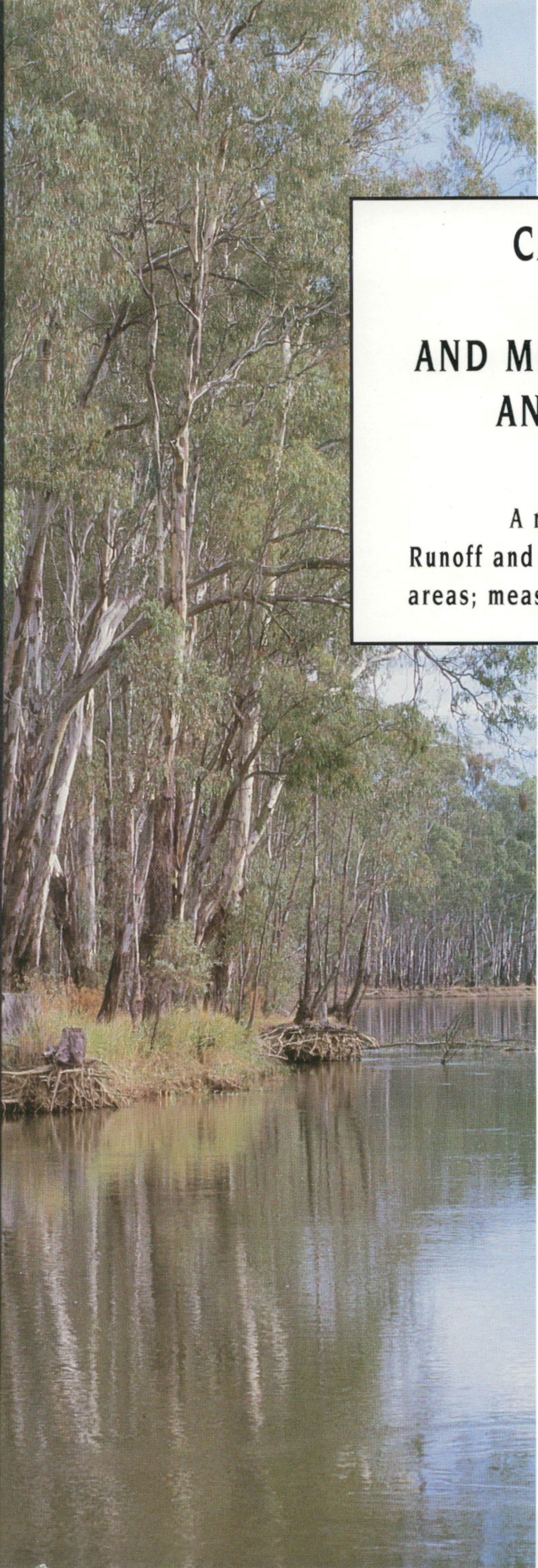

CAUSES, EFFECTS, REMEDIATION AND MEASUREMENT OF LAND AND RIVER SALINITY IN AUSTRALIA

A report as part of Project A1: Runoff and solute processes in high water table areas; measurement, modelling and management

M. Walker

Report 95/6
June 1995

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

CAUSES, EFFECTS, REMEDIATION AND MEASUREMENT OF LAND AND RIVER SALINITY IN AUSTRALIA

A report as part of Project A1:
Runoff and solute processes in high water table areas;
measurement, modelling and management

M. Walker

Report 95/6

June 1995

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Walker, Mark, 1970 -
Causes, effects, remediation and measurement of land and river salinity in Australia.

Bibliography.
ISBN 0 7326 0862 7.

1. Soil salinization - Australia. 2. Water salinization - Australia. 3. Soil salinization - Control - Australia. 4. Water salinization - Control - Australia. I. Cooperative Research Centre for Catchment Hydrology. II. Title. (Series: Report (Cooperative Research Centre for Catchment Hydrology); 95/6).

631.416

Keywords

Salinity
Remediation
Salinity Transport
Salts
Water Movements
Groundwater
Recharge
Discharge
Land Clearing
Irrigation
Soil (Characteristics of)
Determination
Remote Sensing

ISSN 1039-7361

PREFACE

The material in this report is a contribution to one of the core research projects in the Cooperative Research Centre for Catchment Hydrology (CRCCH). The project, led by Dr Luke Connell, is entitled "Runoff and solute processes in high water table areas: measurement, modelling and management" (CRCCH Project A1). It is concerned with water and salt transport processes and how these are affected by land management. The CRCCH has undertaken this work because of the grave environmental problems posed by land and water salinisation in Australia.

This report summarises the background understanding and state-of-the-art research on land and water salinisation in Australia. It was prepared by Mr Mark Walker (and his supervisor Dr Luke Connell), a recipient of a CRCCH Vacation Scholarship over the summer of 1993/94. It is hoped that the report will be of use to researchers already working in the field of salinity, as well as to people seeking an introduction to the factors responsible for land and water salinisation.

Dr Rob Vertessy
Deputy Director
Cooperative Research Centre for Catchment Hydrology

ABSTRACT

The salinisation of soil and water is a severe problem in many arid, semi-arid and temperate parts of Australia. Substantial areas of low lying prime agricultural land are affected by saline groundwater discