catchment scale, often referred to as farm-scale drainage. Within the dryland agricultural environment, this scale equates to about 5000 hectares (Keen 1999). The complexity of engineering drainage schemes on a catchment to regional scale increases, due to changing landscapes, flood management and broader social and environmental concerns. Regional scale or arterial drainage is not included in this review.

2 Background

A significant proportion of the south west agricultural region is affected by salinity, waterlogging or both (Short and McConnell 2001). The rate and extent at which salinisation will increase, varies greatly throughout the region and is dependent on the climate, geomorphology and hydrology of catchments. Salinity affects water resources, biodiversity, agricultural productivity, flood risk, infrastructure, communities and individuals. The main cause of salinity expansion is the clearing of the native vegetation, which has altered water use and movement, creating a relative excess of water within the landscape.

Various options are promoted to restore the hydrological imbalance either by reducing recharge and/or by enhancing discharge. Recharge management options are preferred, as these treat the cause of salinity. However, discharge management options, such as deep drains, have been favoured in recent times due to their immediate impact.

A number of studies and reviews (i.e. Coles *et al.* 1999, Taskforce 2000, Chandler 2002) have been published which examine the effectiveness of deep drainage as a salinity management option. This review is concerned with the use of deep drains and its implications for water and salinity management.

2.1 Use of deep drains in Australia

Traditionally, deep drains are used to manage waterlogging and salinity in irrigation systems, and in recent years, there has been a trend towards their use in dryland agricultural systems. The specifications of deep drainage systems are highly variable as they are determined by site specific hydrogeology. Closed or “covered” drainage technology, mainly pipe drainage, is well understood and documented on a world scale. This technology has transferred to Australia and is now the most common form of deep drain.

Closed drainage systems are mainly used in intensive agricultural regions and are usually at least partially funded by individual landholders (NSDP 2002). Closely spaced (10 to 20m) interceptor drains have been successful in managing hillside seeps in Emerald, Riverland and Sunraysia and in the wheatbelt of Western Australia. Similarly, mole drains used in conjunction with open drains (70m spaced) have successfully managed shallow watertables in Kerang, Victoria (Christen and Hornbuckle 2000) and on the swan coastal plain in Western Australia.

The use of deep drains in areas supporting irrigated or dryland pasture enterprises has significantly increased over the last decade due to reduced productivity levels caused by waterlogging and shallow watertables (NDSP 2002). Deep drains are commonly used in soils that are unsuitable for groundwater pumping and where the groundwater problem is localised or perched (Christen and Hornbuckle 2000).

The use and research of salinity management options in Western Australia far exceeds that of other States, owing to an immediate and widespread the risk of dryland salinity. Therefore a significant proportion of information pertaining to salinity management using drains comes from WA (NDSP 2002). The most prominent use of a deep drainage system outside of WA, is that of the Upper South East (USE) region in South Australia (PIRSA 1999a,b).

In 1998, Stage 1 of the USE Dryland Salinity and Flood Management Plan was constructed to combat the increase in areas affected by salinity and waterlogging in that region (PIRSA 1999a,b). The plan is centred on a large arterial drainage system, and included other salinity management techniques such as revegetation, high water use plants, use of salt torerant species and protection of remnant vegetation. An intensive site evaluation was conducted before construction to achieve optimal design and to identify and minimise the risk of downstream impacts. Trials showed that the soil was relatively permeable and that a 2m deep drain would be as effective as one which was 3m deep (Ebsary 1999). The drain was likely to have a significant impact on downstream environments such as the Messent Conservation Park (Owens *et al.* 1995). Thus, a number of measures were included to reduce impacts such as diversion structures to divert relatively fresh water to wetlands, and wildlife crossings through vegetated areas (PIRSA 1999a,b). Preliminary results suggest that the drain has been successful with watertables influenced up to 2.0 km from the drains.

2.2 Use of deep drains in Western Australia

In 1864 irrigation agriculture commenced in south west WA and drains were used to lower watertables and manage waterlogging during the growing season on the swan coastal plain (Cole 1980, Cox 2001a). High-value produce in the irrigation area made the cost of setting up drainage infrastructure feasible (NDSP 2002). Apart from some experimentation in the 1960s, the use of drains in non-irrigated and inland south west WA was relatively uncommon until the 1980's (George 2002).

In the 1970s, landholders inland from the coast began to advocate drainage to increase discharge and manage rising watertables and waterlogging (Coles *et al.* 1999). Implemented on a farm-scale, drains were constructed to depths of 1.0 to 3.0 m into the soil to intercept groundwater, and thus became commonly known as "deep drains". Research and anecdotal evidence suggested that watertable response varied significantly between drainage sites, along the length of individual drains and on opposite sides.

The drains that appeared most effective were those constructed in soils of greater permeability, or those that intercepted permeable lenses within the mixed soil matrix (Coles *et al.* 1999). Deep drains constructed in calcareous sediments near Watheroo were the most publicised example, where the watertable was influenced up to 80m from the drain edge (Nulsen 1982, George and Nulsen 1985).

Research conducted in some other areas of the Wheatbelt found the extent of influence to be much less than that at Watheroo. It was concluded that closely spaced drains would be required at these saline affected sites (George and Nulsen 1985, Negus and Eales undated). Issues such as design, cost-effectiveness, construction, maintenance, soil amelioration and downstream impacts were also raised (Coles *et al.* 1999).

In the 1980s, deep drains were common in most of the north eastern Wheatbelt. Deep drains were used for a variety of purposes, such as managing and collecting suitable stock water from sandplain seeps (Nulsen 1982, George 1991b) and protecting threatened remnant vegetation (Lenane 1987). Research continued to highlight the variability of performance between sites (George 1987). For example, pipe drains at some hillside seeps were successful at reducing waterlogging, while others had little discernible effect (Bettenay 1982, Burdass 1982, George 1982, Negus 1982).

The measure of success of deep drainage schemes has not always been determined by the ability to lower groundwater levels. Landholders at some sites experienced improvements in crop productivity, with limited change in the depth to watertable. The main benefit of deep drains in these cases appeared to be reduced waterlogging and inundation. This suggests that, it would be more economical to achieve these benefits through alternative earthworks (i.e. spoon and W-drains) that are designed to manage surface water (Coles *et al.* 1999).

The area of salt-affected land continued to increase in the 1990s and the “Decade of Landcare” commenced with the promotion of Landcare options such as revegetation to manage recharge and increase discharge (George *et al.* 1999c). Many landholders, especially those at a higher risk of land salinisation, continued to install deep drains, due to the immediate and visible increase in discharge. Drainage regulations were introduced in 1992, in response to concerns over the impacts of drainage water on receiving waterbodies (CSLC 1999). There was far more interest in *open* drains than *closed* drains and the drains were constructed deeper and wider (George 1991a).

Drainage trials were primarily landholder driven and based on increased contractor experience. The introduction of drainage regulations in 1990 led to some improvements in design, such as leveed drains to exclude surface water. However, most drains were constructed with limited site investigation and site specific design. New closed and partly closed drainage systems emerged, such as tyre drains and deep drains used in conjunction with passive relief wells.

In the late 1990s, more drainage sites with increased crop productivity became apparent and farm-scale deep drains were linked to form larger-scale networks (e.g. Belka and Narembeen). The number of proposed large regional drainage schemes (e.g. Kalgoorlie, Yenyenning, Yarra Yarra, Beacon and Blackwood) also increased following the apparent success of the drainage works in SA (PIRSA 1999) and Narembeen (Ali and Coles 2001). Drainage was seen by many as the “stand alone” solution to salinity, and the use of deep drains overshadowed recharge management and other salinity management options (Taskforce 2000). The ABS (2002) reported that over 1300 landholders in WA had constructed deep surface drains on their properties (1700 nationally) and 184 had constructed subsurface drains (643 nationally). An audit of deep drains by Chandler (2002) showed that drains were used for different purposes, including channelling water from upslope, as a conduit for transferring water between sub-catchments, redefining and deepening drainage lines, breaking(or blasting) subsurface barriers to flow and managing shallow watertables.

A number of cross-site drainage analyses were conducted which showed similar findings to earlier studies, including variability of impact, and design, maintenance and construction issues. Coles *et al.* (1999) related the variability of success to drain placement and the site specific issues. The most effective deep drains intercepted permeable lenses in the soil profile, were located at the break of slope or were draining hillside seeps. Ferdowsian *et al.* (1997) found sand seams and saltlakes often contributed a much larger proportion of flow than the remaining length of drain and the distance of influence at these points extended much further than expected.

Keen (1998) developed preliminary best practice guidelines for deep drains in WA, which formed part of an agricultural earthworks design package and outlined the need for adequate site investigations and competent engineering standards, layout and construction techniques. In 2001, conservation earthworks courses commenced where contractors could gain accreditation for competencies in planning, designing and constructing earthworks including deep drains (Keen 1999). Techniques for assessing the impact of deep drains on downstream environments were drafted by Actis (1998). Potential hazards impacting on downstream environments included additional water (of variable quality), salts, changes in pH, nutrients, and organic and metallic pollutants.

In 1999, the Taskforce (2000) stated “that deep drainage is not often seen as a preferred salinity management option as the fundamental cause of salinity (recharge) is not addressed.” However, the report concluded that deep drainage could be a valid starting point for a wider range of Landcare and wetland management works. The Taskforce found that low permeability and often unstable clay soils, excessive velocities (erosion, deposition, silting), cost, high risk of failure, lack of integration, disposal and storm damage were the limiting factors of deep drainage in WA.

Recommendations included that, among other things, priority be placed on projects aimed at developing best practice guidelines for design, assessment and construction of deep drains and identifying suitable receiving bodies. In particular, these guidelines were required for larger drainage schemes, owing to the number of stakeholders involved and the higher risks associated with failure (NDSP 2002). The Minister for Agriculture, accepted the recommendations of the Taskforce, however they were not formally adopted as policy or acted upon by the Department of Agriculture at the time of submission.

3 Applications of deep drainage

Drainage is the removal of surface or subsurface water from a given area by natural or artificial means. The term is commonly applied to canals, drains and ditches designed to collect and transport water either by gravity or by pumping. In WA, deep drainage is used to enhance discharge from areas that are waterlogged, and/or at risk of or have become saline.

Within the rural landscape, the purpose of drainage is to improve the soil environment for plant growth, by the removal of excess soil water (Cox 2001a). The enhanced leeching and removal of salt from the soil is considered of secondary benefit. Drains are typically required where the water balance of the site favours groundwater accumulation, even if only intermittently. Accumulation usually occurs where the soil is unable to remove groundwater at sufficient rate due to low soil permeability, low surface and hydraulic gradients and/or long groundwater flow paths.

The wide flat valley floors of catchments within the Wheatbelt provide an accumulating environment that may possess all of these attributes to varying degrees. These dryland landscapes have evolved to trap and maximise the use of all available water (Cox 2001b). Within this cleared landscape today, the accumulation of water and salts in the upper soil profile decreases land productivity and causes environmental degradation and loss of biodiversity.

An artificial drainage scheme may enhance discharge from the system, removing water and allowing fresher rainfall to leach accumulated salts. Firstly, it will provide an increased hydraulic gradient towards the excavated channel that will allow the groundwater to flow faster towards this outlet (relief). Secondly, it can reduce the distance or length of flow path that the groundwater has to travel before being able to discharge (Schwab *et al.* 1981).

Drainage of saline agricultural land can significantly improve crop production through the removal of water and salt. This comes about as crops can tolerate higher levels of salinity or waterlogging than they can when both are combined (Figure 3.1) (Barrett-Lennard 1986, McFarlane *et al.* 1992, Barrett-Lennard and Malcolm 1995).

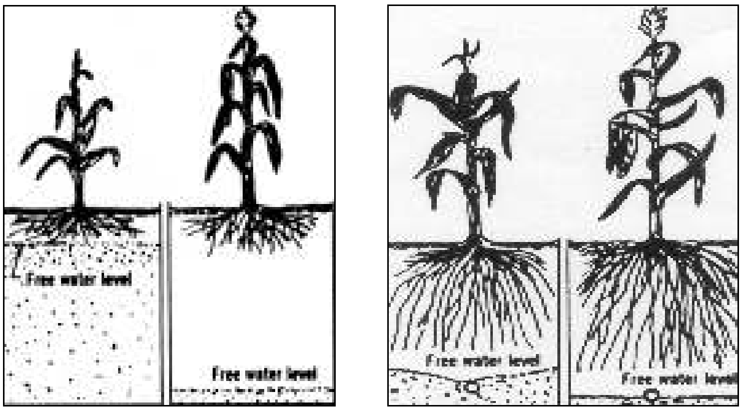

Figure 3.1. Crop root development in un-drained and drained soil (Schwab et al. 1981)

Drainage processes and design criteria are well researched and published in various engineering texts (e.g. Schwab *et al.* 1981, Skaggs and van Schilfgaarde 1999). Most literature focuses on drainage of high-value lands (i.e. wetlands and infrastructure), as well as the management of the saturated zone in irrigation systems (Ali and Coles 2001).

Effectiveness of drainage systems is judged by the ability to lower groundwater levels (Schwab *et al.* 1981). In many cases, landholders have also reported reduced soil salinity, improved crop yields, reduced waterlogging and inundation after installing deep drains (Coles *et al.* 1999). Drainage can also help prevent water borne diseases, improve trafficability, reduce erosion, aid in flood protection and attenuate peak flows by reducing watertables and increasing soil storage capacity (WAWRC and SLCCWA 1992, Green 1990).

3.1 Drainage mechanisms

Relief and interception are the two main terms applied to the way in which deep drainage influences the watertable. Deep drains constructed to manage the depth of shallow watertables are referred to as “relief drains” (Figure 3.1.1). Relief drains manage watertables by creating a steeper hydraulic gradient from the original groundwater surface to the base of the drain. This encourages lateral flow through the soil profile towards the drain (Green 1990).

By lowering watertables, drains are able to reduce the accumulation of salts through capillary rise and evaporation and allow rainfall to leach salt from the upper soil profile into the drain (Coles *et al.* 1999). Smedema *et al.* (1983) provide a salt balance equation that is used to determine the amount of salt deposition that would occur within the root zone given varying depths to watertable and groundwater salinity. This could be used to estimate the potential impact of drainage on reducing surface salt deposition.

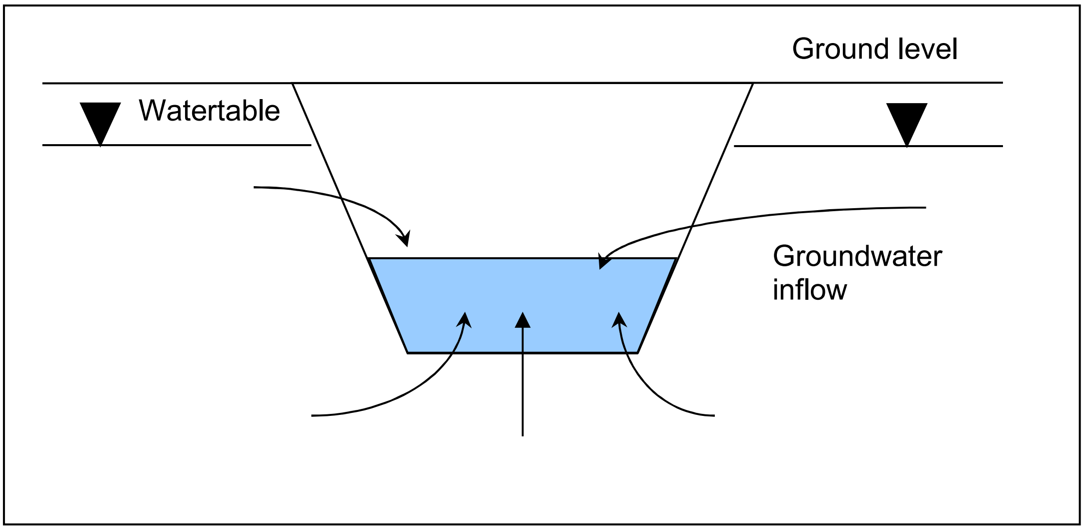

Figure 3.1.1. Cross-section of a relief drain

Deep drains are also placed to behave as “interceptor drains”. This term has more to do with placement than the design of the drain, with the objective being to position the drain in order to intercept lateral flows. This works best in duplex soils, where drains are placed along the break of slope that occurs where the valley flank meets the valley floor. The correct design and placement of these drains can reduce waterlogging and salinity associated with lower hillside seepage (Figure 3.1.2) (NDSP 2002).

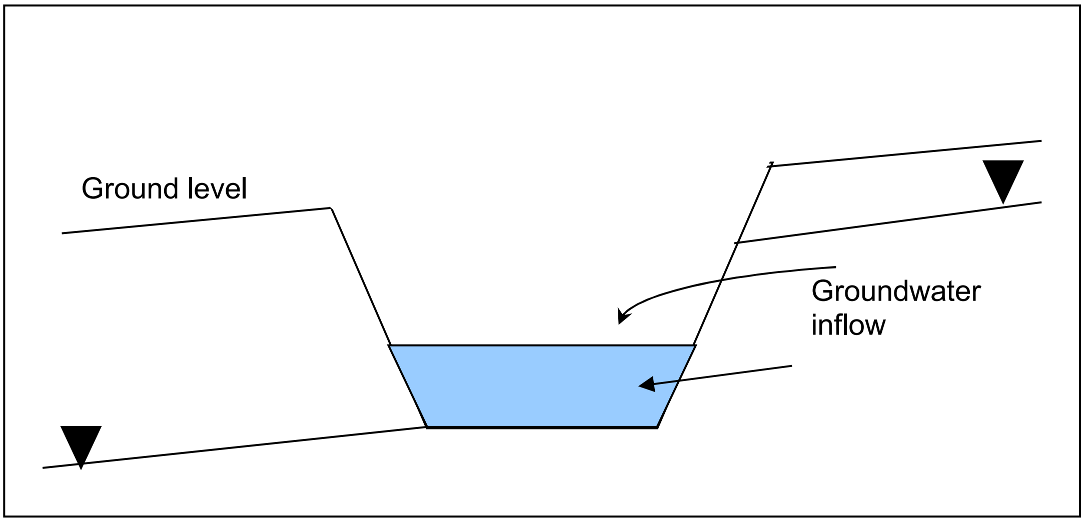

Figure 3.1.2. Cross-section of an interceptor drain

The two parameters relating to plant production that are used to support the design and placement of drains, these are critical depth and critical duration (Cox 2001a). *Critical depth* in the context of this report, is the minimum depth from the surface that the watertable may persist indefinitely, without waterlogging the root zone of the crops.

Critical depth will vary between areas that are fresh and those that are salt-affected, those that are drained and undrained, and is strongly affected by soil texture (capillary rise). Critical depth may be less in sites that are fresh, or those where leaching is enhanced through drainage. In salt-affected areas, critical depth is the depth where the leaching of salts from the upper soil profile equals the accumulation of salts through capillary rise (Franzen *et al.* 1994). Critical depth varies with soil type and can range from 1 to 6m in uniform sand to clay soils, respectively. For agricultural purposes, it may not be necessary to reduce watertables to a point where the soil is completely leached of salts, as even small reductions in waterlogging and salinity can significantly increase crop yields (Barrett-Lennard and Malcolm 1995).

Critical duration is the length of time that the watertable can be closer to the surface than the critical depth before crop productivity is reduced (Cox 2001a). This is crop, landuse and soil dependent. In the horticultural areas of WA, where waterlogging is often more significant than salinity, the criterion adopted is usually 0.75m for up to 3 or 4 days and 1m for less than 7 days. Schwab *et al.* (1981) classified the health of agricultural land in arid irrigation areas according to depth of watertable depth, which dependent on salinity and soil type (Table 3.1.1). These may have applications to the Wheatbelt region of WA.

Table 3.1.1 Agricultural soil drainage classification (Schwab et al. 1981)

Classification	Range in watertable depth (m)
Good	Static watertable below 2.10m; up to 1.80m for 30 days per year (max.)
Fair	Static watertable below 1.80m; up to 1.20m for 30 days per year. No general rise
Poor	Static watertable 1.20 to 1.80m; up to 0.90m for 30 days per year. Some salts may accumulate on the surface for short duration.
Bad	Watertable at less than 1.20m and rising. Soil salinity may become prevalent.

Critical depth and duration vary with climate, soil type and intended land use. In humid regions where the watertable will rise to near the surface during heavy rainfall, the rate of drop is an important factor (Schwab *et al.* 1981). In arid regions under irrigation, the drainage criteria are determined more by the minimum depth of the watertable, than the rate of drop. Inland agricultural regions of WA are likely to be influenced by both arid and semi-arid conditions and a watertable greater than 2 m below the surface is used as an indicator of "good" watertable conditions (Nulsen 1982).

3.2 Drainage efficiency

3.2.1 Drainage rate

The drainage rate (also referred to as the drainage coefficient) relates to the depth of water over the drainage area (**A***) that needs to be removed from the soil profile within a given time period (Schwab *et al.* 1981). This value is expressed in mm/day and refers to the depth of acquired water to the watertable (infiltration) and not the change in groundwater level (Cox 2001a).

The design drainage rate is used to determine the peak groundwater flow rate in the drain. This estimation is required for the design of closed drains, as selection of the correctly sized conduit is required to accommodate the design flow. For open drains, channel size is not often a limiting factor in terms of restricting groundwater inflow. However the estimation of flow rate is required for all drainage schemes where these discharge into a sump from which the water is pumped, or an evaporation basin (Leaney *et al.* 2000). For more intensive drainage systems (mainly irrigation systems), the leaching requirement of the soil is also required to design the drain (Christen and Ayars 2001).

The variables of critical depth, critical duration and drainage coefficient are applied under steady state conditions. For example, its is assumed that preceding an infiltration event, the watertable is at critical depth. The infiltration event, which is equivalent to the drainage coefficient, will cause the watertable to rise above the critical depth. The objective being to design a drainage scheme that would return this watertable to the steady state condition within the critical duration. In Western Australian dryland agricultural regions there is currently:

- *sufficient information relating to critical duration;*
- *limited information relating to critical depth; and*
- *no information relating to drainage coefficients on saline land.*

For practical purposes, the drainage rate is often calculated by applying a simple water balance using the estimated recharge and change in groundwater levels at the site (Cox 2001a). The following equation is used:

$$Q = R + (S_{IN} - S_{OUT}) + (Z_{IN} - Z_{OUT}) \text{ -------} \qquad [1]$$

Where:

Q = the depth of water to be removed from the drainage system (drainage rate) (mm/day);
R = recharge (via rainfall or irrigation) (mm/day);
S_{IN} = lateral seepage from upslope (mm/day);
S_{OUT} = lateral seepage to downslope (mm/day);
Z_{IN} = upward groundwater percolation (mm/day); and
Z_{OUT} = downward or outward groundwater infiltration from the drainage area (mm/day).

Recharge (**R**) will vary from site to site and across the drained landscape. Rainfall infiltration and runon recharge will be greater in landscapes with more permeable soils, profiles that have preferred pathways and good connectivity, and in areas receiving run-on.

Most sites have components of both **S** and **Z,** which may vary along their length and during the year. However, in many instances, these may be assumed negligible. For example:

> $\mathbf{S_{IN}}$ and $\mathbf{S_{OUT}}$ can be estimated where this is significant by taking field measurements and applying Darcy's Law. $\mathbf{S_{OUT}}$ may assumed zero in interceptor drains if the drain does not allow through flow;
> $\mathbf{Z_{IN}}$ maybe assumed zero in a recharge site. This situation may be a significant contributor to much Wheatbelt salinity, as it may be the cause of the recharge in the top few metres of soil water; and
> $\mathbf{Z_{OUT}}$ may be assumed zero under typical Wheatbelt valley floor conditions where $\mathbf{Z_{IN}}$ is occurring.

At present there is no quick and easy field test for deeper groundwater interaction (**Z**) at a site (CHG 2001). In most cases, this type of discharge is low and diffuse throughout the year, and can be estimated through analysis of groundwater pressures. For field practitioners, it may be practical to use simple field tools or definitions, which use soil and landscape features to indicate likely groundwater interactions.

In the absence of groundwater data, **S** is estimated using matrix flow theory, assuming that flow is uniform along the entire width and depth of the seepage face. **S** is a function of soil permeability, hydraulic gradient and area of inflow and is determined by a number of different methods, including complex groundwater models. Where there are limited input parameters, Darcy's Law is used to estimate **S**:

$$S^* = K_{sat} \times A \times \frac{\Delta H}{\Delta L} \quad \text{-------} \qquad [2]$$

$$S = \frac{S^* \times 1000}{A^*} \quad \text{-------} \qquad [3]$$

Where:

S* = the flow rate of lateral seepage (m^3/day);
A* = designated drainage area (m^2)
A = area of the seepage face (m^2);
$\mathbf{K_{sat}}$ = the saturated hydraulic conductivity of the soil (m/day);
ΔH = the difference in depth between the watertable at the discharge face, and at a distance where it is unaffected by the drain. In the absence of groundwater data, the ground surface immediately upslope of the drain can be used (m/m);
ΔL = the distance between the watertable points from which **ΔH** was derived (m/m)[1].

The area of inflow (**A**) is estimated by multiplying the wetted perimeter of the drain by the length of the drain. Table 3.2.1 list some typical soil hydraulic conductivity measurements for various soil types. As these are usually an indication of the hydraulic conductivity of the soil, they may not provide a very accurate indication of field hydraulic conductivity, particularly in soils that possess preferred pathway flow networks. A simple test for soil hydraulic conductivity in the field is required.

Table 3.2.1 Saturated hydraulic conductivity (K_{sat}) for uniform soils (Vesilind et al. 1994)

Uniform soil type	K_{sat} (m/day)	Uniform soil type	K_{sat} (m/day)
Gravel	100 – 1000	Fine sand	1 – 5
Coarse sand	20 – 100	Loam soils (surface)	0.1 – 1
Sand and gravel mix	5 – 100	Clay soils	0.01 – 0.2
Sandstone	28	Clayey sand and gravel mix	0.001 – 0.1
Medium sand	5 – 20	Deep clay beds	10^{-8} – 10^{-2}

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[1] *Note: ΔH/ΔL is often referred to as hydraulic gradient and the rate of inflow will be higher when the drain is first constructed due to pressure exerted by this gradient on the hydraulic conductivity.*

The current recommended method for determining field **K_{sat}** in WA is a standard auger hole or sump test (Berhane 1999). The rate of water level rise that occurs in an unlined cylindrical hole (usually 10 to 20cm diameter) is used to estimate hydraulic conductivity of the surrounding soil (Cox 2001a). Holes of various depths are drilled to evaluate potential differences in **K_{sat}** at different soil depths and the results used support the decision as to what depth the drain should be constructed.

The hydraulic conductivity has been found to vary by several orders of magnitude within a small area. For example, Berhane (1999) found that permeability using the auger hole method ranged from 0.01 to 0.2 m/day in the clayey subsoils of the Belka Valley. Furthermore, hydraulic conductivity commonly varies with depth, as different layers in the soil profile are intercepted (George 1987).

3.2.2 Drain depth and spacing

The principle design parameters for deep drains are drain depth and spacing, as these are manipulated to manage the depth to watertable (draw-down) over a designated drainage area. The ability of a deep drain to draw-down the watertable at some distance from the drain, is a function of the physical parameters of the soil matrix, primarily hydraulic conductivity and hydraulic gradient. Generally, the deeper the drain penetrates into the watertable, the greater the drawdown in terms of depth and distance away from the drain. Given all other variables remaining equal, this allows the spacing between the drains to be increased or results in a greater zone of influence or radial impact. The radial impact of deep drains constructed in the Wheatbelt has ranged form less than 10m to more than 300m. It must be noted that other parameters such as the required drainage rate, also affect the performance of drainage schemes. This means that drainage systems will not necessarily perform poorly in soils of low hydraulic conductivity, although this is often assumed to be the case.

The depth of a deep drain is measured from the soil surface to the base of the drain and generally ranges from 1.0 m to over 3.0 m. Within a drainage scheme, outlet conditions, topography and the design depth of laterals, determine the depth of collectors and risers. The depth of laterals is determined from the design inputs from the previous sections into some of the equations that follow (Coles *et al.* 1999).

There are a number of standard quantitative mathematical methods available to estimate the required spacing or zone of influence of a deep drain constructed in a particular landscape and soil type. In WA, these methods are rarely applied to open drains and only sometimes to closed drains.

As previously mentioned, steady state conditions are assumed for most formulae, as are parallel drainage lines, homogenous soil types and constant recharge (Figure 3.2.1). The calculated slope of the watertable surface that develops towards the drain conforms to that of a fourth degree parabola. Most methods involve the completion of similar basic steps:

(1) determine the required drainage rate (**Q**) (see section 3.2.1);
(2) decide on the minimum desired depth to watertable (**H**);
(3) select a suitable depth (based on soil profile, equipment available, outlet and intended land use) (**m**);
(4) estimate or measure the hydraulic conductivity (**K_{sat}**), using the auger hole (or similar) to the selected drainage depth. Determine other soil characteristics, such as depth to the impermeable layer (**d** + **m**) (see section 3.2.1);
(5) estimate drain spacing (**L_e**) and use tables or Hooghoudt formula to calculate the "equivalent depth" (**d_e**);
(6) use preferred drainage formula to calculate required drainage spacing (**L**) using desired mathematical formula. If the calculated drain spacing is not similar to that estimated in step (5), then steps (5) and (6) must be repeated

until the estimated spacing is similar to the calculated spacing. In other words, using a trial and error approach.

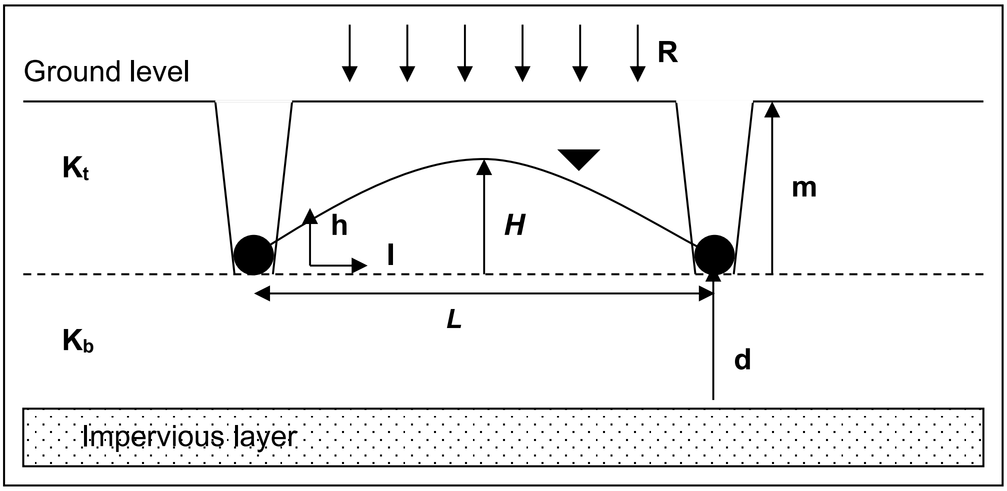

Figure 3.2.1 Idealised draw-down between two parallel drains

Determining equivalent depth (d_e)

The equivalent depth, $\mathbf{d_e}$ is a function accounts for the fact that groundwater flow occurs radially as well as laterally into some drains. Radial flow can occur where there is no constricting layer within close proximity to the base of the drain. If there is a constricting layer, such as an impervious hardpan at the base of the drain, only lateral flow through the sides of the drain can occur. If the hardpan is at a greater depth, the flow can occur through both the base and the sides, making it easier for water to discharge into the drain. The improved performance is acknowledged in the formula by converting it and expressing it as extra drain depth. The calculation of $\mathbf{d_e}$ is theoretically derived and based upon the Dupuit-Forchheimer assumption (which states that the vertical components of flow are neglected, and the flow is considered as purely horizontal). The equation was developed by Moody (1966) and referenced in van Schilfgaarde (1963):

$$d_e = \frac{d}{\left(\frac{8d}{\pi L_e}\right)\ln\left(\frac{d}{r}\right)+1} \qquad 0 < \frac{d}{L_e} \le 0.3 \quad \text{----} \qquad \text{---} \qquad [4]$$

Where:

d

$\mathbf{d_e}$ = equivalent depth of the channel due to the thickness of the water conducting layer below it. When the channel floor and confining layer are the same, $\mathbf{d_e}$=**d** (m);

d = the actual distance between the impermeable layer (bedrock, heavy clay or hardpan) and the depth of drain (m);

$\mathbf{L_e}$ = estimated drain spacing between two parallel drains (m);

r = radius of pipe for closed drains (m).

Formula for calculating drain spacing

Examples of three commonly used formula for drain spacing are given below. The Steady State Ellipe Equation (Schwab *et al.* 1981) is one mathematical formula that is used, when the soil profile is assumed constant to the base of the drain. Mainly used when the spacing (**L**) is large compared to the depth of the impermeable layer (**d**):

$$L = \left[\frac{4K_{sat}\left((d+H)^2 - d_e^2\right)}{Q}\right]^{0.5} \qquad \text{-------} \qquad [5]$$

Bouwer's equation is another approach to the steady-state modelling of a drained soil profile has involved using the equation:

$$L = \left[\frac{4K_{sat}H(2d_e + H)}{Q} \right]^{0.5} \quad \text{-------} \quad [6]$$

Hooghoudt's equation (from which the Steady State Ellipse Equation is derived) is another formula that can be used to used to calculate distance (**L**) between drains for steady state rainfall, with two different soil layers (Figure 3.2.1). Hooghoudt derived his equation first for parallel drains, and then modifications were added for drain pipes:

$$L = \left[\frac{(8K_b d_e H) + (4K_t H^2)}{Q} \right]^{0.5} \quad \text{-------} \quad [7]$$

The draw-down curve between two parallel deep drains can be estimated using the steady state one-dimensional flow equation. Assuming that the centre of origin is half way between the drains, the watertable is equivalent to drain depth at the drain (**l**=**L**/2, **h**=0), and the maximum occurs half way between the drains (**l**=0, **h**=**H**), then the equation becomes:

$$h(l) = \left[-R(l)^2 + \frac{RL^2}{4K_{sat}} \right]^{0.5} \quad \text{-------} \quad [8]$$

Where:

l = horizontal distance from origin (centre of the two drains) (m)
h = height of watertable above drain at **l** (m)
R = constant and uniform recharge over the area (m/day);
L = the required drain spacing of two parallel drains (m);
K_{sat} = the saturated hydraulic conductivity of the soil (m/day);
K_b = the saturated hydraulic conductivity of the layer below drain level (m/day);
K_t = the saturated hydraulic conductivity of the layer above drain level (m/day);
H = maximum height of watertable above the drain (at L/2) (m);

The use of steady state drainage criteria may not be satisfactory in all cases. The first limitation applies to countries where groundwater drainage has only recently been introduced, or where there is not a history of scientific drainage research. The second applies to climates in which the rainfall is distinctly non-steady in nature (Smedema *et al.* 1983), as is the case in the dryland areas of Western Australia that experience episodic rainfall events.

Drain spacing design or evaluation under these conditions may be more appropriately undertaken using the 'falling watertable' equation, the Glover-Dumm formula (Smedema *et al*. 1983). The equation uses the calculation of the reaction factor (change in watertable over time) as well as the other variables (**K_{sat}** etc.) required for the Steady State formula. The combined formula is:

$$L^2 = \frac{9.89K_{sat}dt}{\mu} \left[1.16\frac{H}{h_t} \right]^{-1} \quad \text{-------} \quad [9]$$

Where:

L = the spacing of two parallel drains (m);
K_{sat} = the saturated hydraulic conductivity of the soil (m/day);
H = initial watertable level above the drain floor level (m)
h_t = watertable head at time = days (m)

d = depth to impervious layer beneath the drain (up to 8 m). Hooghoudt's equivalent depth is used for pipe drains (m);
t = change in time that drain has been installed (days);
μ = drainable pore space (m^3/m^3);

Figures 3.2.2 and 3.2.3 below have been generated from Equation 7 to give an example of how it is applied and the results that are obtained. These illustrate the draw-down resulting from deep drains constructed in homogenous soils, spaced 200m and 100m apart. Steady state conditions are assumed, the drain is 2 m deep, constant recharge is 0.04 m/yr, the original depth to watertable is 0.5 m and soils are homogenous.

In the 200m spaced drains (Figure 3.2.2), the watertable dropped approximately 0.5m (0.5m below the surface to 1m) for those constructed in homogenous fine sandy soils (K_{sat}=1 m/day). A 1.3 m drop was calculated for drains constructed coarse sandy soils (K_{sat}=20 m/day). Those constructed in loam soils (K_{sat}=0.1 m/day), clay soils (K_{sat}=0.01 m/day) and deep clay soils (K_{sat}=0.001 m/day), showed some response up to 30, 10 and 3 metres away.

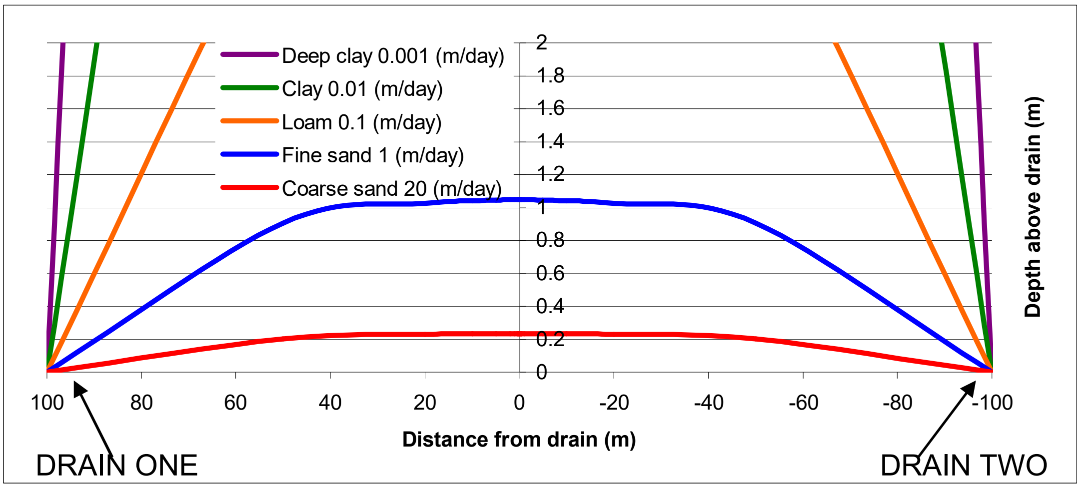

Figure 3.2.2. Draw-down of a 200m spaced deep drains constructed in homogenous soil

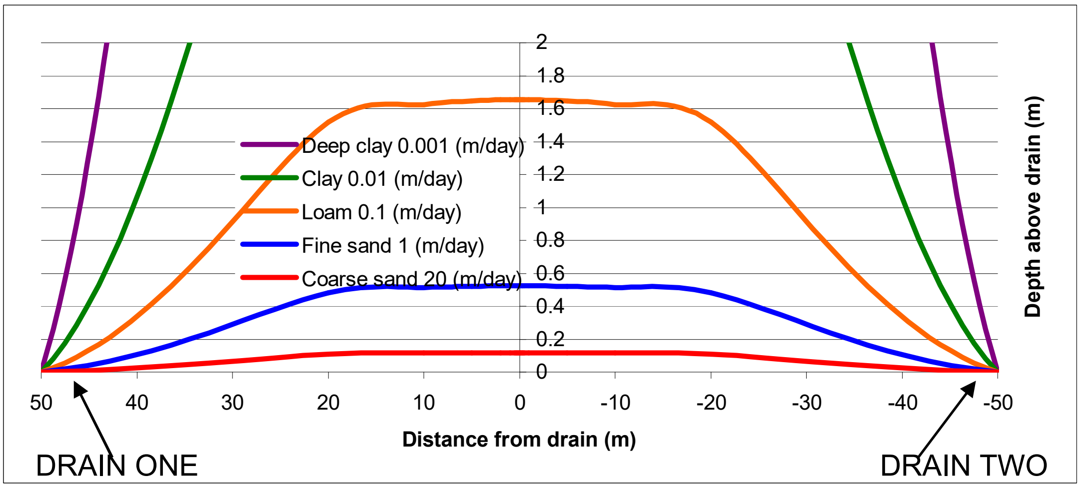

Figure 3.2.3. Draw-down of 100m spaced drains constructed in homogenous soils

Deep drains constructed 100m apart (Figure 3.2.3) in loamy soils showed no drop in the watertable, with those constructed in fine sands and coarse sands showing a minimum drop of 0.9m and 1.4m. Those constructed in deep clay or clay showed some influence up to 5 and 15m from the drain.

Many deep drainage systems in the dryland agricultural areas of WA are configured in a natural layout (see Section 4.4). The draw-down of a non-parallel system of deep drains can be estimated theoretically using the one-dimensional steady state flow equation. The equation is integrated twice, assuming that the watertable close to the drain is equal to that of the base of the drain (i.e. **h(0) = 0**) and the watertable reaches a maximum height at some distance (**L)** metres from the drain, (i.e. **h(L) = hmax**). The distance of influence (**L**) has to be assumed, or determined from shallow bores or pits. The equation becomes:

$$h = \sqrt{-\frac{R}{K_{sat}}(l)^2 + \frac{h\max^2}{L}(l) + \frac{RL}{K_{sat}}l} \quad \text{-------} \qquad [10]$$

The draw-down of the watertable at a distance (**l**) away from the drain (**d(l)**), is calculated by subtracting **h** from the depth of drain:

$$d(l) = D - h(l) \qquad \text{-------} \qquad [11]$$

where:

D = the depth of the drain;
h(l) = height of watertable above the drain floor at distance **l** away from drain; and
l = a nominated point between the drain and distance of influence (**L**) at which you want to determine **h(l)**

In terms of application, this formula becomes more useful when used to determine the potential zone of influence of a drain. If the watertable level is measured in the field within close proximity (**l**) to the drain, Eqn 10 and 11 can be used to calculate (**L**), through trial and error.

Equations 10 and 11 have been used to generate Figures 3.2.4 and 3.2.5, to illustrate the potential draw-down resulting from drains constructed in homogeneous soils, with two different assumed drainage influences (200m and 500m). Assumptions include:

- sufficient time has passed for the systems to reach steady state conditions;
- there is constant recharge of 0.040 m/yr;
- the drain is 2m deep and the watertable is 0.5m below the surface (i.e. the drain has been constructed 1.5m below the watertable);
- the depth of watertable is at the base of the drain;
- assume arbitrary datum is the base of the drain;
- soils are homogenous;
- watertable is not influenced 200m (Figure 3.2.4) and 500m (Figure 3.2.5) from drain; and
- there are no subsurface geological barriers (no flow boundaries) in the vicinity of the drain.

As is expected, the drain is able to draw the watertable down further and at greater distances, where the soils are more permeable (higher K_{sat} values). Figures 3.2.4 and 3.2.5 reveal that a drain constructed in homogenous loamy soils may be expected to influence the watertable up to 10m, whilst those constructed in homogenous fine sand may extend up to 100m. It is important to note that although a deep drain may influence watertable levels significant distances away from the drain, the extent of influence may be infinitesimally small.

Whilst the permeability co-efficients expressed above represent that of homogenous soils, they do not reflect the soil permeability's of the Wheatbelt region. That is, a soil which is classified heavy clay via hand-texturing, is unlikely to be the same permeability as a laboratory tested homogenous clay soil. Amongst other things, the difference in permeability between laboratory and field soils can be preferred pathway or macropore flow, present in heterogeneous soils. Field measured hydraulic conductivity measurements are the most accurate way of estimating the saturated hydraulic conductivity of a potential drainage site.

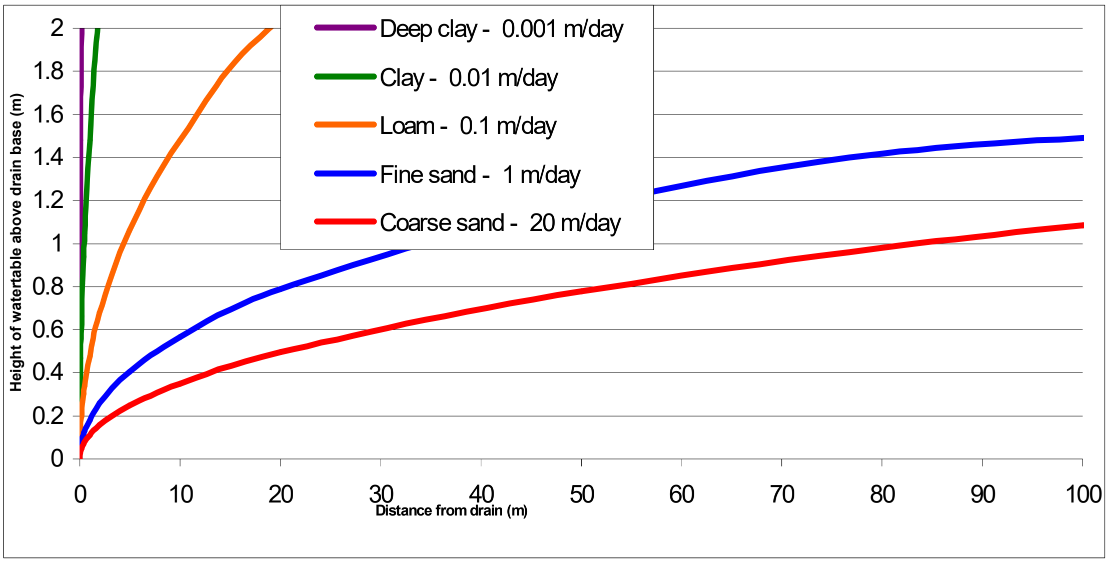

Figure 3.2.4. Draw-down of a deep drain constructed in homogenous soil types of different hydraulic conductivity, assuming zone of influence ends 200m from the drain

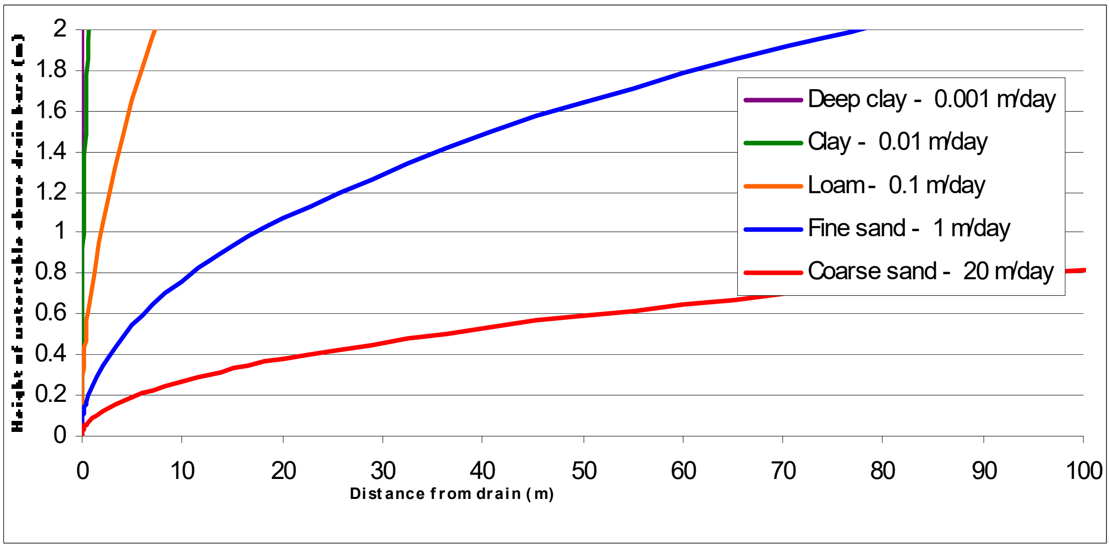

Figure 3.2.5. Draw-down of a deep drain constructed in homogenous soil types of different hydraulic conductivity, assuming the zone of influence ends 500m from the drain

The formulae above also assume that the land is flat alongside the drain, and that the watertable within the zone of influence can not be higher than the top of it. In reality, cases exist where drains have been constructed along the footslopes that create a greater head difference between the watertable surface and the base of the drain. The zone of influence is greatly increased under these conditions.

What is often overlooked, and very relevant to dryland conditions in WA, is that the zone of influence of a drain also greatly increases with decreasing drainage coefficients. In basic terms, the less water that is infiltrating into the soil profile, the less there is to be drained; hence the greater the distance from the drain water can flow. Using the basic formula above it can be seen that a unit reduction in drainage coefficient will lead to a greater than a unit increase in drain's radial impact.

Various "look-up" tables are available as a quick guide to drain depth and spacing. On average, drain depth and spacing on land with good crop and soil management should range within those outlined in Table 3.2.2. Homogenous soil conditions and conductivity of the soil are assumed in the table, similar to the assumptions used in the equations discussed above.

Table 3.2.2 Average depth and spacing for pipe drains (Schwab et al. 1981)

Soil	Hydraulic class	Ksat (m/day)	Drain spacing (m)	Drain depth (m)
Clay	Very slow	0.02	9 – 15	0.9 – 1.1
Clay loam	Slow	0.02 – 0.1	12 – 21	0.9 – 1.1
Loam	Moderately slow	0.1 – 0.4	18 – 30	1.1 – 1.2
Fine sandy loam	Moderate	0.4 – 1.3	30 – 37	1.2 – 1.4
Sandy Loam	Moderately rapid	1.3 – 2.6	30 – 60	1.2 – 1.5
Peat and muck	Rapid	2.6 – 5	30 – 90	1.2 – 1.5
Irrigated soils	Variable	0.5 – 500	45 – 180	1.5 – 2.4

There are a number of computer models of varying levels of complexity that enable the calculation of drain spacing using the inputs discussed above (i.e. NDSP Model, DRAINMOD). However, these are not generally applied to support the design of drains, due to lack of availability of, and familiarity with, the parameters required.

3.2.3 Drainage flow and losses

Predicting the potential flow of an existing deep drain requires measurement of the depth of the watertable alongside and at some distance from the drain, as well as knowledge of drain condition and soil conductivity values. Attempts to predict flow have been made by applying Darcy's Law, after first calculating the area of the side-wall seepage face and base of the drain (Keen 1999). Without knowledge of the hydraulic gradient alongside the drain this parameter can only be assumed, or estimated and even in homogeneous soils, the gradient will not be uniform, as is assumed in Darcy's Law.

Transmission losses are the loss of water from the drain during transfer of flows from one drain section to another. The two main forms of losses occur due to evaporation and seepage through the drain base. Evaporation from the drain is not considered to adversely impact on the function of the drain, and may be beneficial in cases where the discharge water is not being used and there is a suitable but storage limited disposal site. Whilst the high evaporative rates in WA can be used to remove excess drainage water, concentrated salts, nutrients and low pH in the remaining drainage water may still have detrimental impacts on downstream environments. The effect and impact of evaporative concentration of drainage water has had only cursory study in the past. However, recent studies suggest that flow along a deep drain may vary by more than 100 per cent during a 24 hour period.

If drains intersect areas of high permeability, such as sand seams, where the drain is not below the watertable, water conveyed within the drain can be lost via infiltration to the soil profile beneath it. ILACOB (1981) have suggested that in the absence of through-flow, there are three likely senarios: gaining, losing to a shallow watertable, and losing to a deeper aquifer (Figure 3.2.7).

Cox *et al.* (2001b) noted that the potential for transmission losses was highest in larger scale networks. This was merely because of the size of the scheme and hence the potential to encounter pervious soils and lower watertables along their alignment. Transmission losses have the potential to recharge the groundwater within the soils and aquifers beneath the drain channel, causing high watertables in areas previously unaffected. This can be particularly significant in arid (or semi-arid) zones of Australia (Cordery and Fraser undated).

The processes of transmission loss are well understood and documented in many irrigation scheme design texts. The process of estimation of these losses involves the use of the

Darcy's Law applied to the wetted perimeter of the drain. The slope of the watertable can be assumed to be unity, and the conductivity of the underlying strata can be measured using the reverse auger hole method (Smedema *et al.* 1983).

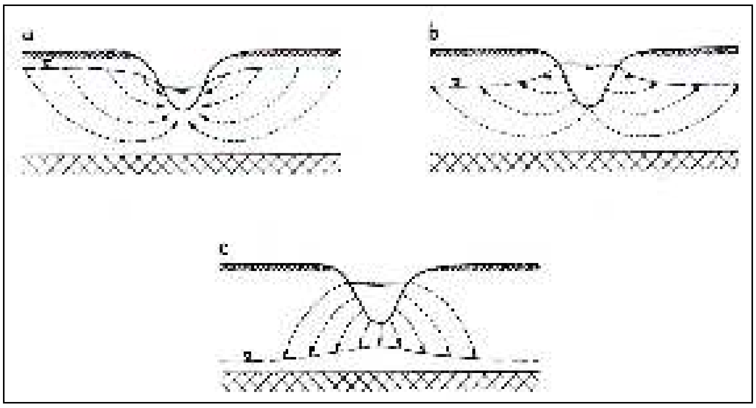

Figure 3.2.7. (a) Gaining drainage system, (b) losing to a shallow watertable drainage system, (c) losing to a deeper watertable drainage system (ILACOB 1981)

3.3 Measuring the success of deep drains

The methods used to determine success have varied throughout Australia. Measuring success firstly requires "success" to be defined, and secondly, the selection of appropriate monitoring techniques to measure that success. From a decision approach, the success of a drain is judged by its ability to enhance discharge and lower groundwater levels to the desired depth, with a given level of probability. The final determination of drainage success comes from the assessment of improved productivity or return to intended use. Changes in the depth to watertable are generally measured over time, using a combination of shallow and deep, observation bores and piezometers at various depths and distances from the drain (Lennard 2000, Berhane 1999). Various computer programs are currently available (i.e. HARTT) to separate rainfall events, changes in barometric pressure and drain influence from the bore data.

Flow is often used as an indicator of enhanced discharge and therefore success. Experience has shown that the larger volumes of water are generated during the initial construction of a drain and normally decline with time. However, successful drains continue to flow at reduced volumes (base flow) or flow in response to rainfall events. Unsuccessful drains are considered to be those that have dried up completely after the initial flows subside. However, some may point out that in de-watering or draining the immediate area the drain has been successful. Even within high rainfall zones, most properly designed closed drainage systems stop flowing over the summer months.

Coles *et al.* (1999) discussed the limitations in evaluating the effectiveness of deep drains by groundwater levels and flow rates alone and suggested that reductions in waterlogging and enhanced solute leaching should be measured. In several, more recent studies, solute leaching has been added as a criteria for success, and measured using changes in soil salinity along the drain (Christen and Hornbuckle 2000, Berhane 1999). Leaching has also been estimated through a mass balance, using the salt concentration of drainage water (Ferdowsian *et al.* 1997).

In an agricultural setting, the aim of most drainage systems is to improve the productivity of either crop or pasture production; success is gauged by the extent to which this is achieved. Crop yields at various distances from the drain, aerial and point photographs and visual observations are used to measure changes in crop and pasture productivity. However using crop productivity is limited in many cases, due to lack of pre-drainage data, climate variability, difficulties in allocating a suitable control site, seasonal conditions, crop rotation, soil condition, and the interference by weeds, pests and diseases.

The ability of deep drains to maintain their physical structure (i.e. degree of slumping, depth of sediment, cost of maintenance) over time can be used as a measure of success. The capacity of deep drains to remove water decreases significantly, as the physical structure decays. Paice and Donohue (1999) used a rating scale (A to D) to assess the condition of drains in the south west drainage districts. A drain with an “A” rating resembled a natural watercourse with established riparian vegetation, limited weed invasion, meanders and a variety of aquatic life. A drain with a “D” rating was usually unfenced, with either bank degraded, silted and with very little riparian vegetation, except for some weeds. This classification system is based the way the drain reflects natural flow conditions or riparian river environments and does not necessarily focus on drainage capacity and radial impact.

Monitoring data of many deep drainage studies have been incomplete due to lack of pre-drainage data. Ideally, a monitoring program should commence at least 6 months to a year before the drain is installed. Cox (2001a) recommended that the minimum amount of monitoring for deep drains involve the measurement of:

- volumes, salinities and nutrients from at least at one drain section and at the outlet;
- depth to natural groundwater at least seasonally in at least one drain section and the outlet;
- changes in line with goals (e.g. increased productivity, protection of remnant vegetation); and
- changes to vegetation and water quality in receiving watercourse, both upstream and downstream of discharge point.

4 Types of drains

Open (leveed and un-leveed) trench drains and closed drains lined with Corrugated Plastic Tubing (CPT) are the two most common types of deep drains constructed in WA (NDSP 2002, Fonstad 2002). Each has advantages and disadvantages and will be more effective in different sites.

Open drains remove land from production, restrict the use of machines and movement of livestock, may require bridges and culverts, have a higher risk of slumping and transmission losses, and require frequent maintenance (Fonstad 2002). The area of land lost and the maintenance requirements can be less in closed drainage systems (e.g. French, pipe and mole). However, the installation costs are generally higher depending on installation techniques and the requirement for envelope material. Generally, open drains are most suitable for larger-scale drainage schemes that emcompass significant length alignments (>2000m) and closed drains are most suitable for smaller, more intensive drainage systems required for high value crops or property. The distinction between the two id related the high cost and difficulties involved maintaining large scale closed drain (CPT) system. This may involve high pressure water jetting or rodding and is difficult to do effectively where pipe lengths exceed 300m (Cox 2001a).

Open drains have become the preferred type of drain in many areas of WA as they are cheaper and are readily applied to large areas (McFarlane and Cox 1991). Furthermore, closed drains are not as effective in soils with heavy clay subsoils or those dominated by preferred pathway flow. The drains become stressed at points of concentrated discharge and are generally unable to collect groundwater at a sufficient rate at these points to be effective (Cox 2001a).

4.1 Subsurface drains

4.1.1 French drains (tyre and rubble)

French drains are trenches partially filled with permeable materials. This type of drain is used where the volume of water to be removed is small, to replace culverts in paddock crossing, or were there is too much sediment to permit pipe drains (Schwab *et al.* 1981). In WA, they are most common in small isolated drainage areas, such as hillside seeps, where there is sufficient gradient. Depending on the materials used, French drains cost up to $5000[2] per km.

Traditionally, wood and stone were placed in the base of trenches, with gravel and hay or tarpaper used as a filter between it and the back fill (Figure 4.1.1). The coarsest material is placed at the base of the trench, with decreasing particle size towards the top. Tyres have replaced wood and stone in some areas of the south west, the tyres positioned vertically to form a pseudo pipe drain (Cox 2001a). Detailed design and construction guidelines for French drains are not formally available in WA.

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[2] *Note: cost does not include site investigation, design, pegging and supervision during construction*

French drains last for a number of years until they start to become blocked with fine soil particles, tree roots, iron ochre and magnesium or calcium carbonate and need to be reconstructed (Schwab *et al.* 1981, Cox 2001a). Highly saline and acidic drainage water, may cause materials used in construction of French drains to decay at a faster rate than in other areas. Drains will remain effective for longer where protective filters or materials cover the drain.

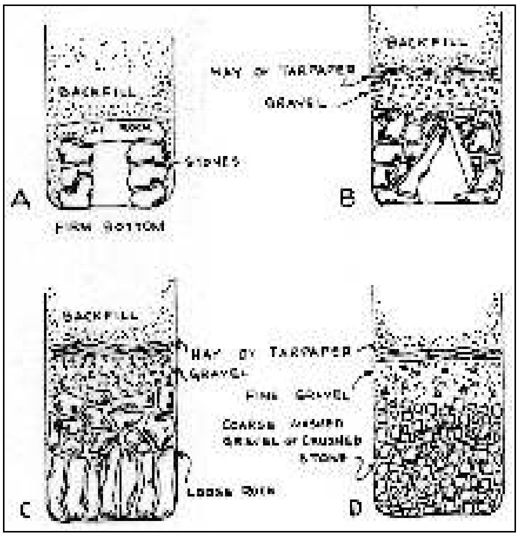

Figure 4.1.1 French or rubble drains (Schwab et al. 1981)

4.1.2 Pipe drains (tile and tube)

Pipes are laid in a trench to act as a conduit and back-filled with excavated soil and/or a more permeable aggregate (i.e, blue metal). In WA, pipe drains are commonly used to manage salinity and waterlogging problems in areas that support high-value agriculture, such as the south west irrigation area (Christen and Hornbuckle 2000, NDSP 2002). They are used in conjunction with mole drains to intercept through-flow in niche areas such as hillside seeps and in the irrigation areas of the coastal plain (Bennett *et al.* 1999, NDSP 2002).

Pipe drains can also be used to remove groundwater from shallow watertables in flat valleys, however high installation costs and marginal returns have limited their use in dryland agricultural areas (NDSP 2002). Likewise, the lateral effect of pipe drains is considerably less in soils of lower permeability and this limits use in many saline sites as very close spacings (2 to 6 m apart) are required (Bennett *et al.* 1999). Pipe drains are also not as effective as deep open drains in areas dominated by flow via preferential pathways (Cox 2001a).

Various materials are used to construct pipes, including concrete and clay tile, concrete, corrugated galvanised steel, bituminous-fibre and plastic pipe tube (Fonstad 2002). Plastic tube drains (CPT) are the most commonly used closed drainage systems used in WA, as this is most readily available and least labour intensive to install and is the most resistant to deterioration or deformation (Cox 2001a).

Tile drains are permeable pipes made from porous baked clay or concrete (NDSP 2002). Water is able to enter the pipes through a 1 to 3 mm gap left between each pipe joint as shown in Figure 4.1.2 (Cox 2001a). CPT tube drains are similar to tile drains, but are supplied in 100 to 200m lengths and made of made from slotted or perforated flexible high-density polyethylene (HDPE) or polyvinylchloride (PVC). Perforations in the tube are approximately 5mm long and 1mm wide and make up 7 to 10 per cent of the surface areas of the tube. Tube drains are marketed as Ag-Pipes and Draincoil. (Figures 4.1.3 a & b)

The efficacy of pipe drains is increased when the pipe is surrounded with an envelope of coarse material such as sand, gravel or blue metal (NDSP 2002, Fonstad 2002). The use of pipe drain envelopes is common in WA, with bluemetal (Figure 4.1.3a & b) being most popular (Bennett *et al.* 1999, Cox 2001a). Envelopes are used to increase the hydraulic connection between the pipe and surrounding soil or mole drains and filter out inflow of soil. They may also reduce the entry of fine soil particles into the pipe slots and pipe its self, that might otherwise block the scheme.

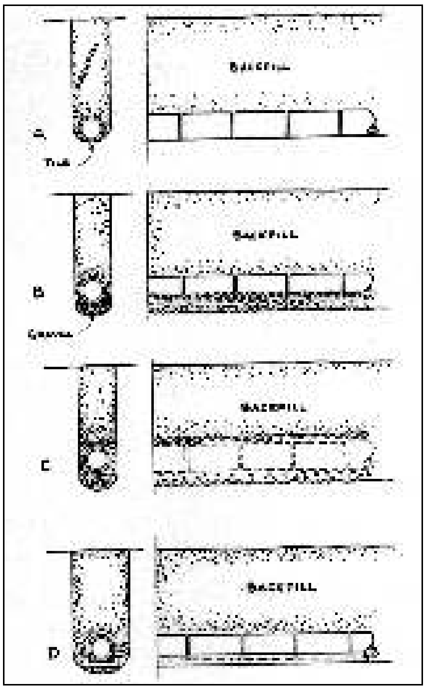

Figure 4.1.2. Tile drains, end and side view (Schwab et al. 1981)

Figures 4.1.3 (a) PVC pipe drain backfilled with bluemetal; (b) A T-junction

Pipe drains usually discharge into open drains, evaporation basins or a natural or modified drainage line (Keen 1998, NDSP 2002). The advantage of managing the outflow from closed drains is that surface water is excluded. This makes it possible to use a sump and pumping system for discharge and disposal. Experience has shown that in open drains, even those with levees, a greater portion of flow is found to be generated from direct rainfall onto the drain channel, berm and spoil banks than from drain seepage. This creates a large volume of surplus water to dispose of that can overwhelm a sump and pump system.

Pipe drains are relatively expensive to install, as they require specialist equipment. The total cost is governed by the relative spacing. Christen and Hornbuckle (2000) estimated costs for horizontal drainage to range between \$3000 and \$5000 per hectare, while Bennett *et al.* (1999) recorded costs of \$1500[3] per hectare.

Design considerations

The groundwater hydraulic design criteria for open and closed drains relative to the determination of spacing and layout is almost identical. The main differences in design do not relate to soil hydraulics but to other variables, including:

- the maximum length of the pipe that can be installed;
- the need to select the correct size of pipe to accommodate the expected flow;
- outlet water management options;
- greater flexibility of scheme layout as it is buried;
- the load baring strength of the pipes; and
- generally higher drainage coefficients used in the design.

The diameter of pipe drains is dependent on the length of system and expected inflow, and range from 50mm to over 450mm (Cox 2001a). The diameter of the pipes commonly used range between 75 to 100mm. The pipes used as collectors for mole drainage systems will be larger (Bennett *et al.* 1999, NDSP 2002). The capacity of the pipes need not be the same throughout the scheme, as the volume of water that is to be conveyed within the upper portions of the scheme may be considerably less than that of lower sections. The required hydraulic capacity of the drains and collectors can be determined from the Manning's velocity equation (Schwab *et al.* 1981).

The required depth of a pipe drain is a function of the depth to watertable, the soil profile and conductivity, pipe gradient, outlet requirements and load bearing strength. The main factors influencing sub-surface drain spacing are the outlet requirements, drainage rate or coefficient, soil hydraulic conductivity, soil profile depth, watertable critical depth and pipe installation depth.

The most common methods of determining drain spacing are past experience on similar sites, the use of drain spacing tables available in many drainage engineering texts. The use of groundwater theory, and calculations such as the steady state ellipse and other equations previously discussed (see section 3.2.2). Soil permeability verses drainage coefficient are the biggest determinants of the effectiveness of pipe drains. Pipe drains placed in relatively permeable soils (about 1 m/day) with lower drainage coefficients are most effective. Success can also be achieved in soils with K_{sat} as low as 10 mm/day (NDSP 2002), which may be related to lower drainage coefficients. Soils of lower permeability and higher coefficients can be drained, however the required spacing is greatly reduced.

Most pipe drains are laid at 0.8 to 2 m below ground level, with 20 to 80 m spacing. Pipe drains installed to manage waterlogging in heavy clay and duplex soils, as well as those, which collect water from mole drains, are usually less than 1m deep (Bennett *et al.* 1999, NDSP 2002). Pipes must be laid on a stable foundation to ensure the continuity of the gap width for tiles and a constant pipe gradient. A cradle is used to lay tiles in unstable soil conditions (Cox 2001a), or trenchless techniques (see below) are suitable for CPT laying. In all cases, where an envelope is used, the width of the trench should be at least double the width of the pipe and constructed with a grade no greater than 1 per cent (Bennett *et al.* 1999, Keen 1998). Generally, an envelope should be included which is thick enough to provide at least a 10 cm coverage of the pipe. The aggregate should be graded and be between 0.7 mm and 38 mm in size. Ten to 12mm bluemetal is the most common and versatile aggregate used in WA.

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[3] *Note: cost does not include site investigation, design, pegging and supervision during construction*

Iron precipitate from drainage water is a significant problem for pipe drains in WA (Bennett *et al.* 1999). Permanent inspection points (usually a junction box) are recommended, and individual sections should be less than 300m long to allow for high-pressure air and water jetting or rodding (Cox 2001a).

Construction and maintenance

Pipe drainage schemes can be installed using open trench and trenchless techniques with the use of a variety of specific and multipurpose earthmoving equipment (Figure 4.1.4 a & b) (Cox 2001a). Trenching of pipe drains is often carried out using a backhoe, but for large-scale installations, specialised equipment may be required and prove economic. Trenchless techniques usually refers to a situation where a purpose built machine is used to both excavate and back fill the trench whilst installing the pipe (and envelope) in one pass (Figure 4.1.4b) (Cox 2001a). Trenchless technique can be used to install drains up to 1.8m deep (ILACOB 1981).

George (1987) suggested that the efficiency of tube drains could be reduced if the soil was smeared by the plough during construction. Thus, trenching and other installation activities should be undertaken when the ground watertable is at its lowest. Where this is not possible, machinery capable of installation under waterlogged conditions will need to be employed, and/or open drains may need to be installed before the pipe drains (Cox 2001a).

Figure 4.1.4 (a) Trench digger (b) Trenchless installation

Accuracy of construction can be improved with laser controlled equipment and a 'tile box' may be needed in unstable soil types (Bennett *et al.* 1999, Cox 2001a). Care with transferring and unpacking materials, placement of pipe and envelope, coupling of pipes and backfilling is important to ensure that the designed drainage scheme is implemented correctly and maximum benefit is gained (Cox 2001a).

Maintaining pipe drains can be expensive. Pipes will eventually become clogged with sediment, tree roots, iron ochre and/or magnesium and calcium carbonate. Cox (2001) describes a number of preventative and maintenance measures, however some or all the system may need to be replaced in the longer term.

4.1.3 Mole drains

Mole drains are a series of stable unlined passages in the soil that improve internal drainage and allow the collection of surface and perched water (Figure 4.1.5a) (Bennett *et al.* 1999, Cox 2001a). Mole drains are formed by a tractor-drawn mole plough, where a vertical blade cuts the soil, and a bullet and expander form and compact the cut into a channel (Fonstad 2002). The soil is lifted and expanded, resulting in the ground heaving and fusing 300 to 600mm either side which create preferred pathways for flow into the drain (Figure 4.1.5b)

(NDSP 2002). Mole drains can be backfilled with a permeable aggregate such as gravel to increase stability.

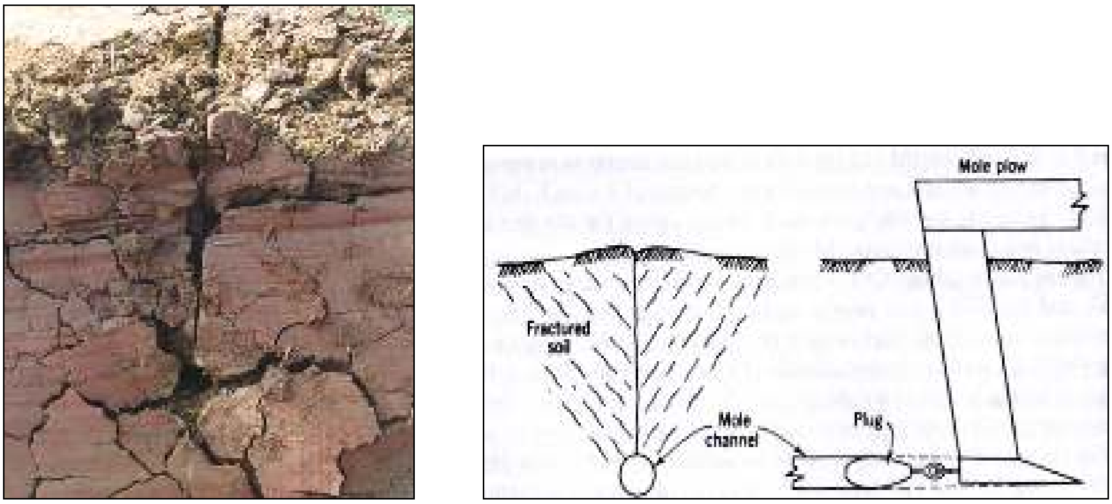

Figure 4.1.5 (a). Mole drainage outlet at a tail drain showing the network of fine soil fissures (Cox 2001a) and (b) Mole drain and method of construction (**Scwab et al. 1981*****)***

Mole drains are used in soils of low permeability such as heavy clays, as well as other stable soils with impermeable soil layers (Fonstad 2002, NDSP 2002). Mole drains are usually used in conjunction with other forms of drainage, and have gained popularity in the south west irrigation district where extensive pipe drainage networks are uneconomical or physically impractical to undertake (Bennett *et al.* 1999, Cox 2001a). Localised waterlogging and salinity caused by perched watertables usually affect these areas rather than regional groundwater rise (Christen and Hornbuckle 2000).

Iron and silica-rich clay hardpans are common throughout the agricultural region in WA and can prevent the construction of mole drains using standard equipment (Bennett *et al.* 1999). Similarly, saline and sodic soils reduce the stability of mole drains and should be avoided. Thus mole drains are not likely to prove an effective engineering option for managing salinity in the dryland areas of WA. Gravel filled mole drains may be an option, however these are expensive to construct and have not been well researched and documented to date.

Mole drains are relatively inexpensive as 1ha of 1.5 to 2m spaced mole drains can be installed in an hour using a 120 to 150hp tractor. The large expense comes with the installation of the collector pipe system by a contractor using specialist equipment over \$1500/ha[4] at 50m spacing (Bennett *et al.* 1999).

Design considerations

Design criteria for use of mole drains to manage waterlogging in the south west irrigation area of WA has been well documented by Bennett *et al.* (1999). The success of mole drains is highly dependent on soil types. Mole drains must be constructed into at least 0.2m of soil with an adequate clay content and soil moisture (Cox 2001a). Furthermore, in duplex soils, the A-horizon must be well above the top of the mole channel (NDSP 2002). Other soil chemistry factors such as sodicity and clay type also affect the stability of mole drains. Observations suggest that mole drains are most stable in the yellow, orange and light brown clays and clay loams of the south west irrigation area. Heavy blue, grey and dark brown "Bungham" clays, as well as saline and sodic soils are unsuitable. Mole drainage is best suited to land with a consistent surface, free of stones and grade between 0.4 and 2 per cent (Bennett *et al.* 1999, NDSP 2002).

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[4] *Note: cost does not include site investigation, design, pegging and supervision during construction*

The spacing of the drain varies, depending on soil permeability, usually 1 to 2 m although it can be up to 5 m (NDSP 2002). If moling is to become part of the drainage system, the desired spacing is estimated using the same method as for any other groundwater drainage works (see section 3.2.2). However, in practice most combined systems have a mole spacing of 2 to 3 m, with collectors at 50m providing these can cope with the peak discharge from the moles (Cox 2001a).

A mole depth of 400 to 600 mm with a width of 75 mm is optimal for most conditions, however mole drains are constructed to depths of 1.2 m (Cox 2001a). Shallower drains are generally more effective and easier to construct than deeper drains (NDSP 2002). The depth of the mole drain must be at least 6 times the diameter of the passage to ensure the channel is stable and adequate compression results (Bennett *et al.* 1999). Stability of mole drains decreases as the passage is enlarged, and with the exception of saline and sodic soils, increases with depth. This type of drainage is most easily installed in the 'parallel' scheme layout where they can be orientated at a right angle to the CPT laterals and parallel to the mainline or collector channel (Cox 2001a).

In general, a mole drain should be no more than 50 to 60 m in length, before there is an outlet as this reduces the risk of uneven gradients and lenses of unstable soils (Bennett *et al.* 1999). Water collected in mole drains is usually disposed of in pipe drains, however deep surface drains may also be used (NDSP 2002). The number of collector drains is a crucial design feature to ensure adequate drainage during storm events. Reducers may need to be installed along collector drains during the summer irrigation season to ensure that the land is not "over-drained".

Construction and maintenance

Generally, the land surface should be levelled prior to drain installation and moles are started within an open channel by lowering the plough into it, before commencing forward motion up the slope. At the end of the 'run' the plough is progressively drawn to the soil surface over the last 10m or so (Cox 2001a).

The tool used to construct mole drains is crucial in achieving stable mole channels and the construction methods used are described in detail in Bennett *et al.* (1999). The ideal configuration for a mole drain is a 200mm wide and less than 20mm thick leg, 65mm bullet, followed by a 75mm expander. A leg slot closing wedge is required where the paddock will not be ploughed or re-seeded after moling. Floating beam and scrubbing beam machines are the most effective for constructing mole drains in WA. Three point linkage machines should be avoided as any surface undulations or loss of traction can cause the tractor to pitch resulting in an unstable and uneven mole channel that may collapse after installation.

Mole drains are only constructed at certain times of the year, and late autumn and early to mid-spring are considered the optimal. Soil moisture is critical and should be as close to its upper plastic limit as possible, and ideally, the soil should be moist but not waterlogged at depth and quite dry and friable near the surface. The moles should be compacted after installation and then left for as long as possible (1 to 2 weeks is ideal) to settle before use (Bennett *et al.* 1999).

If designed correctly, placed in suitable soil types, and heavy vehicle access is avoided, mole drains usually last up to 5 years, however can in special circumstances last up to 15 years (Bennett *et al.* 1999, NDSP 2002).

4.2 Deep open drains (leveed and non-leveed)

Open drains or deep surface drains (trenches) can be leveed or non-leveed, and used to remove both excess ground and surface water (Bligh 1999, Fonstad 2002). Non-leveed drains have no spoil banks, or spoil banks on one or alternating sides of the drain, so are open to unregulated inflows of surface water (Figure 4.2.1a). The drain and berm of these should be designed to carry surface and subsurface water. Leveed drains have spoil placed along both sides to prevent the unregulated of entry of surface water into the drain (Figure 4.2.1b). These drains predominantly remove sub-surface water, however they also carry rainfall falling on the drainage berm, batters and spoil banks. Leveed drains often redirect surface water that is trapped behind the spoil banks, especially in large networks.

In WA, open drains are used to control watertable levels, channel water from upslope properties, redefine drainage lines and as disposal points for sub-surface drains (Chandler 2002). To maximize cost-effectiveness, many open drains are used as relief drains and are constructed in the middle of drainage depressions (Bligh 1999). Basic deep drainage structures costs between \$3500 to 8000[5] per km to construct depending on soil type, location and channel dimensions. More complex systems and those with additions such as culverts can cost over \$10 000 per kilometre to construct.

Figure 4.2.1 (a) Open deep surface drain in Watheroo and (b) Leveed deep surface drain in Kulin (Chandler 2002).

Design considerations

The theoretical and practical design and layout of drains that convey surface water are well understood and documented. The application of hydraulic theories and formulae (i.e. open channel flow) will yield reasonably accurate results (Chadwick and Morfett 1999). Open channel flow is covered in many texts (e.g. French 1985, Chow 1959, Chadwick and Morfett 1999) which explain the variety of equations and methods available. In WA, Manning's formula is commonly used to calculate the capacity of open channels:

$$V = \frac{1}{n} R^{2/3} S^{1/2} = \frac{Q}{A^c} \qquad \text{-------} \quad [10]$$

Where:

V = velocity of the flow (m/s);
n = Manning's roughness coefficient (1/m);
R = hydraulic radius (m) = $\mathbf{A^c/W}$;
$\mathbf{A^c}$ = cross-sectional area of flow (m^2);
W = wetted perimeter of the drain (m);
S = slope (m/m); and
Q = flow rate (m^3/s).

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[5] *Price does not include planning, design and pegging*

Table 4.2.1. Manning's roughness coefficient (n) for flow over bare soil (Keen 1998)

Bare soil type	N	Bare soil type	n
Fine sand, colloidal	0.020	Coarse gravel <60 mm	0.025
Sandy loam, non-colloidal	0.020	Low plasticity (stiff) clay	0.025
Loam and plastic clay	0.020	Soils with stony surface, rounded	0.035
Fine gravel >2 mm	0.020	Soils with stony surface, angular	0.040

The shape of a groundwater drain is determined by depth required to intercept the groundwater surface, whilst excavating as little soil as possible. Theoretically, the 0.2m wide vertical slots that are excavated into the soil by trenchless closed drain installation techniques would perform equally as well if left as open drains. However, as open drains they would quickly deteriorate due to:

- rapid filling by sedimentation from adjacent land;
- erosion from water cascading over and flowing down the batter;
- batter slumping due to vertical unsupported batters; and
- undercutting of the batters by flow within the channel.

Open drain design practitioners are required to assess site conditions and limitations. Once the evaluation is complete the most appropriate channel cross-section that will achieve both drainage and stability objectives is recommended. The availability of earthmoving equipment that can construct drains with variable cross-sections is a limiting factor in drain design.

The proportionally lesser hydraulic radius (**R**) in deep verses shallow drains is usually the limiting factor to deep drain design. The relatively square channel section of deep drains (**R**≤1) means that they are unable to achieve full channel capacity before erosive velocities are reached and the channel is scoured. Non-leveed drains that are subject to unregulated flow are most at risk of this form of damage. Experience has shown that those drains constructed in natural drainage alignments are more susceptible erosion.

Velocity is related to the hydraulic radius of the drain and this can be manipulated to prevent critical velocities (**V**) during periods of high flow, and sediment deposition during periods of low flow (Keen 1998). Sediment transport and deposition can increase maintenance costs, reduce the capacity of the drain to carry water and deposits material into downstream environments. Critical velocities range from 0.4 m/s in sandy soil to 1.2 m/s in medium to heavy clay soil (Table 4.2.2).

Table 4.2.2. Estimated critical velocities (V) for flow above bare soil (Keen 1998)

Bare soil type	Critical velocity (m/s)	Bare soil type	Critical velocity (m/s)
Sand	0.4	Sandy clay loam	0.7
Loamy sand	0.4	Clay loam	0.75
Sandy loam	0.6	Sandy clay	0.75
Loam	0.7	Medium to heavy clay	1.2

The risk of exceeding critical velocities can be reduced by:

- modifying the cross-sectional design of the drain to increase the wetted perimeter verses the cross-sectional area (**R**);
- reducing the volume of water flowing in the drain by placing spoil on both sides of the drain to exclude or regulate surface water (**Q**);
- reducing the pressure on spoil banks by ensuring that the drain does not block or enter a natural drainage line;
- placing velocity traps (such as culverts) along the drain to temporarily detain and regulate flow along the channel during peak flow events (**V**);
- constructing the drain with a grade that will result in flow velocities that are within permissible design limits (usually less than 0.2 per cent) (**S**).

The source of flow (**Q**) in leveed deep surface drains is a combination of groundwater inflow, through-flow (seepage) and direct rainfall. Groundwater inflow and seepage are discussed in Section 3.2.2. The peak flows generated by drain seepage are small and rarely result in the need to apply channel design formula to ensure the channel can safely convey the flows. The more significant limitation with leveed drains is that sediment dislodged from the berms and batters accumulate in the channel, as flows are inadequate to flush this from the system. There have been a number of attempts to alter the design of spoil banks, berms and batters to reduce erosion. The limitation here is that by increasing the batter slope to reduce erosion, the catchment area of the batter is also increased, thereby increasing runoff and associated erosion, if water is channelled into the drain.

The design of non-leveed drains must account for the seepage and localised rainfall components, as well as the runoff and peak flows of the contributing catchment. The peak flow of the catchment can be estimated using a variety of methods, with the rational or index flood method. The 1 in 20 average recurrence interval (ARI) for rainfall events is normally used for this purpose (Keen 1998). An open drain can be designed to convey larger events such designs significantly increase the cost of construction and often unnecessary, as the probability of significant runoff events diminishes with increasing magnitude. This means that the drain designed to cater for a 1 in 20 ARI may only function at capacity once in 20 years.

In larger-scale drainage systems, it is necessary to design the drain to convey surface water from the entire catchment above which it is situated. The design of the drain may change further up the system as the contributing catchment decreases (Bligh 1999). In most cases, the peak flow generated from direct rainfall will exceed baseflow in the drain after the initial de-watering of the site is completed.

The angle of batters is also a critical factor for managing erosion and sedimentation within the drain and is shown as 1:**Z** (vertical to horizontal) in Figure 4.2.2. The recommended batter angle to prevent erosion depends on soil type. Permissible batter slopes range from 1:1 in medium to heavy clays to 1:3 in sandy soils. However, side slopes up to 1:0.5 have been observed to be stable in materials textures finer than clayey sand which do not slake or disperse (Table 4.2.2). Keen (1998) discusses this in detail.

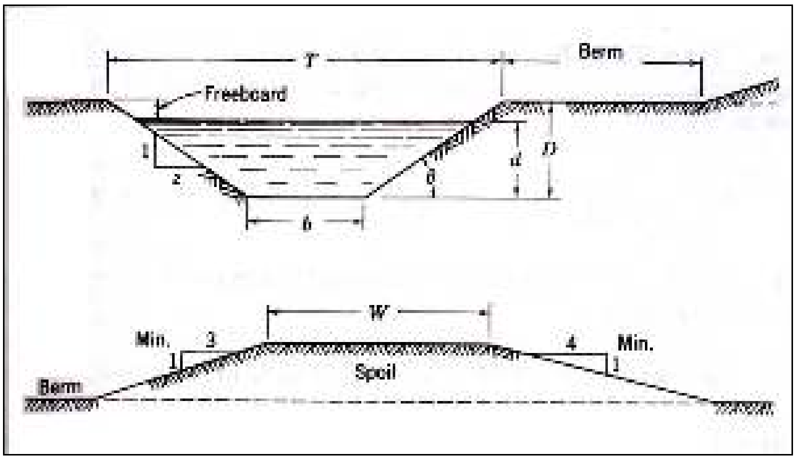


Figure 4.2.2. Elements of a deep surface drain cross-section (Schwab et al. 1981)

Dispersive and slaking soils (especially sodic soils) are constructed with shallower batters to increase stability, and in coarse sandy soils, it may be necessary to measure the angle of repose in a laboratory. The angle of repose can be estimated by pouring samples of dry soil through a funnel and determining the angle at which it comes to rest (Bligh 1999).

The ability to vegetate drain batters is dependent on slope and soil type. The main benefits of doing this is that vegetation reduces raindrop impact on the bare slopes and protects them from scouring during periods of high flow. Vegetation also increases roughness and can act to reduce velocities during periods of peak flow.

Table 4.2.3. Recommended batter slopes for drains in different soil types (Keen 2002)

Soil type	Batter Slope (vertical : horizontal)
Sand – clayey sand	1:3
Sandy loam – silt loam	1:2
Sandy clay loam – light clay	1:1.5
Light medium clay – heavy clay	1:1

All bends along open drains should be designed to have a radius equal to at least 2.3 times the channel width at maximum flow. For example, if the drain is 3 m wide at ground level, then the radius of the bend should be at least 6.9 m. Where this is not possible, stabilisation devices such as cementing or geotextiles may be required to stabilise the bend (Pen 2000).

An open drain must have sufficient gradient or slope (**S**) to permit flow during periods of low flow, yet not exceed its design gradient, which will cause instabilities during peak flows. The maximum gradient of the drain floor should not exceed 0.5 per cent (Keen 1999). Many deep drains in WA are constructed on very flat landscapes and channels may need to be of significant length to ‘rise’ to the surface, in the absence of significantly lower outlet points. This is often the motivation for constructing arterial drains to provide outlet points for local schemes.

The spoil banks placed alongside leveed drains need to be of sufficient height to exclude catchment runoff events. Keen (1999) states that the design height of the spoil bank should be able to exclude runoff generated from a minimum 1 in 50 ARI runoff event. An adequate freeboard (usually 0.2m), should be maintained to cater for low points caused by excessive settlement (Bligh 1999). Spoil banks should be constructed with sufficient height to account for settlement. Schwab *et al*. (1981) recommends varying the berm width depending on the width and cross-section of the drain and spoil banks should be shaped to promote as much runoff as possible away from the drain. They also suggest that a slope of 1:3 used on the inside and 1:4 on the outside spoil banks (Figure 4.2.2).

Localised surface ponding at low points outside the levees, may be drained by installing PVC pipes through the levee banks (Figure 4.2.3a). The outlet of the pipe should also be directed at the channel floor to prevent erosion of the batters that would result if the water were allowed to flow over their edge. Ponding is removed to avoid promoting waterlogging. Care is required in siting and installing piped inlets to avoid pipe failure along the sides of the drain (Figure 4.2.3b The hydraulics of the drain will need to be rechecked to account for increased inflow (Bligh 1999), as sufficient pipe inlets could increase it significantly. Standard pipe flow equations are used to calculate maximum flow through pipes of various specifications.

Culverts are placed in the drain channel at selected points to provide vehicle, stock and sometimes wildlife crossings, and for regulating flow within the channel. The correct size of culverts is selected based in intended purpose. Different types and combinations of culverts are placed in drain channels as follows:

- small diameter culverts (300mm) are usually use in leveed drains where only low flows are expected. Peak flows that might occur (i.e. through piped inlets) may cause the water level in the channel to build up upstream of the culverts thereby attenuating flow within the drain channel;
- culverts of similar cross sectional area as the drain are used where the channel carries non-regulated surface water flow and restrictions to this are not desirable. In some cases, bridges may be more suitable as they do not interfere with the channel hydraulics;
- culverts of various sizes as determined by design are placed in the drain channels to deliberately restrict flow. Where the channel may be too steep, for example, culverts

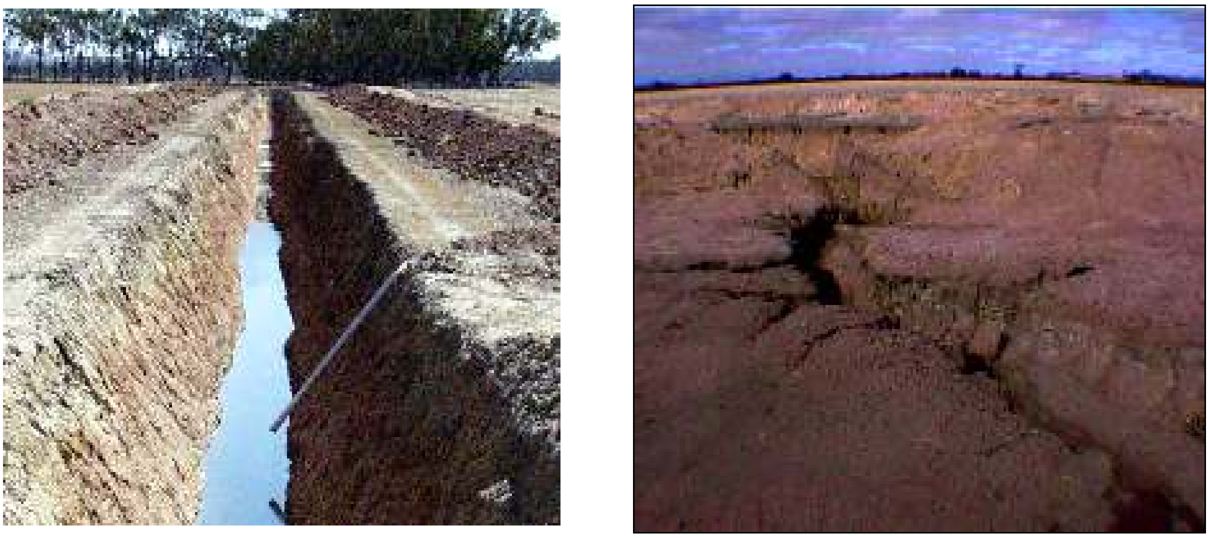


Figure 4.2.3 (a) Piped inlet to drain. (b) Gully erosion caused by failure of piped inlet

can restrict the amount of water that will flow in it, down stream, or will reduce the hydraulic gradient (slope on the water surface within the channel) upstream. The placement of culverts can also cause the channel to inundate during runoff events. This can protect the channel from damaging flows.

All culvert crossings should be designed to fail. On road crossings, this is provided for by a floodway alongside. The correct installation of culverts requires that they have a covering depth of soil equivalent to their diameter in order to achieve their full load bearing potential. Overbank channel flow should be directed around the culvert to avoid a wash-out. Drain waters may also be highly saline and sometimes acidic which will cause some culverts (e.g galvanised iron or concrete) to deteriorate rapidly.

Integration of deep drains with farming practices and other water management options is an important and often overlooked design consideration. Surface water management works can prevent run-on to the drainage site and this reduces the required drainage rate.

Apart from road and rail crossing, long drains may constitute a barrier to normal farming activities including movement of machinery and livestock. Livestock will attempt to cross drains that they can not easily go and may become trapped in the drain. For this and other safety reasons, long drains should be fenced to form working farm boundaries. The implication of this, in terms of farm management, needs to be considered before the drain is constructed. Fencing is also recommended for occupational heath and safety reasons as a landholder may be liable if someone falls into the drain and is injured.

Shrub and grass revegetation along the drain enhances soil discharge, assists in re-establishing soil structure, and can stabilise spoil banks and batters. Trees and single stem plants should be avoided (Green 1990). Salt-tolerant species can be established in saline areas.

Construction and maintenance

Once a works plan is developed and the regulatory requirements are met, the drainage system can be constructed. At this stage, the successful completion of the scheme should depend solely on the ability of the drainage contractor to transfer the plan to the field, which involves surveying and pegging the scheme (Cox 2001a).

Open drains can be constructed with an excavator, bulldozer or road grader each performing different tasks (Bligh 1999). The correct equipment must be selected for the job as machines will possess limitations with regards to the maximum depth of excavation, manoeuvrability and ability to excavate stony or waterlogged soil (Cox 2001a). For example, small excavators (25 tonne) may not be large enough to construct deep drains in stony soils. The drainage practitioner should have a knowledge of the capabilities and limitations of the various types of construction equipment and should consider these factors in the design of the system (Schwab *et al.* 1981).

When the depth of drain is less than 1m and the ground is not too boggy, shallow relief drains can be constructed using a bulldozer or road grader. However in WA, they are usually constructed with an excavator when only a narrow width is required. Winged excavator buckets can be used to construct deeper drains with a smooth sloping batters. Excavation commences at the scheme outlet to allow water that might enter the trench to drain freely (Cox 2001a).

Open drains will deteriorate at varying rates and is determined by the soil stability and the magnitude of rainfall and flood events that occur after installation. Drains constructed in soils prone to slaking and dispersion will erode rapidly. Drains accessed by livestock will experience greater rates of deterioration and erosion (Christen and Hornbuckle 2000). Desilting is required to ensure that the gradient and cross-section of the system are maintained allowing the system to operate effectively.

The sides of deep drains may also need to be scraped to remove the build up of iron oxides and salt crystals normally associated with drains in WA, and where drainage water is fresher (e.g. Watheroo drains), removal of weeds may be necessary (Chandler 2002).

4.3 Other drainage options

4.3.1 Biopolymer drains

NDSP (2002) outlined biopolymer drains in their review of engineering options to manage salinity in Australia. These drains are similar to tile drains, only constructed to a greater depth and vertical bores are used to extract water from the pipe, similar to a horizontal pumping system. The name biopolymer comes from the materials used to stabilise the deep trench during construction. This is a new approach to salinity management and has not been used in Australia. It is likely to be costly and not applicable to management of dryland salinity in WA, unless high value environmental areas or infrastructure is involved (NDSP 2002). Therefore further details have not been included in this review.

4.3.2 Passive relief wells

Passive relief wells are used in other parts of the world to enhance the effectiveness of deep drains. Holes are drilled vertically into the base of the drain and may or may not be backfilled with permeable substrate such as rubble or tyres. These resemble vertical French drains and are installed to intersect more permeable strata at depth. The objective being to relieve groundwater pressure and allow the water to up-well into the drain until the piezometric head is equal to the base of the drain.

Gravel filled passive relief wells have been used in conjunction with pipe drains in Israel to successfully reclaim salt-affected land (Schein and Livne 1998). Chandler (2002) concluded that the majority of water entering a drain near Kendenup, WA came from a lateral with a passive relief well installed.

4.4 Components and layout

Both open and closed drainage schemes can consist of a single drain, or a series of interconnected drains. For more complex schemes, there may be a number of conduits or channels that serve different purposes. The design and placement of these components will vary depending on their function.

Cox (2001a) described the layout of a closed drainage scheme as follows:

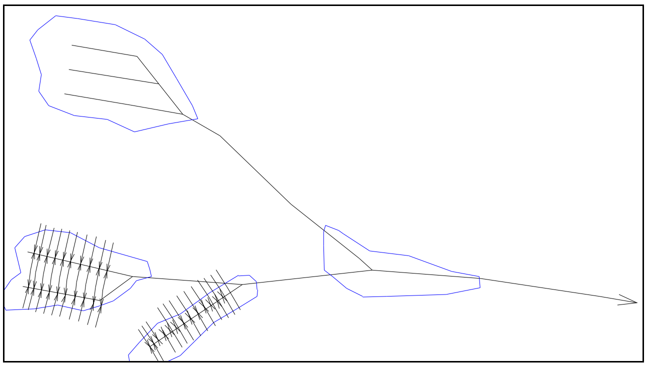
- **Laterals** –drains (French, pipe and/or mole) installed to collect and convey drainage water. A simple scheme may consist of one lateral discharging to the disposal point;
- **Sub-mainlines** – are required as schemes become larger and are used to link the outlets and collect discharge from one or more laterals; and
- **Mainline** – is required to convey discharge from both laterals and sub-mainlines to the disposal point.

This system can be modified and applied to an open drainage scheme of similar layout, where interconnected components served similar functions to the closed system:

- **Laterals** – are channels of depth, spacing and layout as determined by drainage theory or experience;
- **Collectors** – collect discharge from one or more laterals and may serve to provide groundwater drainage in itself. The collector may direct outflow straight to the outlet or connect to a 'riser';
- **Riser** – conveys discharge from the scheme to the discharge point. The term riser is used, as this section of channel may need to convey discharge to ground level, downstream. The drain becomes progressively shallower along its length and so will be at a lower gradient than the rest of the scheme. On flat land, the riser may have to be several kilometres long before reaching ground level discharge point (Keen 1998).

Drainage schemes are laid out so that the channels have the greatest ability to intercept and remove groundwater, and minimise the land area that is 'double drained'. Double drained land is that which falls within the zone of influence of two or more grains. Drainage schemes laid out in a natural (dendric) pattern usually contain the greatest proportion of double drained land as channels converge at acute angles. The most common layouts for drainage schemes are:

- **Natural** – most effective where the areas to be drained are orientated along natural drainage depressions. This layout is widely used for deep drainage systems in inland parts of WA where drains are usually constructed along the natural drainage line, or lowest point in the landscape (Figure 4.4.1a);
- **Herringbone** – most suitable for large areas of land with a very gentle uniform slope. This layout is often applied to hillside seeps (Figure 4.4.1b); and
- **Parallel grid** –this layout is used where the land is fairly level and uniform, with a relatively uniform and high watertable. Drains are spaced in parallel lines across the paddock and provide uniform drainage over the site (Figure 4.4.1c).



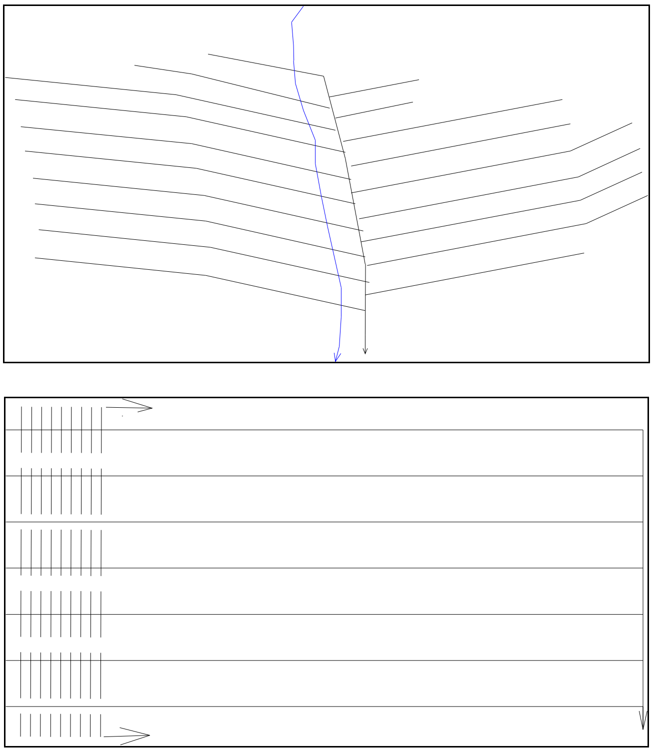


Figure 4.4.1 (a) Natural drainage layout and (b) Herringbone drainage layout (c) Parallel drainage layout (Cox 2001a)

4.5 Placement

Placement of a deep drainage system is an important aspect of planning and design and can determine the difference between an effective and ineffective system. In many cases, deep drains are constructed without adequate site investigation and problem definition. Investigations are required to ensure that a deep drain is the most effective solution for the problem. With more landholders choosing to install deep drains, there is a need to determine where in the landscape these structures are best suited. At present, there is limited amount of information available to determine where it is best to place deep drains in the landscape.

4.5.1 Drainage zones

There is not yet sufficient credible technical information based on the quantitative assessment of groundwater drainage to be able to predict how well a drain will perform at a particular location. We do yet not understand the interactions of the soils, shallow hydrology climate and land use within the south west to be able to make such assessments.

Deep drains are used for different purposes and have achieved different levels of success in the four drainage zones of the south west of WA (Figure 4.5.1). The *coastal* zone is a high rainfall area, with low gradients and frequent waterlogging and inundation. Previously, drainage systems were designed to manage surface water inundation and runoff related problems that caused waterlogging. On a regional scale, these schemes were constructed and managed by Government. With the increase in land use intensity, agricultural diversification and an increased knowledge of salinity issues, closed drainage schemes are being constructed in the coastal areas. Research in this zone has demonstrated that these schemes can operate with co-efficients as high as 20 mm/day and leach salt from the soil. This has lead to improvements in pasture production, but has highlighted problems associated with soil structure after the removal of saline water.

The *rejuvenated* and *plateau* drainage zonea are characterised by high relief, high to medium rainfall and well-defined natural drainage. Drains used for both relief and interception have had varying degrees of success in this region. Steeper hydraulic gradients often result in greater capacity for groundwater to flow into the drain. The variable depth of the regolith, combined with geological structures, results in strong preferential pathway development. This can negate the benefit of steeper hydraulic gradients, as drains will need to intersect these pathways to enhance discharge. This drainage zone also generates high energy and prolonged surface runoff events, and makes the design and construction of 'stable' drains to accommodate these events more complex.

The ancient drainage zone is characterised by flat, poorly drained land with high evaporation rates and low rainfall. The region is characterised by gently undulating landscapes with salt lakes chains on the valley floors. The soils are dominated by sandy and loamy duplex soils, often alkaline and sodic, calcareous loamy earths and sandy lateritic gravels (Mulcahy 1967). The introduction of annual agricultural systems has caused many broad valley floors to become saturated, requiring artificial drainage. Most drainage in this zone has been relief, using open drains, up to 4m deep. Drainage in this zone has achieved varied success due to the constraints that have been discussed throughout this report.

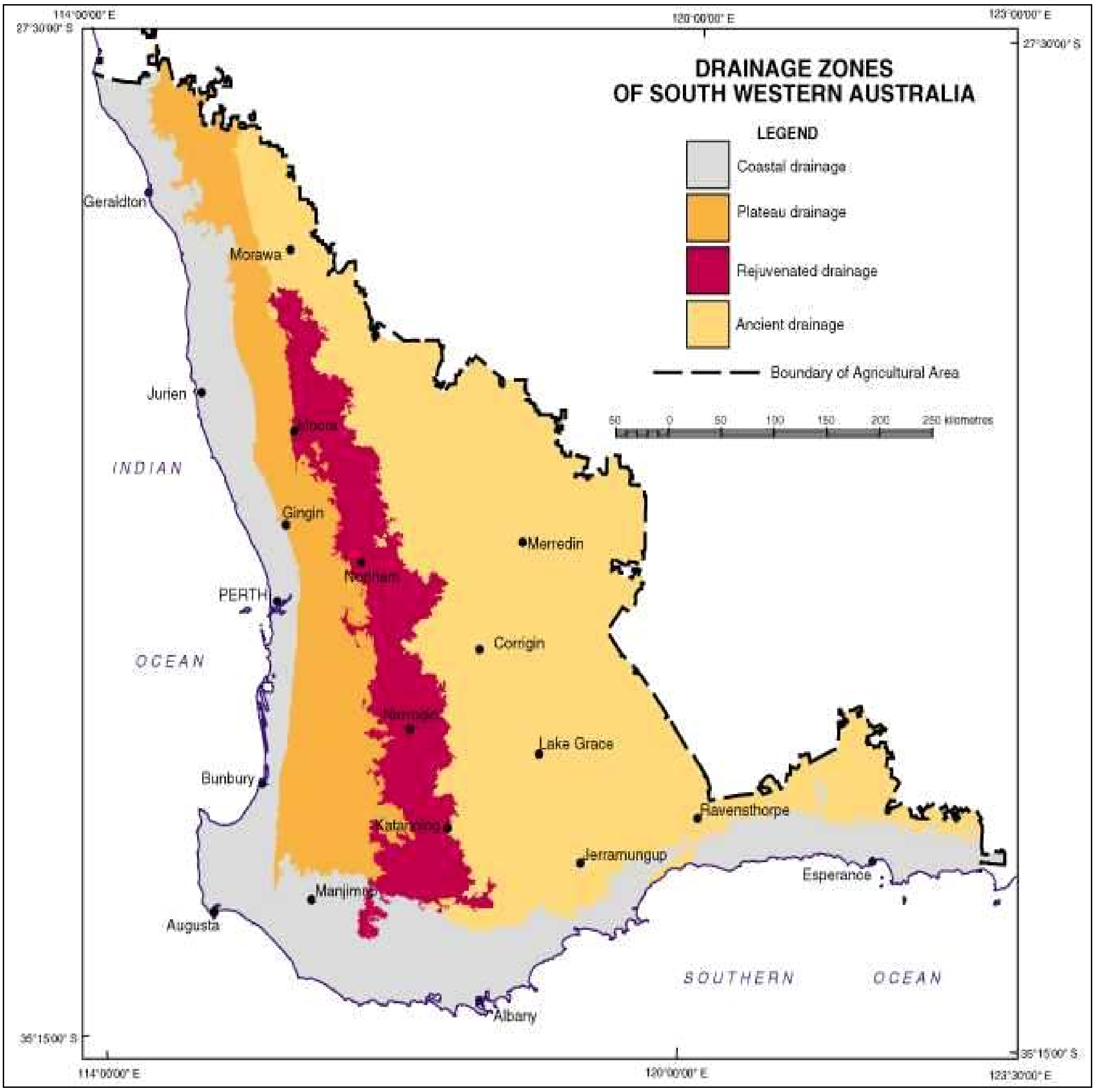


Figure 4.5.1. Coastal, rejuvenated and ancient drainage zones of the south west region (DAWA 2000)

4.5.2 Landscape position

The common use of drains to rehabilitate inundated land of less than 0.5 per cent gradient has promoted their use in WA in the broad valley floors that experience inundation, waterlogging and salinity problems (Keen 1998). Under these conditions, a drainage scheme can be laid out with some degree of flexibility and behave in a reasonably predictable manner. It is often when groundwater drains are constructed within landscapes or in conditions, that exceeded the basic gradient limitation that problems arise.

In the upper catchment, deep drains are used to intercept groundwater before it reaches the lower valley, and to enhance discharge from seeps. Drilling is recommended to determine the cause of a hillside seep before drainage is considered. If the soils are suitable for drainage construction, deep drains placed at the break of slope can be successful in alleviating waterlogging on the valley floor. Break of slope seeps commonly occur along concave slopes (Figure 4.5.2a). Sandplain seeps can be managed in the same manner. Sandplain seeps are usually fresher and commonly occur at the base of a sandy rise, above a clayey valley floor (Figure 4.5.2b).

Drainage of mid-slope seepage caused by outcropping bedrock or dolerite dykes (Figures 4.5.2 c&d), is successful in some cases, however is usually not preferable as upslope surface water management and revegetation is more cost effective. Dolerite dyke seeps can be identified by a change in soil texture near the seep. Drilling may be required to correctly assess bedrock highs.

Deep drainage of valley convergence seeps is not recommended as the amount of discharge is seasonal, and surface water management and sub-surface interception upslope can reduce waterlogging and inundation more effectively.

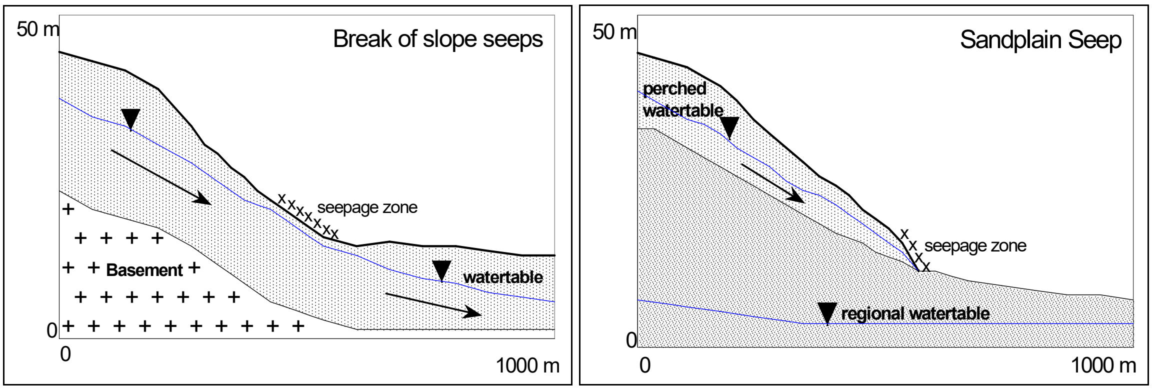


Figure 4.5.2. (a) Break of slope, (b)Sandplain seeps

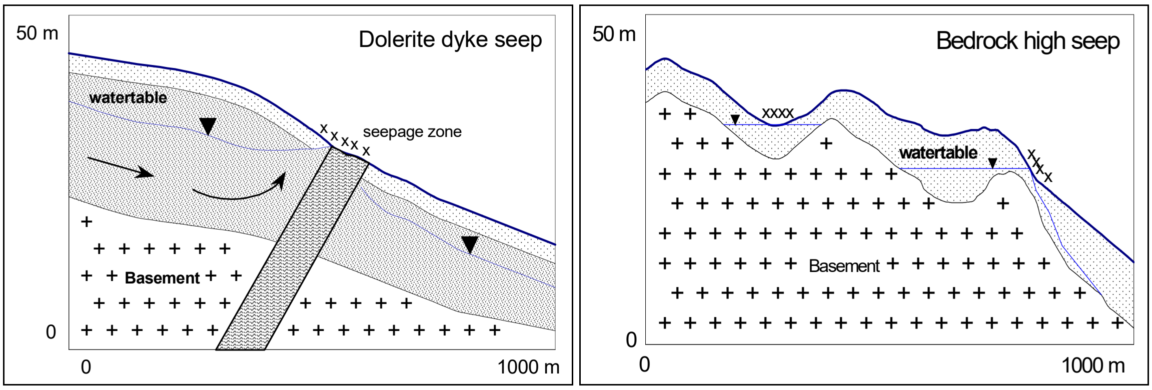


Figure 4.5.2 (c) Mid-slope seepage and waterlogging caused by dolerite dykes, and (d) Mid-slope seepage and waterlogging caused by outcropping and bedrock highs (DAWA 2000)

4.5.4 Soil features

Local soil features are extremely important in determining the effectiveness of a deep drainage system. Many studies have shown that deep drains can be successful in areas of duplex soils with relatively low permeability, if they intercept enough preferential pathways. Preferential pathways include sand seams and old root channels (Figure 4.5.3) and in the east and north eastern Wheatbelt may also include secondary cemented sand horizons that have lost primary permeability but gained secondary permeability. Where these layers are well-connected the watertable may be lowered considerable distances from the drain, and reduce groundwater pressures. P

referential pathway flow and sand seams should not be confused with palaeochannel sediments. Palaeochannel sediments are located much deeper in the soil profile than deep drains (usually >> 20m) and drainage is only possible by vertical drainage through pumping or relief wells (Dogramaci 2002).

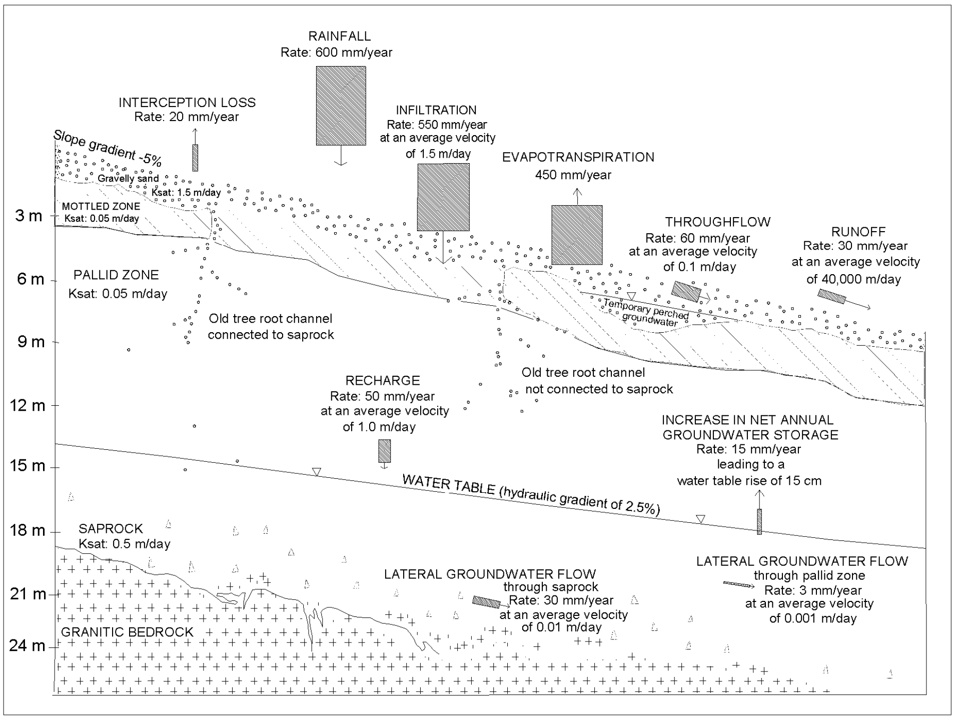


Figure 4.5.3. Old tree roots acting as preferential pathways in the water balance of a hillslope in a 600mm rainfall zone

4.5.5 Sodic soils

Leaching of salt from some saline soils can improve crop yields, however, removal of salts from sodic soils can cause a complete loss of soil structure making them difficult to cultivate and maintain productivity.

Saline soils are those that contain sufficient water-soluble salts to reduce crop productivity. In WA, soils are marginally, moderately and highly saline with a saturated soil extract electrical conductivity (ECe) reading of 200, 400 and 800 mS/m (George *et al.* 1996). Despite losses in productivity, saline soils are in a flocculated condition and as such are well structured. Soil structure is related to soil porosity, strength, stability and resilience and soil structure decline is an important agronomic issue for WA landholders (Needham *et al.* 2001).

Soils that become saline through secondary salinity will become sodic with time (Scholz and Moore 2001). Sodic soils are low in total salts but high in exchangeable sodium, ESP (Lamond and Whitney 1992) and are defined sodic if the ESP is within the range 6 to 15 and highly sodic if the ESP >15 (Scholz and Moore 2001). The degree to which sodicity affects any given soil is influenced by factors such as soil mineralogy, pH, texture and organic content (Lindsey 2000). Sodic soils are normally de-flocculated, meaning that they have limited soil structure, which reduces permeability and workability. These soils are sticky and have a slick look when wet, are nearly impermeable to fresh water, and as they dry, they become hard, cloddy and crusty (Lamond and Whitney 1992, Needham *et al.* 2001).

Soils that are both sodic and saline are called saline-sodic soils and exist in a flocculated well structured state (Lamond and Whitney 1992, Scholz and Moore 2001). In WA, many deep drains are constructed into saline-sodic soil. Leaching of dissolved salts from these soils through drainage can cause soil structure decline (Lindsey 2000). The decline of soil structure can reduce the stability of the drain causing the batters to collapse reducing the efficacy and seepage yields along the drain.

Scholz and Moore (2001) suggest that the capacity for sodic soil reclamation is dependent on how readily the salt can be leached from the soil, level of sodicity, effectiveness of drainage at the site and intended land use. However there has been limited research in WA.

Soils should first be tested to determine whether they are saline, sodic or saline-sodic (Lamond and Whitney 1992). A summary of soil properties is given in Table 4.5.1. Saline soils are the easiest of the salt-affected soils to treat if there is adequate annual and the site is well-drained. Deep drains constructed at these sites can reduce water levels and allow rainfall to leach the salt from the upper soil profile. However the low permeability of soils and low annual rainfalls in the dryland areas of WA will increase the time of reclamation.

Table 4.5.1 Salt affected soil classification (Scholz and Moore 2001, Lamond and Whitney 1992)

Classification	ECe (mS/m)	Soil pH	ESP	Soil physical condition
Saline	> 800	< 8.5	*< 15*	*Normal*
Highly sodic	< 800	> 8.5	> 15	Poor
Saline-sodic	> 800	< 8.5	> 15	Normal

Sodic soils can be reclaimed, however it may be a slow and expensive process as the lack of soil structure reduces permeability and thus leach-ability (Lamond and Whitney 1992). Potential treatments for sodic soils include:

- **tillage** – deep ripping soils alongside the drain can increase soil permeability and improve leaching capacity (Needham *et al.* 2001);
- **increased organic matter** – stubble retention, pasture cover and revegetation can be very beneficial in increasing organic matter, microbial activity and improving aggregate stability (Needham *et al.* 2000). Treatment with bagasse has been used in some sugarcane production areas (Lindsey 2000). Salt tolerant species may need to be adopted until the soil is sufficiently leached of salt;
- **gypsum ($CaSO_4.2H_2O$)** – applying gypsum to the soil can improve structure by replacing exchangeable sodium with calcium, and by increasing the concentration of total salts in the soil solution. This option is generally considered the cheapest. Gypsum application rates depend on the ESP of the soil and application rates have been documented (Lamond and Whitney 1992, Needham *et al.* 2001). Gypsum should be applied before the break of season and if gypsum is naturally present in the soil, deep ripping can help to distribute it through the profile. Repeated applications may be required as the gypsum will be leached after two to three years;
- **other chemical treatments** – treatment with other chemicals such as calcium chloride ($CaCl_2$) is possible, but is expensive in WA (Franzen *et al.* 1994, Lindsey 2000). Calcareous soils (soils with excess $CaCO_3$) may be treated with acid forming chemicals

such as elemental sulfur to mobilise calcium naturally present in the soil. However this is a slow process due to the oxidation of sulfur (Lamond and Whitney 1992, James 1993).

Saline-sodic soils can be reclaimed with the same treatments as sodic soils. However excess exchangeable sodium must be replaced by another cation at the same time (or before) the site is drained to ensure that the soil does not begin to display sodic characteristics. Reclamation may not be economical in areas that have low soil permeability, inadequate drainage or low annual rainfall (James 1993).

5 Options for disposal

Disposal of drainage water is an important aspect of design and can be complex where there is no suitable disposal point to receive the quality and quantity of drainage water. The criteria for accessing the success of a drainage scheme must include safe disposal of drainage discharge. In WA it is common practice to discharge drained water into downstream drainage lines, wetlands and salt lakes (Coles *et al.* 1999, Christen and Hornbuckle 2000, Fonstad 2002). Unfortunately most natural drainage lines in inland areas of WA are ill-defined or internally drained and the water is confined to wetlands or salt lakes immediately downstream of the discharge outlet. Therefore disposal into natural drainage lines or evaporation basins "should only be used for disposal of drainage water after all potential productive uses have occurred or the water is shown to be economically unsuitable for use" (CRC Catchment Hydrology 2000).

This disposal method has the potential to impact on the health of receiving ecosystems through additional water, salt, nutrients, sediment, heavy metals and changes in pH and is becoming more restricted (Christen and Hornbuckle 2000). Disposal in WA is also complicated by evaporative concentration of the drainage discharge (Pen 2000). The use of evaporation as a technique to manage drainage water is possible, however concentration of salts in evaporating water can have greater detrimental effects on the downstream receiving body.

Actis (1998) have developed criteria for evaluating the effects of additional water, salts, nutrients, organic and metallic pollutants and acid to the environmental and recreational values of receiving waterbodies. The options available for disposal of drainage water in WA are: (1) reuse; (2) natural drainage line, wetland or saltlake; (3) arterial drainage network; (4) winter release, and; (5) evaporation basins. These are discussed below. A comprehensive review of safe disposal options is being compiled for the EEI Steering Committee.

Reuse

There is potential for drainage water to generate a direct economic return if reused on farm. If suitable quality and quantity, drainage water may be used directly or mixed with fresh water as a source of water for livestock. Fresher water is usually gained by intercepting groundwater flows higher in the landscape.

Inland saline aquaculture is possible where a sufficient volume of drainage water with suitable chemical composition is available (Tille *et al.* 2001, George and Coleman 2001). Similarly, irrigation of salt tolerant plants is possible where water is of good quality (usually <<3000 mS/m) and there is adequate drainage at the site (Sampson 1996). There is also potential for salt and mineral harvesting from water of lower quality, however this may not be viable in WA due to transportation costs (Actis 2000).

Natural drainage line, wetland or saltlake

In some situations, drainage water can be discharged into a natural drainage line, wetland or saltlake. Generally the quantity of water must not significantly change the natural hydro-period of the waterbody and the quality of water must be similar (Actis 1998). The landholder will be held liable for any damage or environmental harm resulting from drainage water discharging onto downstream environments.

A sump and pump disposal technique may be required where land is particularly flat, there is excess sediment or the drain is unable to discharge across a neighbouring property. The size of the sump and capacity of the pump will need to be configured to match the drainage coefficient of the scheme (Cox 2001a).

Where the water is of poorer quality than that the receiving land, it may need to be treated, diluted during large flows, or evaporated on site in a correctly designed basin.

Arterial drainage network

Arterial drainage systems can be used to redefine surface flow in catchments where flow is discontinuous. These systems can manage surface water and/or be used as a disposal point for drains. The arterial system in the Upper SE system in South Australia is a prominent example, where both surface water and drainage water are channeled to the coast. In 2002, funding was allocated to a WA consulting engineering company to conduct a feasibility study of constructing such a system in the Upper Blackwood Catchment.

Arterial drainage system significantly interfere with the natural flow patterns of a catchment and must be adequately planned to ensure that the risks, such as increased flooding, are minimised.

Winter release

Where water is of unsuitable quality to release into a natural drainage line or arterial drainage system, it may be stored (i.e. in a dam). This water is then released during rainfall events (e.g. winter) that generate significant runoff so that the environmental impact of the drainage water is reduced due to dilution (DAWA 2000).

Evaporation basin

Evaporation basins can be used in situations where drainage water is not suitable for reuse, or disposal into natural drainage lines. Water is stored in a large shallow basin, where the water is evaporated during the summer months. Evaporation basin design principles are well defined (JDA and Hauck 1999) and the technology has been used in the Mid Murray, Riverland, Sunraysia and Murrumbigee irrigation areas (Christen and Hornbuckle 2000). In WA, evaporation basin have been used for disposal of groundwater generated from pumping schemes (e.g. Bodallin, Merredin, Katanning).

Evaporation basins must be designed correctly so that they are of adequate capacity, are not at risk of flood damage and leakage is kept to a minimum (Tille *et al.* 2001). They should be located close to the outlet point, away from floodwaters and in areas of low relief (ASAE 1987). Evaporation basins are also a relatively expensive disposal option, however costs may be offset when basins are combined with salt and mineral harvesting or aquaculture ventures (DAWA 2000).

6 Case studies of deep drainage

6.1 Case studies of deep drains in WA

A review of available research data and a site inspection was carried out on 34 drains at 22 locations in the Wheatbelt of south western Australia (Figure 6.2.1). Information for each site is summarised in Table 6.2.1. Information included in this review is reflective of the data available at the time of publication, additional data may become available for these sites in the future.

6.2 Snap shot case studies

In 1999 and again in 2002, reviews of deep drains were conducted in WA through a snapshot or rapid appraisal approach, in which the sites were evaluated on a one-off site visit. A summary of snapshot investigations is included Table 6.1. In addition to the site inspection conducted by the Department of Agriculture additional information was available for the some of the sites selected. Depending on the intensity of research or anecdotal evidence, data was collected on drainage construction, pH, salinity, flow rate, water table depth, productivity improvements and drainage performance.

The review of drainage sites highlighted the seasonality of the response of drains to rainfall (after the initial de-watering phase is completed) that is exhibited by all drains constructed in the Wheatbelt, whether they are open or closed systems.

6.2.1 Snap shot case studies (Coles *et al.* 1999)

Twenty-five drainage sites were visited and evaluated by staff of the Department of Agriculture in 1998 and 1999. The evaluation of the sites highlighted the significant variability in soils, landscapes and drainage performance between sites. However, drainage design, placement and construction did not vary greatly, suggesting that a “universal” drainage design was applied with variable results being achieved in terms of watertable management, land reclamation, changes in productivity and drain stability.

At a number of sites waterlogging and inundation exacerbated the impact of salinity. Upon drainage construction, both surface and subsurface water was “drained” resulting in improved productivity. Work conducted by George *et al.* (1990a,b) suggested that landholders are more likely to achieve success if marginally saline land is treated as these areas can be rehabilitated with lower costs. The decision to drain should be made with the with full consideration given to value of the assets that are to be protected or rehabilitated.

Owing to the expense of implementing large-scale deep drainage projects, one of the basic aims was to reclaim marginal salt affected areas of farms. Distance of impact from drainage works in relation to watertable management varied from 10 to about 100m on the sites evaluated and significant areas previously affected had been returned to some level of productivity. No economic analysis of the trial sites was available.

The productive benefit gained from cropping the affected lands offset the cost of the drains. However the study found that full cost recovery may be difficult to achieve, particularly if regular maintenance was required for drains in unstable soils or on sites that are exposed to flooding. The need for good site evaluation is highlighted. This is required in order to assess the feasibility of drainage methods so that each proposal for drainage can be treated on its merits.

Shallow drains, properly designed and integrated with other surface water management options (agronomic manipulation and strategic tree planting) were suggested as a more cost-effective alternative in some cases. Anecdotal evidence from landholders indicated that the drains improved affected areas of the farm. The marked improvement of the sites evaluated was attributed to increased infiltration, revised capillary balance, waterlogging control and leaching of salts from the upper soil profile. Data from the trial sites supported the notion that the best results were achieved through the installation of remedial works before land becomes completely saline, causing the soil structure to collapse. In a number of cases, farmers had to employed further remedial work like deep ripping and the addition of gypsum and trace elements required before any significant improvements in yield were achieved. This increased the cost of rehabilitation.

Drainage placement and protection was highlighted with a number of drains being severely affected by surface runoff, particularly in the Moora area after the 1999 floods. The placement of open un-leveed drains in natural drainage lines would inevitably result in a drain being eroded, with batters undercut and slumping resulting in sediment build up and blockages. Most drains had some evidence of erosion and siltation with some containing 0.5m or more of sediment if the bottom of the drain.

Draincoil or tube drains were installed in the Moora district with mixed success. The initial dewatering phase improved production and reduced the expansion of salt affected areas. However, the effectiveness was reduced over time owing to the tubes becoming blocked and discharge outlets being covered by sediment. Regular maintenance was not performed at these sites. This is a similar story with other drainage projects, although some landholders had desilted their drains 3 times in the last 17 years.

The most common disposal method in the small scale schemes was the local salt lake system or creekline adjacent to the affected areas. No visible negative impacts on the smaller schemes were observed within the salt lake systems. However, large scale system in which much larger volumes of water will need to be disposed of may require alternative disposal options.

6.2.2 Snap shot case studies (Chandler 2002)

Chandler (2002) analysed twelve drainage sites in the dryland agricultural region of WA, and produced similar findings to those of Coles *et al.* (1999). The drainage sites ranged from Watheroo to Cranbrook (Kendenup), with eight of the drains located in areas of ancient drainage, and four in the rejuvenated zone. Information was collected from previous investigation sites (if available), landholders were interviewed and a one-off site investigation was conducted. A number of points were sampled along each drain to determine the extent to which different parameters varied along an individual drain.

Chandler (2002) found that not all of the deep drains included in the study were installed and used to manage dryland salinity. Four of the sites were used to define or redefine drainage lines and were located in the rejuvenated drainage zone, where the natural drainage lines had become inundated with sediment since clearing. The landholders were positive about the benefits of deep drains in this situation, and one reported that the use of banks and shallow drains before constructing deep drains and did not have a significant impact.

At two sites the deep drains were installed to transfer water from upslope deep drains, with onsite salinity management an additional benefit. In these cases, the landholders may not have installed the deep drains without the initiative taken by their upslope neighbour. Both were in the lower end of relatively large sub-catchments of the Lockhart and Yilgarn Catchments. In these large flat areas, it was expected that more landholders would be involved, even if they are not themselves the instigators of drainage. At the remaining six drainage sites, the deep drains were installed with the objective of reclaiming saline land. At one of these sites, the deep drains were constructed as preventative measure to reduce the spread of salinity. Chandler (2002), concluded that a “one design fits all” approach would not be suitable for deep drains intended for different purposes.

At two out of the 12 sites inspected, drains were not discharging water, with one completely dry and the other contained moist sediments. At one of these sites the drain had intercepted a groundwater mound upslope of an underground barrier to flow and now only flowed in response to rainfall events. The second drain was constructed in heavy clay soils and although it flowed when first constructed, five years later the system has ceased to flow.

Water was flowing in at least some sections of the drains at the remaining ten sites. Flow estimates ranged from 0.05 L/s to 1.66 L/s. Flow rates were highly variable along the drain, with flow being intermittent at many of the sites. Preferential flow of water into drains and transmission losses along the length of drains, were identified as having significant impacts on drainability and drain discharge.

The study found that five out of the eleven drains with water flows were acidic with pH < 7, and four were extremely acidic with pH < 3.5. Low pH drainage water was linked to high salinity readings and were most likely to occur in the valley floors of the Avon, Lockhart and Yilgarn catchments (Figure 6.2.1). The pH of drainage water in other catchments may lower over time as the buffering capacity of the soil diminishes.

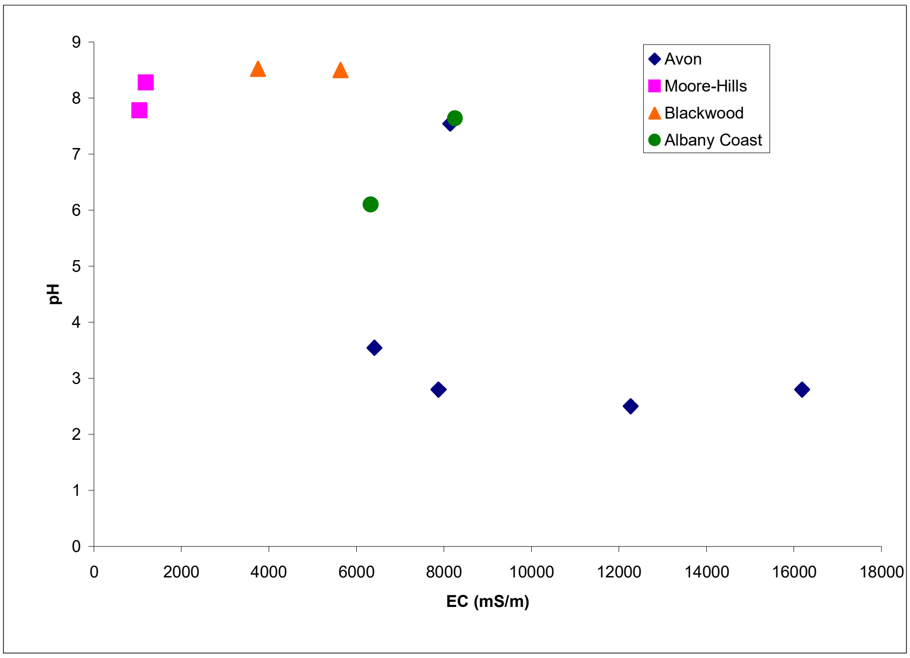


Figure 6.2.1. EC verses pH in drainage water in the Avon, Moore-hills, Blackwood and Albany Coast catchments

The depth of sediment along the deep drains was used as an indication of degradation in the study. Average depth of sediment ranged from 8 mm/yr in a leveed drain in heavy clay soils, to 530 mm/yr which was measured in a recently constructed drain, installed in medium sandy clay soils, in a natural drainage line. The main causes of degradation were exceedence of critical flow velocities, unstable soil types and livestock access.

All of the deep drains included in the study were originally constructed to a depth >1.5 m with an average depth of 1.8 m and a width <4 m with the average width 3.2m. The deep open drains in the study were not designed to control surface water flows generated in the catchments. As the critical velocities were exceed the drains eroded to a more suitable width and depth, or were completely filled with sediment. None of the drains in the study were built with batters recommended as best practice for the soil types found at the sites. However the only drains to have incurred substantial changes to the batters are those that were subject to large runoff flows. Nine of the drains were constructed in heavier clay soils with averaqge batter of 1:0.6. The side slopes had not significantly changed since construction, however slumping and rill erosion suggest that slopes may have been too steep.

Only one drain was constructed with stepped batters to promote stability and encourage vegetative cover. However, excess surface water flowing across the batters had concentrated the flow down the steps and caused severe gully erosion. PVC pipe inlets were used in several sites to promote controlled surface inflow. However at some sites these had failed and the pipe plus surrounding soil was washed into the drain, leaving the drain open to surface water and causing severe erosion and gullying. All of the culverts investigated in the study were blocked with sediment, indicating that they were of inadequate size to carry the peak flow along the drain. These required maintenance. Dead livestock were found in the majority of the drains.

The conclusions of the study were that deep drains had been successful in achieving the required outcomes at some sites. This suggests that the drains are providing an avenue or a mechanism that allows the surface water or shallow perched water to drain from the soil profile over relatively short time periods. This may enable farmers to improve germination and productivity within the affected area without the need to manage the groundwater tables. However inadequate site investigation, and lack of site-specific design and placement, and potential onsite and off-site impacts were reducing the effectiveness of the structures. Use of best practice design could overcome some of these limitations, and regular maintenance would improve the effectiveness of the drains.

6.2.3 Benefits and limitations of snap shot case studies

Coles *et al.* (1999) and Chandler (2002) used a “snapshot” approach for data collection, and found it a useful tool for gathering a large amount of data, with low resource input and within a small time frame. Data collected in such studies includes:

- quantity and quality of water flowing at one point in time;
- evidence of drain degradation and depth of sediment;
- livestock death;
- general soil types and profile; and
- current paddock condition.

Whilst there are several benefits of such an approach, it is important to recognise the limitations. These include:

- lack of transient and pre-drainage data,
- limited groundwater data and subsurface investigations;
- seasonal effects are not included;
- once off flow rate; and
- cannot determine exact cause of drain degradation.

Table 6.2.1 Summary of evaluation data available for the snapshot case studies (adapted from Chandler 2002 and Coles et al. 1999)

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
1 East Nabawa							
(1990)	Valley floor; positioned above lowest point to 'cut off' water movement into the lower landscape. Internally drained.	Heavy red clays; 'sticky black' clays	Limited-negligible on watertable although seasonal fluctuations are observed. Restricted water-logging and salinity. Improved surface drainage.	Moderate Rye grass and saltbush supply substantial fodder	Trees and saltbush have been planted to the east of the drain.	Discharge clay pan site is now virtually perennial lake. 4000 trees established on perimeter of clay pan have perished due to inundation in 1996.	Initial water levels dropped by 1 metre. No further progress and appears to be stabilised at 1.2m. Reduced the incidence and duration of localised waterlogging. Extremely low hydraulic conductivity of clayey profile. Water levels fluctuate seasonally within 1 metre of the surface. Area was bare an salt affected prior to drainage; At least 20 ha of land now cropped, productivity increased. After initial high discharge drain now only flows in winter. Est. 0.70m of drain sediment in drain.
2 Watheroo							
2.1 (1978)	Lower landscape-valley floor.	Grey medium to fine sand to loamy sand overlie calcrete underlain by inter-bedded clay and coarse sand.	Original levels 0.5-1.0m and rising. Effective in reducing water levels to 1.7-2.2m bgl up 50m from drain. Some leaching of soils.	No data.	No data.	81 hectares considered salt-affected using aerial photographs for 1996 up from zero in 1969. Water quality 1024mS/m (1998).. 2002 – 1185 mS/m, pH 8.3, 0.85cm sediment	Problems began after clearing light land in 1968/9. More water in creek. Salt lakes acting as detention basin Deepened outlet near National Park in 1978. 240 ha classed as salt-affected 1979. De-silted twice. Attempted to isolate drains from surface runoff. Linked chain of salt lakes drain to National Park. 2m drains installed in 1980. Deepened to 3m in 1983. Flow est. 1.2L/s. Initial discharge 270kl/day dropping to 60kl/day.
2.2 (1980)	Lower landscape-valley floor.	Alluvial soils. Yellow earth sand. Mottled heavier inter-bedded soils	Decreased watertable depth from 0.6-1.1m bgl.	$2.06 per metre (1981).	Pine trees planted. Area fenced.	No data. Salinity levels in monitoring bores decrease approximately 50% in 4 bores and remained relatively constant in other bores. Drains to creek.	Deep drain used to connect tube drains laid in 30 and 15m grid pattern. Needs de-silting. Still discharging. Effective in lowering watertables in this soil type. Performance limited by depth of lateral tubes (drains). Unstable soil types cause batter slump. Lateral tube drains promote undercutting and slumping.
2.3 (1983)	Lower landscape.	Deep duplex, loamy sand overlying sandy clay. Compacted clay soils at top of subsoil horizon.	Original water table depth at 0.8m bgl. Yield increased on 7 ha site from 0 to 1.2 t/ha Aroona wheat. Waterlogging reduced.	Calculations required. High maintenance cost due to unstable soils. $75/hr (1999 est)	No data.	Est. export of salt 8-9 t/ha/yr. Drains to creek and salt lakes.	Needs de-silting. Seasonal flow response. High incidence of batter slump. Sand layer occurs within 1.6-1.8m in drain-Ks 1-2m/day. Tube drains installed in March 1984. Tube drains effective at lowering watertable depth from 0.8 to between 1.31 to 1.62. Collector drain constructed in unstable materials. Surface soil salinity lowered due to leaching (EM38 survey). Effectiveness decreased due to siltation.

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
2.4 (1978)	Valley floor	Alluvial-colluvial soils. Yellow earthy sands.	Depth to watertable increased from 0.50 to 1.2 (north) and 0.65 (south) to 60m distance. Improved crop to north, limited impact south.	No data	No data	Suspect sediment is discharged from drain due to rapid erosion of batters. Water quality 18,000 mg/L (TSS).	A 2m deep drain sunk in March 1981. Bores installed prior to drain construction.-data 1980-1985. Desilted. Flowing but is silted up-seasonal flows. Sandy soils major batter slump. Sediment filled drain to within 0.5m of surface (in some sections) during Moora flood (March 1999). Poor location of drain.
4 West Wubin							
4.1 (1983)	Valley floor		Reclaimed 20 ha of marginal country. Reduced salinity;	Improved crop growth;	Grade banks, trees, increased cropping, working contours.	Drains to salt lakes	Seasonal flow. Gypsum and trace elements added to soils to improve productivity. Requires de-silting
4.2 (1983)	Saline valley floor-break of slope	gCL (0.5m) grading to mottled SC overlying laterite or silicrete hard pan; Mottled clay to 2.5-3 metres;	Limited impact in heavy clays (lower valley). Appears effective for drains on break of slope (duplex).	Improved crop growth; reduced salinity;	Grade banks and increased storage capacity upslope. Tree planting; decrease in sheep numbers.	Drains to salt lakes.	New drains; Desilting required old drains Successful in some areas. Tube drains blocked. Integrated approach required Silted, but flowing. 0.5 L/s in new drains. Limited leaching of salts from upper profile. Est. Ks 0.01 to 0.08 m/day. Area affected by salinity increased from 122 ha (pre-drain) to 153 hectares (post-drain) Reduced rate of salinity expansion- 3 hectare increase in 7 years.
4.3 (1981)	Saline valley floor-Lower landscape	Red/brown calcareous earth to 1.7m; Underlain by mottled clay. "Coffee rock" indurated layer at 0.90 m.	Limited impact although some revegetation is evident..	No data-reduced or halted salinity expansion. Maintenance cost high	Continuous grade banks constructed 400m upslope from drain. Level banks installed above grade banks to manage surface runoff.	Drains to salt lakes	2m deep open drain, 10 km in length. Part of extensive network in the Buntine-West Wubin area. Effective close to drain (<10m). Crop failure occurred in areas of high soil salinity. Water tables 1.0-1.2m bgl after drain constructed. Limited leaching of salts (except near drain). Later sections closed deep drain (1986). Volunteer bluebush and grasses cover area, once bare salt scald.
5 Kalannie							
5.1 (1997)	Watertable <2m, bare ground. Granite outcrop to NE. Dyke below that. Hilly to W, flat to E.	Start of drain is 20cm coarse sandy loam over hard-setting clay and near end is deeper sands.	Drain released water trapped upslope of a bedrock high.	N/A	Reveg with little success. Grassed waterway NE of drain to carry surface water generated on a granite outcrop	No discharge at time. Poor quality water in lake (6110 mS/m, pH 1.5), thick salt crust and iron stains	Groundwater dropped from 0.5m to 0.7m and 1.2m to 1.4m. Water from neighbour's place no longer inundates crops
6 Ballidu							
6.1 (1997)	Broad flat valley floor. Watertable <0.5m	10-20cm duplex. Sandy loam over light	. Owner can now crop more areas than before, but his salinity problem has not been	N/A	WISALT banks, 40ha trees	Grades into highly saline and eroded waterway, then into Damboring Lake. Water quality of 16,185	Drain has reduced salinity in some areas and not in others. Drained to a couple of salt lakes. Cleaned out after a storm in 1999. Water in WISALTS is 1350mS/m.

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
		clay over heavy clay. Gravel just before first salt lake. Black sediment and sodic soils in salt lake.	solved			mS/m, pH 2.8. No discharge into waterway or water in waterway at visitation.	35 cm of sediment observed in drain in 2002.
7 New Norcia							
7.1 (1999)	Hilly to flat catchment which drains to N. Av slope 0.7%. In waterway. Not much salt-affected land. Drain starts in upper catchment	Loamy gravels to loamy earths over light clay. Some granite and quartz.	Stressed remnant vegetation along the waterway has recovered.		Deep drain for same purpose in 1985 in Yarrawindah Brook (new drain feeds into this)	Grades into eroded Yarawindah Brook (dug out in 1985). Brook runs into Eastern Branch of the Moore River. Drain has increased salinity of Brook (1041 mS/m, pH 7.8). Brook is still fresher than the Moore River.	2002 = 12 cm of sediment
8 Wylkatchem							
8.1 (2001)	Valley floor. Drain runs perpendicular to major waterway	Very shallow loam over heavy grey sodic clay. Ca in upper, green yellow ppt on some batters	Drain has not stopped flowing. Too early to tell effectiveness. Piezometers monitored by the owner. Landholder estimates 2 tonnes salt has drained away since construction	N/A	Revegetation (was dying in parts). Groundwater pumping in 2001.	Graded into salt lake on the same property and into Cowcowing lakes (7877 mS/m, pH 2.7). Thick salt crust with Fe stains on lake. Small drain flows have little impact at this stage.	2002 = 1 cm of sediment
9 Korbelka							
9.1 (1998)	Large flat (<0.1%) c/ment. Drain in valley floor.	Shallow loam over heavy sodic clay. Green/yellow ppt on some batters	Crop yields have increased from o to 1 to 1.2 t/ha.	N/A	WISALT banks and oil mallee plantings (almost all dead now). Natural waterways leveed on both sides	Grades into chain of salt lakes (10101 mS/m, pH 2.5). Within 8km of CALM reserve. Dead trees patchy samphire. Severe wind erosion.	Saline for last 40 yrs. Periodic flooding. In flood plain, between 2 leveed waterways. 42 cm of sediment observed in drain in 2002.
10 East Belka							
10.1 (1997)	Valley floor	Duplex soils. Heavy clay soils, underlain by hardpan and weathered granite.	Reduced water logging. Draining of perched aquifers and surface runoff. Limited impact on watertable depth.	Not known	No data	No data. Est. average salt yields from two sites 1.3-2.0 t/ha and 0.4-1.5 t/ha.	New drains. 3-5 km of 1.5m deep drains. Soil permeability ranged from 0.01 to 0.2 m/day and were highly variable. EM 38 survey indicated some leaching at semi-permeable sites. Nil at others. Flow varied from 0.03 to 0.1 L/s. Shallow surface drains could have achieved similar

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
							outcome. To improve drainage spacing at 8-15m for heavy soils. Increased costs.
11 Narembeen							
11.1 (1996-7)	Deep drains (2-3m) placed in existing creek system in bottom of valley floor.	Medium to heavy soils (eg. Mallee sand and loam duplex; morrell; salmon gum clay)	Drain collects surface runoff in summer and winter. Limited impact at this stage. May drain perched water tables. Batter slump and siltation evident in some parts of the drain.	Opinion varies. No data available.	Trees and shallow drains examined but not considered effective for magnitude of problem.	No Data. CALM refused permission for drains to be constructed in the reserve down stream.	Salinity and water logging major problem in broad flat valley system. New drains Lateral drains. Seasonal flows. Drainage designed by contactor. Not all landholders convinced drains were best option. Percentage of healthy vegetation <10%. Occasional sand lens evident in drain batters. Zone of impermeable mottled clay grading to laterite coffee rock at between 0.3 and 1.0 m. Est. 80km drain constructed.
12 Bulyee							
12.1 (1996)	Closed deep drains constructed on valley floor near existing creek line.	Medium to heavy soils (eg. Sandy duplex; morrell; salmon gum clay)	Little change in watertables.	Improved productivity suggested. No data	Not investigated.	No data.	New drains Limited success. Positive feedback. Lateral drains. Seasonal flows. Zone of impermeable mottled clay grading to laterite coffee rock at between 0.3 and 1.0 metres. Likely to drain perched watertables. Drains designed for farmers in lower landscape. Flow not measured. Car tyres used in lateral drains as experiment.
13 Yealering							
13.1 (1982)	Mid to lower slope. Break of slope at the base of sandplain-salmon gum/ti-tree clay flats.	Sandplain soils. Salmon gum clays.	Limited or no impact.	No. Not going to install more.	95% of drains fenced and area near drain re-vegetated (trees, shrubs and grasses).	None	Closed deep drains. Seasonal variation in water table depth. Water levels remained above 150 cm and within capillary range of soil surface. Discharge from the drain decreased. None noted in January 1999.
13.2 (1982)	Valley floor	Salmon gum clays.	Silted-tube drains blocked. Drain acts as interceptor for water moving downstream.	Crop improvement downslope from drain.	W-drains;	No data	Initially, but tubes blocked Tubes blocked. Some secondary surface erosion evident. Minor improvement in crop production. Watertable at 0.9m (Jan. 1999)
13.3 (1982)	Valley floor-drainage line	Sandplain soils. Salmon gum clays	Reduced water-logging. Improved productivity and access. No impact on water tables on salt flat.	Improved productivity ($1000/km)	W-drains and grade banks. WISALTS	No data	Alleviated waterlogging. Saline areas evident. Piped inlets for surface drainage undercutting batters causing slump. Pooling of water behind spoil causing salinity. Maintenance 7-10 years (1996). Long term evaluation required due to low-transmissivity of clays. Poor placement of drains may contribute to there performance. Flood run-on experienced from upper valley.

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
13.4 (1982)	Valley floor	Salmon gum clays.	Reduced water-logging. No impact on water tables	Improved productivity. ($1000/km, 1982)	Tree planting. WISALTS	No data	Alleviated waterlogging. No measurable fall in water levels. Not effective drain-seasonal factors more important.
13.5 (1982)	Valley floor-break of slope	Sandplain soils. Salmon gum clays	Improved drainage from sandplain. Area below drain remained waterlogged.	No data	Lateral drains.	No data	Improved drainage from sandplain. Lower flats remained waterlogged. Preferred pathways influential. Maintenance 7-10 years. Reduced salinity expansion.
14 Hyden							
141 (1999)	Broad valley floor (0.12%), next to waterway. Constructed in old seepage interceptor bank.	Shallow brown loam over med. to heavy grey clay. Alluvium area - silt and gravel in sheet wash areas. Ca in upper soil profile.	Used as a channel, as well as drain. Always flowing, but most water is coming from upstream neighbour. Land can be cropped but still prone to waterlogging.	N/A	WISALT banks, dams, seepage interceptor banks and revegetation. Natural waterway is leveed in parts (40 wide)	Little effect on downstream Lake as it is saline and was in poor condition before drain installation. However quality of drainage water is poor (6412 mS/m, pH 3.5). Risk of road flooding due to outlet orientation.	May be recharging at site. Some water coming from onsite ponded WISALT banks and dam. Immediate drop in bores at 30 and 100m from drain. Levels in bores very responsive to rainfall. Spoil broke and required de-silting after 2000 floods. Inaccurate grade at outlet as water has banked back. 46 cm of sediment obs. in drain in 2002
15 Kulin							
15.1 (1996)	Midslope, up from flat valley floor. Runs underneath waterway upstream and grades into it downstream	40cm sandy loam over medium to heavy clay (dispersive in parts). Sand mount (alluvial) towards valley floor. Gravel in upper, Ca in lower.	Has not reclaimed but stopped the spread of salinity. Good yields of barley, lupins & mix pasture are not achievable	N/A	Contour banks, reveg, and 16m-grass w/way (1 in 10 ARI).	Grades into eroded saline waterway. Saline water (8144mS/m, pH 7.5), however no discharge upon inspection. Concentration of flow in drain has caused some erosion at disposal point.	Maintenance was required after 2000 floods. No known dykes or intrusions but hardpans have been identified that may act as an aquitard. 27 cm of sediment obs. In drain in 2002. Shire upgraded road culvert for leveed waterway
16 Dumbleyung							
16.1 (1998)	Saline valley floor	Grey clays. Sand seams present.	Too early to judge effect.	Unknown. Depends on the final result.	Scrapper drains and W-drains tried initially.	Initial water quality 5000 mS/m now 5600 mS/m. 2002 = 3750 mS/m, pH 8.5, 0.39 cm of sediment	New drains Spoil heaps eroded. Flow rate est. 2.3 L/s. Some controlled inflow of surface water. Will not be installing further drains unless current project is successful.
16.2 (1998)	Dissected Salmon Gum valleys.	Salmon Gum valley soils	Too early to judge effect	Unknown. No data as yet.	Trees; revegetation.	Downstream impacts not evident (as yet).	New drains Country drier. Trees healthier. Flooding along side drain. Seasonal variation in drainage flow. Flow rate est. 2.3L/s (>2000 mS/m).
16.3 (1985)	Seepage area: Valley floor; Break of slope	Avoided sandy areas during	Mixed response:- effective in some areas, but drain has	Farmer considers cost effective in	Installed contour banks and has re-vegetated sections	No monitoring of offsite impacts. Discharge into Doradine Creek was already	Drains worked in some areas, useless in others. Halted spread of salinity in marginal land in section 500m long, for 10-

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
	to the west; Creekline to the east; Large recharge area upslope.	construction. Sandy Clay duplex soils. Heavy clay subsoils	had no effect in areas near seep on valley floor, approx. 300m from break-of-slope. Improved marginal country	places, where saline expansion has been contained. Not in others. Would construct more drains.	of the farm. Fenced remnant vegetation..	occurring via the seepage area at base of slope on valley floor.	12 years, but has become in-effective due to siltation.. Needs cleaning, clogged with silt and vegetation. No batter slump, surface inflow in seepage areas on valley floor but not upstream. Drainage was considered by landholders as most appropriate treatment of the site. Discharge measured @ 0.16 L/s (1370 mS/m). Water discharged from drain is less than amount discharge at surface by seep.
16.4 (1990)	Broad valley floor. Modified creekline. Drain follow contour of low points in valley.	Sandy loams, sandy clay loams and shallow sand-clay duplex soils. Coffee rock clay layer of variable thickness evident at 0.30m	Improved productivity of marginal land near drain. Improved growth of native vegetation. Reduced hydro-period and waterlogging.	Drain not considered as cost effective by landholder, but drains have improved productivity, reduced waterlogging and restricted salinity expansion.	Minimum tillage improved surface drainage; Surface water management and Landcare works installed upslope to assist drains. Deep ripping; Piped inlets for surface ponding; perennial pastures trialled.	Drain discharges near main road. No immediate impacts evident. Landholder responsible for damage to road in agreement with Shire. Water quality not to exceed 5000 mS/m.	Minimal silting. Surface water excluded Localised depressed water levels. No obvious offsite degradation hazards. Closed drain. EPA and CALM involved through NOI assessment process. Flows recorded (02/99) 0.05 L/s (3300 mS/m) start of drain; 0.11 L/s (19710 mS/m) mid-drain, 0.16 L/s outlet (4850 mS/m). Sand seams evident in sections of the drain. Relatively fresh water discharged into drain. Flow increases during winter discharge (est. @ 0.34 L/s). Will not be installing further drains until convinced current drains are working.
17 Lake Grace							
17.1 (1989)	Drains follow contour approx. 1m above break of slope near valley floor.	Coarse sandy loams.	Landholder considers drains have controlled surface water and groundwater. Area saline affected decreased; vegetation growth improved.	Implied cost effective through improved wheat yields; Paddocks back into production in 5-10 years.	W-drains tried.	Drains discharge into creek that flows into Lake Grace. Saline environment. Impacts not monitored.	Installed to control waterlogging and salinity. Difficult soils to construct drains extensive erosion and batter slump. Possible leaching of salts as area affected has decreased. Improved crop yields. Regular maintenance required (7-10 years). Landholder may construct more as they have been effective. Estimated hydraulic head of 2.5-3.0m above lower valley floor.
17.2 (1972)	Valley floor near break of slope.	?	Improved productivity on about 300 hectares	Improved crop yields; 1972 - $5,000 on 3-4km drains. Spent further $30,000 on 10 km of drains since 1980..	?	Drains flow to Mears Lake on to Avon River. No data on off-site impacts.	10-15 kilometres of drain with a maximum of 1.5 m. Began drainage network in 1972. Redirects runoff from the Kunjin and Wogerlin catchment that caused waterlogging. Farmer happy with performance and considers them to be a good investment.
18 Nyabing							
18.1 (1999)	Lower end of the catchment.	Very smooth white to grey	Rapid improvement in surrounding land and	N/A	40km contour banks. Reveg and	Grades into Nyabing creek, which was dry and covered	Specific effect is difficult to quantify due to dry seasons over the period since

Region	Landscape Position	Soil Type	Effect	Cost-effective	Other treatments	Off site impacts	Comment
	Runs through saline discharge area	dispersive clay. Granite high mid drain. Quartz stones present in upper part.	constant baseflow. However paddock has been cropped		fencing of saline area.	with salt crust when inspected. Iron oxide stains in base of drain. Water ponded at outlet (pH 8.7, 7450 mS/m)	construction. 37 cm of sediment obs. in drain (2002).
19 Nth Stirling							
19.1 (1983-4)	Lower valley.	Duplex soils. Red brown loam to pale sands over silty clay; Fine to medium sand lens.	Watertable lowered near drains. Salt affected area near drain reduced by 27 ha. 8 ha cropped.	Not cost effective. Area required to be recovered is 40 ha. Total cost $30,000.	No data.	Increase sediment and salt discharge to six-mile creek system.	!0 km of drains constructed. Overall effect of drainage system could not be measured and its long-term impact not predicted. Some visible improvements in crop production near drain. Reduced incidence of water logging. Considerable erosion on either side of drain. Batters relatively stable. 1300 ha in catchment salt affected. Low gradients. Variable flow 0.2-2L/s. 8300 mS/m
20 Gnowangerup							
20.1 (1994)	Broad flat depression with poorly defined drainage line (longitudinal slope of 0.3% and side slopes of 1%). 200m wide saline area	Sandy loam over heavy clay to 2m and coarser sandy clay below that. Sandy area with rock barriers to groundwater flow. No Ca or gravel noticed.	Initial groundwater levels dropped by 0.6m and on-going decline of 0.07m/yr. Some improvements in crop yields due to reduced watertable levels and waterlogging.	N/A	Contour banks used with little success	Water in drain (8255 mS/m, pH 7.6) of similar quality to Pallinup River (pH 8.1, EC 8200 mS/m). Concerns drain might “freshen up” Pallinup River	Aerial photographs suggest that saline land has not been reclaimed, however no further land has been lost. 66 cm of sediment obs. in drain in 2002
21 Kendenup							
21.1 (2001)	E to W along Potter's Creek. Av. slope 1:450. Saline discharge area.	Sandy loam (0.4 to 0.8m) over domed sandy medium clay. Hardpan layers within profile. Quartz particles along drain.	Improvement of crops and trees along drain.	N/A	Fencing and reveg (trees were dying). Passive relief well and tyre drain	Drain has redefined waterway, however it remains undefined at outlet. pH levels have dropped (from 8 to 2.6).	Site is still waterlogged. In 2000, salt scalds had disappeared although still moist and samphire. 54 cm of sediment obs. in drain in 2002

Region	**Landscape Position**	**Soil Type**	**Effect**	**Cost-effective**	**Other treatments**	**Off site impacts**	**Comment**
22 Esperance							
22.1 (1986-7)	Drainage depression surrounded by flat plain with less than 3% slope.	Grey shallow alkaline sandy duplex soils. Scaddan Series	Minor impact on watertable. Used for management of perched watertables and surface water.	Managed as saline land. Farmer considered it to be cost effective as it halted spread of salinity (cost $8,000)	W-drains and trees (Euc) trialled prior to drain construct. Gully fill and grassed waterways added to reduce erosion	Disposal into natural saline salt lake system, part of the upper Neridup creek. Water evaporate before reaching creek system. No impacts evident at this stage. Minor sediment deposits (VISUALY ASSESSED).	Flows most of year (0.2 L/s) Area of saline land unaffected. Improved surface and sub-surface drainage to allow establishment of trees, saltbush and barley grass. Watertables not affected. Most siltation occurred in years 3-4 slight batter slump. Surface water allowed to enter drain via gaps in spoil heaps and shallow spur drains.

6.3 Case studies in a landscape context

The 22 sites evaluated in this review, have been plotted on large-scale soil-landscape maps. Through analysing the case studies in this context, any trends or similarities been evaluation sites may be quantified and provide a link to soil-landscape units and drainage performance.

The characteristic soils map (Figure 6.3.1) outlines surface soil units found throughout south west WA. Tables 6.3.1 and 6.3.2 summarise the case studies in the context of their respsective characteristic soils and hydrogeological zones.

Such an analysis has not been conducted prior to this review, and as such a more formal analysis is required. Likewise, it is likely that 22 drainage sites are an inadequate sample size for the entire region, and the data that is available is generally not specific enough to determine exact groundwater trends and impact of the drain. More detailed information is required. Furthermore, this analysis assumes that all drains were constructed the same, to the same depth and for the same purpose. This is not true at all sites. Lastly, the scale of map, is limiting as the each mapping unit encompasses a wide range of soil units. Analysis of each site, using a more detailed map may prove more rewarding.

The preliminary analysis suggest that:

- drains that intercept confined groundwater systems will have low pH values, as it contains a higher concentration of dissolved sulfur (S^{2-}). This is particularly important in the valley floors of the ancient drainage zones;
- at times, drains have performed well in the Northern Zone of Ancient Drainage A, such as in Narembeen, Belka, Korbelka, and Wylkatchem;
- there have been variable results in the South-Western Zone of Drainage B, with the deep drains at Bulyee out-performing those at Yealering; and
- drains have performed well in the rejuvenated drainage zone, such as Watheroo, New Norica, Kendenup, Gnowangerup and the North Stirlings due to the improved hydraulic gradients, relief and higher rainfall.

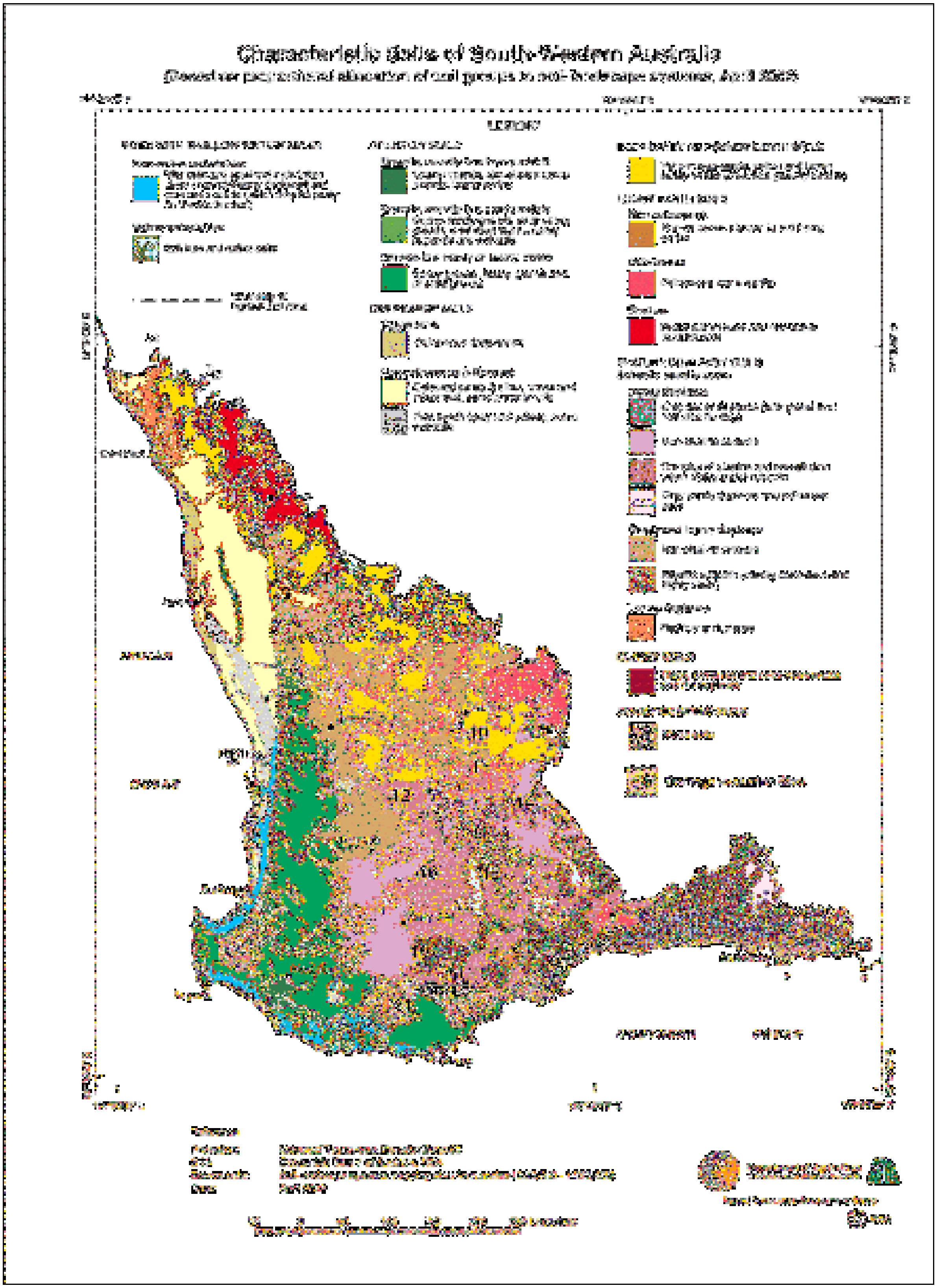


Figure 6.3.1 Drainage sites plotted on the characteristic soil zones of south west WA

Table 6.3.1. Summary of case studies and snapshot sites, in relation to Characteristic Soil Units

Location	Characteristic Soil Unit	Performance	Flow (L/s)	pH	EC (mS/m)	Sed (m)
1. East Nabawa	*Deep yellow sand, yellow and brown sandy earths (often with gravelly subsoil)*	Reduced waterlogging – negligible impact on watertables	N/A	N/A	N/A	N/A
2/3. Watheroo	Deep yellow sand, yellow and brown sandy earths (often with gravelly subsoil)	Reduced waterlogging - impact watertables up to 80m away	0.005	8.3	1185	0.85
5. Kalannie	Deep yellow sand, yellow and brown sandy earths (often with gravelly subsoil)	Drained groundwater mound over 50m away	0	-	-	0.11
7. New Norcia	Loamy gravels, also duplex sandy gravels, loamy earths	Significant improvement to waterway	0.15	7.8	1041	0.12
21. Kendenup	Sandy gravels, loamy gravels, shallow gravels	Limited impact on waterlogging, although salt is leaching away	0.22	5	3700	0.54
8. Wylkatchem	Calcareous loamy earth soils	Too early, but drain has not stopped flowing	0.5	2.7	7877	0.01
10. East Belka	Calcareous loamy earths	Reduced waterlogging – limited impact on watertable	0.03 – 0.1	N/A	N/A	N/A
9. Korbelka	Grey sandy duplex, usually sodic	Crop yields increased from 0 to 1.2 t/ha.	0.01	2.5	10101	0.42
4. West Wubin	Non alkaline sandy and loamy duplex	Variable success	N/A	N/A	2840 – 4330	No
6. Ballidu	Non alkaline sandy and loamy duplex	Variable	0	2.8	16185	0.35
16. Dumbleyung	Non-alkaline sandy duplex	Impact up between 30 and 70m (Tetlow 2002)	0.28	8.5	3750	0.39
11. Narembeen	Complex of alkaline and non alkaline (often highly sodic) sandy duplexes	Impact up to 100m away (Ali 2002b)	18.5	3	5000	0.5
12. Bulyee	Complex of alkaline and non alkaline (often highly sodic) sandy duplexes	Limited impact	N/A	N/A	N/A	N/A
13. Yealering	Complex of alkaline and non alkaline (often highly sodic) sandy duplexes	Limited impact	N/A	N/A	N/A	N/A
17. Lake Grace	Complex of alkaline and non alkaline (often highly sodic) sandy duplexes	Partial reclamation of saline area	N/A	N/A	N/A	N/A
18. Nyabing	Complex of alkaline and non alkaline (often highly sodic) sandy duplexes	Improvement in surrounding land – constant baseflow	0.19	8.7	7450	0.37
20. Gnowangerup	Duplex sandy gravels, deep sandy gravels, deep sands, sandy duplexes	Stopped spread of salinity, reduced watertable by 0.6m	0.78	8.1	8200	0.66
14. Hyden	Alkaline sandy and loamy duplex (usually calcareous and highly sodic)	Impact over 100m away	1.66	3.5	6412	0.46
15. Kulin	Alkaline sandy and loamy duplex (usually calcareous and highly sodic)	Stopped the spread of salinity	0.03	7.5	8144	0.27
19. North Stirlings	Alkaline sandy and loamy duplex (usually calcareous and highly sodic)	Reclaimed 27ha – crop improvement, waterlogging reduced	0.2 - 2	N/A	8300	N/A
22. Esperance	Alkaline sandy and loamy duplex (usually calcareous and highly sodic)	Minor impact	0.2	N/A	N/A	N/A

Table 6.3.2. Summary of case studies and snapshot sites, in relation to Hydrogeological Zones

Location	**Hydrogeological zone**	**Performance**	**Flow (L/s)**	**pH**	**EC (mS/m)**	**Stable**
1. East Nabawa	*Victoria Plateau Zone A*	Reduced waterlogging – negligible impact on watertables	N/A	N/A	N/A	N/A
2/3. Watheroo	N of Ancient Drainage A	Reduced waterlogging - impact watertables up to 80m away	0.005	8.3	1185	0.85
4. West Wubin	N of Ancient Drainage B	Variable	N/A	N/A	2840 – 4330	No
5. Kalannie	N of Ancient Drainage B	Drained groundwater mound over 50m away	0	-	-	0.11
6. Ballidu	N Zone of Ancient Drainage B	Variable	0	2.8	16185	0.35
7. New Norcia	E Darling Range Zone A	Significant improvement to waterway	0.15	7.8	1041	0.12
21. Kendenup	Stirling Range Zone D	Limited impact on waterlogging, although salt is leaching away	0.22	5	3700	0.54
8. Wylkatchem	N of Ancient Drainage C	Too early, but drain has not stopped flowing	0.5	2.7	7877	0.01
9. Korbelka	N of Ancient Drainage D	Crop yields increased from 0 to 1.2 t/ha.	0.01	2.5	10101	0.42
10. East Belka	N of Ancient Drainage D	Reduced waterlogging – limited impact on watertable	0.03 – 0.1	N/A	N/A	N/A
11. Narembeen	N of Ancient Drainage D	Impact up to 100m away (Ali 2002b)	18.5	3	5000	0.5
12. Bulyee	SW Zone of Drainage A	Limited impact	N/A	N/A	N/A	N/A
13. Yealering	SW Zone of Drainage A	Limited impact	N/A	N/A	N/A	N/A
15. Kulin	SW Zone of Drainage A	Stopped the spread of salinity	0.03	7.5	8144	0.27
16. Dumbleyung	SW Zone of Drainage A	Impact up between 30 and 70m (Tetlow 2002)	0.28	8.5	3750	0.39
14. Hyden	SE Zone of Drainage A	Impact over 100m away	1.66	3.5	6412	0.46
17. Lake Grace	SE Zone of Drainage A	Significant impact	N/A	N/A	N/A	N/A
18. Nyabing	SE Zone of Drainage A	Improvement in surrounding land – constant baseflow	0.19	8.7	7450	0.37
19. North Stirlings	SE Zone of Drainage B	Reclaimed 27ha	0.2 - 2	N/A	8300	N/A
20. Gnowangerup	Pallinup Zone B	Stopped spread of salinity, reduced watertable by 0.6m	0.78	8.1	8200	0.66
22. Esperance	Esperance Sandplain ?	Minor impact	0.2	N/A	N/A	N/A

6.4 Landholder's perception of drainage

Toric, B. and Crossley, E., Department of Agriculture

6.4.1 Introduction

In 2000, landholders that visited the AGWEST displays at the Dowerin and Newdegate field days were surveyed in order to assess their views and understanding of the issues associated with deep drains. Seventy-eight farmers expressed their views on deep drains and identified the key issues associated with drainage by completing a short questionnaire.

6.4.2 Results

When asked, "*What do you think of Deep Drains*?," just over half (52%) of respondents viewed deep drains as beneficial, with a third (31%) stating that they can be beneficial in some situations. Five per cent of those surveyed viewed drains negatively.

Social factors (including economic factors) were seen by those surveyed as the most important factor when planning a deep drain, followed by site/landscape conditions, and adverse downstream impacts. Choosing the most effective management option, integration with the farming system and animal and human safety were also highlighted.

Thirty-three of the 78 respondents (42%) had installed deep drains on their property and 18 (54%) of these were linked to neighbouring properties. Thirty (40%) indicated that deep drain had reclaimed previously unproductive land, whilst another 13 (17%) claimed that the drains had lowered the depth to watertable and/or reduced waterlogging. Other landholders reported improved tree survival and creekline conditions. Two respondents indicated that it was too early to assess the effectiveness of drains on their property. Most respondents (94%) indicated that they would monitor deep drains if tools were available to do so.

Most of those surveyed (70%) indicated that deep drains had been economically viable on their properties, two respondents (<3%) indicated that they were not and six respondents (<8%) were unsure. The most significant negative impacts of deep drains judged by the respondents were: reduced access to paddocks (28%); cost of construction (13%); maintenance requirements (11%); downstream impacts (9%); loss of livestock (9%); conflict with neighbours (6%); lack of government assistance (4%); and limited effectiveness (4%). Other concerns (9%) included reduced aesthetics, complex legislation and the harbouring of weeds in drain banks. Three respondents (4%) reported no adverse impacts on their property.

6.4.3 Conclusions

The general perception of deep drains of those surveyed was positive, with nearly all of respondents (91%) indicating that drains are beneficial in at least some, if not all situations. However, whether this is representative of the wider community is questionable, as participation in the survey was likely to be more attractive to those with strong views on drainage.

Over half of the landholders with drains on their properties were linked to neighbouring properties, highlighting the communal nature of many deep drainage systems. However, with social factors being highlighted as the most important factor when planning a deep drain, it is likely that many landholders have experienced tension within their community. Community polarisation was documented by Brooksbank (2002) where disagreements between those who wish to drain and those who do not, had caused the break-down of many catchment and community groups. She found that those who wish to drain were most likely landholders in the lower catchment, while those in the upper were more likely to be in favour of tree planting and surface water management.

Colliver (1998) noted after a phone survey of Avon Catchment landholders that there were two dominant opinions of drainage. Firstly, those who thought that there was enough information about deep drainage and that our efforts should be focused on constructing them. Secondly, those who believed that we should be cautious about drainage until we know more about it. Both groups had common ground, believing that the whole community has a lot to learn about drainage and we have to learn quickly.

Many of the adverse impacts of deep drains experienced by landholders, such as restricted paddock access, would have been known before construction. However, it appears that the potential rewards outweighed the risks, and that despite realised adverse impacts, nearly all (97%) of landholders claimed that their deep drains led to rapid improvements to land and many (70%) claimed that they were economic.

Few landholders highlighted the need to select site specific salinity management options, suggesting that there is a lack of comparative hydrological and economic information about use of different options in specific situations. Furthermore, some landholders reported lack of government assistance and guidance. The majority (94%) of respondents indicated that they would monitor deep drains if tools were available to do so, which may provide an opportunity for landholders to work with industry groups and government departments in joint research efforts.

7 Economic evaluations

Bathgate, A and Coles, N., Department of Agriculture

Deep drains have been used to protect various assets in WA. The most common uses are to protect farmland, infrastructure, water quality and biodiversity. Most investigations have examined the hydrological benefits of deep drains and concentrated on measuring the impact of deep drainage on the watertable. As such, the changes in crop productivity resulting from drainage had not been formally assessed, and the data required to evaluate the economic benefits of drains is limited, and tends to be site specific and anecdotal. Furthermore, most of the studies that have included crop productivity data have lacked pre-drainage data, have been heavily influenced by seasonal conditions, and have been relatively short-term.

Coles *et al.* (1999) gathered anecdotal crop yield information from a range of sites where landholders had constructed deep drains, and this information is presented here. The nature of the data presents verification difficulties and the evidence for crop improvements does not conform to standard methods normally applied. The improvements claimed through the use of deep drains were, in some cases, is not consistent with draw-down of the watertable.

Determining the profitability of drains is complicated by the relatively large number of factors that can influence the impact of drainage on crop production and net returns. The inherent variability of these factors between sites is also of concern in determining any statistically significant differences between sites. The variability and the uncertainty within the data gathered suggests that it may be more appropriate to determine the minimum values of the important parameters that will ensure that the construction and maintenance of a drain is profitable. In other words, conduct break-even analyses. The most important of these factors are described below, followed by the results of nine scenarios using a simple computer model.

7.1 Factors affecting the profitability of deep drains

It is possible to determine the economic impact of deep drains, by comparing discounted cashflows that occur before and after construction. There are a large number of factors that affect the cashflow and hence profitability of drains, however the most influential are:

- **Cost of construction** – varies between regions but appears to be independent of the soil characteristics. The major factor affecting construction costs is the type and design of the drain (i.e. materials and machinery required, depth and width). Choosing the optimal drainage type and design for a specific site is important, so that the most economical solution is implemented. For example, deep drains can be used to reduce the incidence and duration of waterlogging, banks are a much cheaper option that achieves the same result.

- **Maintenance costs** – tend to be a fixed proportion of construction costs and appear also to be independent of soil characteristics. The type of earthworks employed affect the apportioned costs with deep surface drains costing around 40-60% of construction costs. However the frequency of maintenance is dependent of soil stability and may vary from 3-12 years depending on site. The tables include are based on 60% of construction costs of deep drains using annualised cost. Maintenance of pipe drains usually involves flushing the system with high-pressure hoses, and can involve chemical and physical means to remove plant root interfering with the system. Simple maintenance activities can not be performed on French and mole drains, as they generally require complete reconstruction once they become ineffective.

- **Frequency of maintenance** – depends largely on soil type. Deep surface drains constructed in heavier soils are less erodable and therefore are less prone to silting than those constructed in lighter sandier soils. The frequency of maintenance can vary from 3 to 5 years for lighter soil types, to 7 to 10 years on heavier soils. Heavier soils with a higher silt content tend to clog pipe drain systems faster than lighter sandier soils.

- **Years to reclamation** – depends on the type of salinity or waterlogging problem, however is usually related to the annual rainfall pattern, soil profile and leachability, initial soil salinity levels and designated goal. The time to reclamation is important to consider because it affects the increase in average returns per hectare over time due to drainage. This parameter is important, as a delay of only a few years may reduce the cashflow of the drains sufficiently to make construction unprofitable.

- **Area of reclamation** – area, along with years to reclamation, are two of the most uncertain parameters, as the hydrological process occurring at many drainage sites are complex and not simply predicted. Furthermore, if one of the benefits of deep drains is reduced waterlogging, then this varies seasonally. The total area affected is highly uncertain unless estimates have been made over the long term. Accurate estimates of the area affected are expensive and unlikely to be made for many sites. However, the area reclaimed is a critical parameter for economic analysis as small errors in the estimates of area reclaimed can have a large influence on the estimated financial outcome attributed to drain construction.

- **Increased productivity** – the increase in average return per hectare depends largely on the increase in yield and the optimal rotation of the reclaimed area. On face value, increased average returns is easy to estimate, but in reality it can be more difficult to determine. Increasing the arable area of a farm will usually result in higher average net returns but invariably there are costs associated with a higher productive area. Resources of farms are limited and an increase in area will mean that the limited resources are spread more thinly across the farm. This will often mean that the measured yield increase in the reclaimed paddock is more than the actual increase in yield. Similarly, in many cases, saline areas have not been cropped for many years and thus there is limited pre-drainage data in which to compare.

- **Onsite impacts** – loss of arable land for deep surface drainage structures can be significant in areas where the drainage system is large. This is generally not as much of an issue in subsurface systems, as only collector drains remove land from productivity. Loss of livestock in unfenced deep drains can also present a cost to landholders. Furthermore, some landholders have experienced increased weed problems in paddocks with deep drains harbouring weed seeds.

- **Opportunity cost** – the interest rate at which money could otherwise be invested is the opportunity cost of constructing deep drains, and could have a large impact on the viability of expenditure on earthworks. Interest rates, however do not tend to significantly change over the medium term and therefore cannot be changed in the scenario analysis.

7.2 Economic analysis case study results

A simple spreadsheet model was generated in order to determine the impact of the above parameters on the profitability of deep surface drains and thus the economic viability in WA. Deep surface drains have been analysed as they have become the most popular form in WA. Nine scenarios were conducted, with the aim of determining the optimum rotation and yield to recover costs. These scenarios included different costs of construction, frequency of maintenance, maintenance costs and increased gross margin per hectare (Table 7.2.1). Annualised costs and returns and the increase in productive area required to break even were calculated (Tables 7.2.2, 7.2.3 and 7.2.4).

Table 7.2.1. Parameters for the nine scenarios run in economic drainage model

Scenario	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**B1**	**B2**	**B3**	**B4**
Years to reclamation	3	3	3	3	3	3	3	3	3	3
Increase in GM/ha	140	140	140	70	140	70	140	140	140	70
Construction costs	6000	5000	4000	5000	5000	5000	3500	2500	1500	1500
Frequency of maintenance	8	8	8	8	4	4	7	7	7	7
Maintenance costs	0.6	0.67	0.6	0.6	0.6	0.6	0.3	0.3	0.3	0.3
Annualised increase in GM	$110	$110	*$110*	$55	$110	$55	$110	$110	$110	$55
Annualised costs of drains	$713	$594	$475	$594	$968	$968	$347	$248	$149	$149
Area required to break even	6	5	4	11	9	18	3	2	1	3

Table 7.2.2. Annualised increase in profit, according to years of reclamation and increase in gross margin

Increase in GM ($)	**Increase in profit – annualised ($)**									
	Years to reclamation									
	1	2	3	4	5	6	7	8	9	10
20	19	18	16	15	14	13	12	12	11	10
40	38	35	33	31	29	27	25	23	22	20
60	56	53	49	46	43	40	37	35	32	30
80	75	70	66	62	57	54	50	46	43	40
100	94	88	82	77	72	67	62	58	54	50
120	113	105	99	92	86	80	75	70	65	60
140	131	123	115	108	101	94	87	81	75	70
160	150	141	132	123	115	107	100	93	86	80
180	169	158	148	138	129	121	112	104	97	90
200	188	176	165	154	144	134	125	116	108	100

*Costs of drains have NOT been deducted

Table 7.2.3. Annualised cost of drains, according to frequency of maintenance and cost per kilometre

Cost/km ($)	Annualised cost of drains ($)									
	Frequency of maintenance (years)									
	3	4	5	6	7	8	9	10	11	12
1000	238	194	160	140	133	119	114	102	99	97
2000	475	387	320	281	266	238	229	204	199	195
3000	713	581	480	421	399	356	343	306	298	292
4000	951	774	639	562	532	475	458	408	398	389
5000	1189	968	799	702	665	594	572	509	497	486
6000	1426	1161	959	843	798	713	686	611	597	584
7000	1664	1355	1119	983	931	831	801	713	696	681
8000	1902	1548	1279	1124	1065	950	915	815	796	778

Table 7.2.4. Area reclaimed to break even, according to frequency of maintenance and cost per kilometre

Cost/km ($)	Area reclaimed - break even									
	Frequency of maintanence									
	3	4	5	6	7	8	9	10	11	12
1000	2	2	1	1	1	1	1	1	1	1
2000	4	3	3	2	2	2	2	2	2	2
3000	6	5	4	4	3	3	3	3	3	3
4000	8	7	6	5	5	4	4	4	3	3
5000	10	8	7	6	6	5	5	4	4	4
6000	12	10	8	7	7	6	6	5	5	5
7000	14	12	10	9	8	7	7	6	6	6
8000	17	13	11	10	9	8	8	7	7	7

Years to reclamation	3
Increase in GM/ha	140
Maintenance costs	0.6

The analyses showed that deep surface drains (or subsurface), which cost around $5000/km to construct, need to reclaim at least 6 to 8ha of land per km of drain to recover costs. Such reclamation requires a watertable drawdown (to the critical depth) of between 25 and 90m from the drain. The extent of the influence of the drain on the watertable varies markedly according to soil type. In heavy soils drawdown on the watertable may only extend to a distance of 10m either side of the drain (George and Nulsen 1985, Speed and Simons 1992). This is equivalent to a total area of 2 ha/km of drain. In sandier profiles the influence of the drain may extend (in exceptional circumstances) up 80m either side of the drain (or 16 ha/km) (Nulsen 1982). Through a survey of 25 drainage sites, Coles *et al.* (1999) found that watertables are often lowered less than 20m from the drain (4 ha/km), and rarely exceed 40m (8 ha/km). However in more recent studies, drawdown greater than 200m either side of the drain has been recorded and may prove economic.

The area required to be reclaimed increases with lighter soil types, however, the frequency of maintenance increases in these soils, from once every 7 to 10 years to once every 3 to 5 years. Scenario 4 demonstrates the impact of more frequent maintenance. The area of reclamation needs to be 8 ha/km of drain where maintenance is required every 4 years. Scenario 2 shows the impact of reducing the frequency of maintenance to once every 14 years, reducing the minimum area to be reclaimed to around 4ha. However, less frequent maintenance is likely to reduce the effectiveness of the drain, such that some of the reclaimed area may revert to the previously waterlogged state.

The increase in returns per hectare has a marked affect on the profitability of using drains to ameliorate waterlogging or salinity. Scenarios 1 to 4 assume that the higher levels of production lead to an increase in the gross margin of $140/ha. This is only likely to be achieved where production prior to the construction of the drains is negligible. An increase in the rotational gross margin of $140/ha can be achieved with pulse yields of around 0.8 t/ha ($250/t) and wheat yields of around 1.7 t/ha for 2 year following the pulse crop. The gross margin could be higher if canola was to be introduced into the rotation. However, it is likely that the increase in net returns would be lower for much of the Wheatbelt, and most farmers have had most success at growing the more salt-tolerant barley in their drained paddocks.

Scenarios 5, 7 and 9, highlight the impact of lower increases in net returns. An increase of only $100/ha requires a significant larger area of reclamation for cost-recovery. Lower returns could be expected for a number of years after reclamation, particularly for soils that are highly saline, structurally degraded and nutrient deficient.

Waterlogging, rather than watertable rise has been recorded in some sites where deep drains have been installed. Banks are a far more economical method of managing this problem. The economic potential of effective grade banks is illustrated in Scenarios 8 and 9. The results show that less than one hectare of reclaimed land, per kilometre of bank, in order to break-even.

The physical characteristic of the site require investigation and should include an examination of the soil profile, slope, hydraulic gradient and depth to groundwater; in combination with an investigation of the catchment processes that cause the problem. In this way, a simple economic analysis can be conducted, and the most suitable and economically viable option can be selected.

8 Discussion and recommendations

Deep drainage has been used for a number of purposes and in a range of landscapes across the south west of Western Australia with varying success. The use of such drains has become an issue that has had a demonstrated ability to polarise all sectors of the Western Australian community, at all levels. A large number of research activities have coincided with the construction and use of deep drains to manage salinity in WA. Yet, this report has highlighted only a few cases where it can be demonstrated that the scientist or practitioner has conducted an investigation of drainage theory, and used this to guide or question what is being done or said.

Scientists have traditionally undertaken deep drainage investigations in WA with a focus on hydrology. In most other parts of the world, hydrology is combined with other disciplines such soil science and engineering. There is a need in WA to bring these other disciplines into the drainage arena in order to gain a better understanding of the non-groundwater variables that influence drain performance.

The use of drains within the WA environment must be reduced to an understandable quantitative science that will allow the community to effectively assess its pros and cons in an unbiased manner. The following sections serve to highlight specific gaps in information relating to the use of groundwater drainage to manage high watertables and salinity, mainly within the dryland agricultural areas.

8.1 Drainage mechanisms

Drainage for the purpose of groundwater and salinity control has been practiced in just about every country around the world that has experienced these problems. Their application varies, however the governing principles remain the same: to lower watertables, reduce waterlogging and allow salt to leach from the root zone. On a worldwide standard, the land being treated with deep drains in WA is often at the extreme end of being degraded by salinity. There is a need to better understand these soils and the ‘current’ physical and hydrological process to which they are subject. This will help to determine how well, and in some cases, if at all, certain soils will respond to drainage.

Recommendations

- Calculate water balances at drainage sites to determine appropriate drainage co-efficients in WA conditions.
- Consider the impact of episodic events and how these should influence drainage design;
- Evaluate whether drains can lower the watertable sufficiently to change the surface salt balance in favour of leaching.
- Determine the depth to which the watertable must be lowered below the soil surface under various soil types and groundwater salinities to promote leaching;

- Build a greater understanding of the significance and impact of preferential pathway flow on drainage performance. In what soil types or areas are preferential pathways most prevalent, what are their physical properties and how interconnected are they?
- Test known predictive drainage equations (steady and non-steady state) that could be used to support the design and function of a drain. Construct a series of deep drains at sites with pre-existing watertable data and compare draw-down curves at the site, with that predicted using groundwater theory. Determine the parameters and assumptions most crucial to the accuracy of such applications;
- Investigate channel flow (transmission) losses that occur from existing drainage schemes and determine how these could be managed to reduce both on and off site impacts of drainage;
- Analyse the chemistry of drainage water in existing drains, to determine the geochemical reactions and processes occurring. Increase the level of understanding of the off-site impacts of drainage discharge (i.e. low pH water) and investigate on-site treatment methods such as in lime application in drains; and
- Develop an understanding of the physical and chemical changes that occur to soils that are drained and leached of salt. Consider soil treatments (such as gypsum, ripping, organic matter) that may be required and the impact of these on the drainability of soils.

8.2 Measuring success

There have been a large number of deep drainage research activities since the 1970s, each with its own defined version of “success”. Most drainage theory around the world determines the success of a drainage system by the ability to lower watertables at increasing distances away from the channel. However, in the rural community, the success of a drainage system is judged by the ability of the system to improve workability of the land and increase crop yields.

At present, there is no formal and agreed upon definition of a “successful” drainage system. Coles *et al.* (1999) suggested that the impact of deep drains could not often be determined by groundwater levels alone. The success of a drainage scheme also needs to be couched in terms of off-site impacts. That is, has the deep drain really been successful if reclaiming one piece of land has degraded another?

Methods of monitoring the impact of deep drains has been focused on changes that have occurred to the perceived cause of the problem. Hence in WA, these have focused largely on changes to the groundwater level and water quality. Few drainage research publications demonstrate that they have aimed to assess all of the potential impacts of a drainage scheme at the same time, on the same site. This has made it difficult to assess the cross or flow on impacts and the reclamation process.

More complex monitoring programs have appeared in the last few years, which include the monitoring of multiple parameters, such as depth to watertable, soil salinity levels, crop yields, and salt flux (i.e. Dumbleyung, Narembeen). However, analysis has been difficult due to lack of adequate control sites and pre-drainage data.

Snapshot case studies as outlined in this report have been used on a number of occasions to look at the use and performance of deep drains in WA (eg Nulsen 1982, Green, 1990, Coles *et al.* 1999; Chandler 2002). While they can be useful in gathering a large amount of “once-off” data, they are limited in their ability to determine time-dependent data such as performance, downstream impacts and stability. Snapshot case-studies are best used when collecting statistical parameters such as pH, EC, flow and depth of sediment at a particular point in time

The monitoring techniques for drain performance must be standardised so as to allow for effective comparison between sites and different layouts.

Recommendations

- Develop a standardised list of criteria for determining the success of drainage systems in WA. These criteria may include reductions in groundwater levels, salt leaching, land recovered/protected or increased crop productivity. Use criteria to assess existing and future drainage networks;
- Investigate the use of changes to groundwater levels as an early indicator of the likely success of drainage in reclaiming saline land. Evaluate the critical depth that the water needs to be dropped for different soil types and uses in WA;
- Collate all crop productivity data that is available and analyse this to determine whether it is likely to be a realistic measure of drainage performance, given seasonal variability and lack of pre-drainage data. If so it is likely to be an effective measure, determine the number of years of data that is required to make an estimate of improved production; and
- Develop methodology for standard methods that should be applied to the monitoring deep drains and determine the minimum level of pre-drainage monitoring data and controls that are required.

8.3 Site Evaluation

The community and practitioners need tools to assess the likely effectiveness and impacts of drainage before construction. In order to do so, it is essential that the characteristics of the Wheatbelt landscape be able to be described in a quantitative manner. The geology, hydrology and soils and the integration of drainage with farm management systems need to be reviewed and the effectiveness of drainage evaluated in this context.

Effective site evaluation tools have been developed and successfully applied with drainage design tools and equations, on a worldwide scale. These have been discounted as not being appropriate to WA conditions, often without some form of testing. There is a need to agree on a suite of tools that are required, select those that are likely to be appropriate, and test these against design, in a non biased manner. Thee tools could then be packaged so that they are rigorous enough to be used by field practitioners who are able to provide feedback.

Recommendations

- Standardise a method for determining hydraulic conductivity of the drainable soil profile in the filed, similar to the auger hole method. Outline how this method could be applied to assist in determining the most appropriate drain depth and influence of various groundwater flow mechanisms.
- Standardise a method for determining the approximate drainable porosity of soil within a potential drainage site. This is required to assist the prediction of drain discharge volumes and potential off-site impacts.
- Analyse the pH and EC of existing deep drains in the Wheatbelt to determine whether there is a spatial relationship that can be used as an indicator of drainage performance or potential downstream impacts.
- Collate and compare existing surface soil, sub-surface soil and vegetation association data to determine whether there is a relationship between surface and sub-surface features. Examine whether surface features can be used as an indicator of soil permeability, stability and thus drainage performance.

- Develop a list of geophysical tools and their capabilities and potential use in determining subsurface soil parameters. Determine whether these tools can be used to predict the most effective placement of deep drains in the Wheatbelt landscape.
- Develop and promote a simple field tool for determining the level of sodicity of soil and the type and cost of treatments that may be required.
- Through sensitivity analyses, isolate the critical parameters required by assessing officers to estimate the performance and hence the likely off-site impacts of a drain.

8.4 Design and implementation

There are a large number of design tools, recommendations and standards currently available to support the decision making process for the design and installation of deep drains (Keen 1998, Cox 2001a, Bennett *et al.* 1999, Schwab *et al.* 1981). These cover most aspects of drainage design, construction and maintenance, with the exclusion of recent drainage innovations, such as tyre drains, passive relief wells, and treatment of low pH water.

Despite the availability of design standards, these are generally not used or demanded by drainage contractors and landholders. As such, the design and implementation of deep drains has seldom varied across the different landscape and soil types. Many contractors have also chosen to develop their product through a process of trial and error, rather than an analytical approach. Even in cases involving the implementation of large schemes, many drainage contractors do not employ the use of basic farm planning and surveying techniques. Drainage schemes designed in such a manner have a greater probability of failure, leading to reduced efficiency, and detrimental off-site impacts.

This situation is likely to change if and when:

- landholders become more discerning, demanding more information about the quality and likely performance of drainage works constructed on their properties. This role is currently filled mainly by ‘down stream’ landowners whom feel they may be adversely affected by drainage works;
- the industry becomes more regulated either by itself or Government, requiring the preparation of accurate plans, specifications and impact assessments for proposed drainage works;
- the industry becomes more competitive and all contractors are forced to use design tools;
- drainage schemes become more complex and costly, requiring the need for more detailed planning; and/or
- the tools are seen as beneficial and applicable by drainage contractors and landholders and are packaged in a useable format.

Until there is greater incentive for their application, the development of design and evaluation tools may not occur. In order to achieve this we need to:

Recommendations

- Work with drainage contractors in the field to gain a wider understanding of the drainage implementation process, from a practical point of view.
- Evaluate the limitations of the adoption of drainage design, construction and maintenance in WA.
- Standardise the design process and tools applicable to WA conditions.
- Evaluate existing sites that contain passive relief wells used in conjunction with deep drains in order to estimate effectiveness and develop preliminary best-practice design and maintenance regimes.

- Monitor the quantity and quality of drainage water of existing tyre drains (especially acidic), and determine the benefits and limitations of using tyres as filling in WA. Determine whether tyres are a suitable construction material and if so, standardise best practice design and management for their use.
- Evaluate drains with various batter styles (such as stepped) in order to determine the benefits and limitations in different soils and landscapes. Determine where stepped batters are most effective and develop preliminary best-practice design and maintenance standards or guidelines.
- Evaluate drains that are constructed in sodic soils and determine the suitability of the drainage design for that soil type. Develop best practice guidelines for drains constructed in sodic soils.
- Produce simplistic computer programs that will enable drainage practitioners to assess the impact of changes to the variables that affect drain performance to guide them in the selection of the most appropriate drainage scheme.

8.5 Disposal

The disposal of drainage water and potential downstream impacts is not in the scope of this review, however it is an important design consideration. In short, there are gaps in drainage deign and placement that can be explored to reduce the potential downstream impacts. Similarly, there is little information available for landholders to decide on the most appropriate disposal method, and the requirements for placing it in a natural drainage line, linked drain, or arterial drainage system. As such, drainage water from many deep drains has been untreated, disposed of in downstream environments and caused degradation due to increased salt, nutrient and sediment loads, decreased pH and increased volumes of water.

Recommendations

- Evaluate best-practice design and maintenance of deep drains, to determine whether modifications can be made to reduce the risk of downstream impacts. The modified best practice will need to be field tested, and will require the construction and management of a deep drain in a number of different soil landscapes.
- Develop a tool for landholders to determine the most appropriate and cost-effective (including non-market factors) disposal option for their quality and quantity of drainage water generated on their property.
- Develop in-drain methods to treat low pH drainage water before release.

8.6 Economics

There is little information on deep drainage systems, in an economic context. In a purely rational economic approach, it often costs more to install and maintain a deep drainage system than is recovered from productivity increases. However, this approach does not take into account intangible aspects such as preventing further loss of land to shallow watertables, the satisfaction of being proactive in the fight against salinity, or the degradation of downstream environments (WAWRC and SLCCWA 1992). The large costs associated with constructing deep drains and marginal returns often leads to cost cutting through reduced planning and design.

Recommendations

- Develop a list of factors that determine cost effectiveness. This must include intangible (non-market) factors, such as social and environmental costs, as well as opportunity cost. Determine a standardised unit for comparison, such as $/km or $/ha.

- Compile an up to date list of costs for constructing and maintaining deep drains of different design in variable landscapes.
- Use the list of factors to develop a simple economic model for landholders to determine the cost effectiveness of different drainage types in certain environments.

8.7 Social factors

Social factors are not in the terms of reference for the Engineering Evaluation Initiative Committee, however they have been identified as a significant issue for the use of deep drains. A definitive planning and regulation framework is missing from the drainage environment in WA, and current standards of planning, design, construction, maintenance and disposal have not been implemented. Community conflict has arisen and the rights of individuals to drain is not addressed. Inadequacies in legislation have frustrated landholders wishing to “do the right thing” and it is commonly felt that lack of coordination at the policy level within the Government has allowed the opposition to drainage to continue much longer than necessary.

The Taskforce (2000) looked at making drainage work and assessed the social and regulatory issues associated with deep drains. They found that the community and government to be polarised, confused and have limited cohesion in its approach to drainage. The issues raised in this report remain relevant, and the Governments approach to drainage, by the community, is perceived to be negative and regulatory. However, there has been a shift to towards a more conciliatory approach to drainage by the Government, through the:

- adoption of drainage standards;
- development of training courses; and
- provision of advice on the preparation, design and assessment of drainage proposals.

Recommendation

- Determine the most effective method of extending and encouraging the adoption of best management practice techniques generated through the Engineering Evaluation Initiative. This may involve educational programs, regulation and/or the rights of individual landholders to be reviewed.

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Appendix I – Drainage Research in WA

Blackwood

GRDC funded project (Peter Coyne from Agritech) to determine the feasibility of constructing a deep drainage system (similar to the Upper SE) from the Upper Blackwood Catchment. Possibly inclusion of a hydroelectric station at the outlet to aid in cost recovery.

Beacon River Catchment

Site investigation conducted by the Department of Agriculture and through modeling, GHD consultants conducted a feasibility study of deep drainage in the catchment. They analyzed five different options, which ranged in price but ultimately centred on a deep drain down the centre of the catchment. The catchment is considering the options now.

Dumbleyung

NHT funded project, joint Water and Rivers Commission and Department of Agriculture. The Department of Agriculture has been involved in monitoring two deep drains in the catchment (Fence Road and Temby Road). ISCO flow meters have been installed to measure flow and water quality and crop productivity trials have been conducted. Good quality flow data has been achieved and indicates that on average 0.185 L/s of water is flowing along the drains (including surface water). Crop productivity trials have been less successful as dry seasons have dominated yields.

A deep drainage demonstration site (Beynon Road) has been designed by Nick Cox (Department of Agriculture) and was constructed at the end of last year. A monitoring scheme has been implemented to look at the impact of the drainage system over time, and compare the use of 2 and 3m deep drains at the site.

The Dumbleyung Water Management Strategy is also looking at the feasibility of an arterial drainage system. The project will address the feasibility a multiple use corridor, incorporating an arterial drainage system. This will link remnant vegetation, provide habitat for native fauna (WRC 2001).

Yeelana

Analysis of soil types with soil pits conducted by Bill Verboom and Ned Crossley. Estimation of K_{sat} was to happen next, however due to funding limitations, there will be no further involvement by the Department.

Gnowangerup

Groundwater levels have been monitored along this deep drain by the landholder (Michael Lance) since construction (contact – Ruhi Ferdowsian). Photographic records have also been taken. Ferdowsian has conducted a HARTT analysis on the groundwater levels. The levels are still being monitored by the landholder (Michael Lance). This site was included in Chandler (2002).

Potter's Creek, Kendenup
Groundwater levels are being monitored at Potter's Creek. A small amount of NHT funding ($12 000) has been secured to continue monitoring the drain (contact – Ron Master). Three transects of bores have been installed and have been monitored for some time. Data loggers will be installed in the bores of one transect. Flow along the drain will be measured at two sites, using a flume, salt probe and pressure probe. An ISCO sampler has been acquired to take samples for nutrient analysis. This site was included in Chandler (2002).

Narembeen
A GRDC funded joint CSIRO and Department of Agriculture and initiative. The two years of data collection from the site, indicates that the deep drain has been effective in dewatering adjacent soils. The area influenced by the deep drain was initially thought to range up to 400m either side of the drain. As monitoring commenced in a period of extreme variability (a 1 in 50 or above ARI storm in the preceding summer and two drought years), the area of influence is likely to have been over-estimated. This is an ongoing project and the over the next three years of data collection should allow more accurate data analysis.

Honors student Emma Halligan has been working with David Gray (CSIRO) to look at the geochemistry of the site. An analysis of drainage water chemistry and suggested chemical reactions have been produced.

Dalliup Catchment
Dalliup Catchment currently is setting up a deep drainage experiment. Headed by Kaline Parker (WRC Albany), the project hopes to construct analyse six case studies across the catchment (including some deep drainage sites) in a snapshot case-study approach. John Simons (Department of Agriculture) is providing some technical assistance.

Jimberding
The State Salinity Council has funded a surface water management project for the Yarra Yarra Council (Max Hudson). GHD have been involved in constructing the management plan. There is discussions between those who wish to construct earthworks for surface water management and those who want to construct deep drains. The project is currently on hold until the issue is resolved.

Focus catchments
The "Focus Catchments" project was an initiative started by the State Salinity Council to help protect and restore farmland at risk of salinity. Selected sub-catchment groups had access to catchment support teams providing the technical and economic information needed for site-specific decisions on best management practices.

Recovery catchments
Recovery catchments have been identifed where high priority public assets are at risk from salinity and will require on-going investment for their recovery and protection. Recovery catchments are divided into Water Resource Recovery Catchments (WRRC) and Natural Diversity Recovery Catchments (NDRC).

Water resource recovery catchments aim to manage water resources in such a way as to keep them within salinity levels suitable for the region's drinking water supply needs. Water resource recovery catchments work in partnership with the Department of Environment, Water and Catchment Protection (DEWCP). Warren and Collie River Basins have received most resources to date.

Natural diversity recovery catchments aim to protect and conserve key areas of biodiversity through changed farming practices, revegetation and engineering options. Natural diversity recovery catchments work in partnership with the Department of Conservation and Land Management (CALM). In the 1980s, pumping and drainage activities were conducted in the Lake Warden System (John Simons). Pumping and surface water diversion have been used to protect Lake Toolibin (Richard George, Neil Coles) and Lake Bryde (Darren Farmer). Some engineering intervention is expected in the Lake Muir-Unicup catchment, however official involvement by the Department of Agriculture will be limited (Peter Taylor).

Rural Towns Program

The Rural Towns Program (RTP) was developed in 1997 to target town-site salinity. As well as promotion of salinity information and technical advice, this program helps fund the implementation of onsite works for water and salinity management (Pridham 2001). So far, surface water management, revegetation and groundwater pumping have been recommended over deep drainage for management of town-site salinity. However deep drainage schemes may become more common with Nyabing having installed deep drains in the townsite and Bullaring (Corrigin Shire) where deep drains are currently being designed by a private consultants (Bruce Mead *pers comm*). The installation of deep drains with RTP funding is subject to positive response to test drains (Mark Pridham *pers comm* 2002). Pipe drains have also been installed in some towns including Moora, Tambellup and Wongan Hills.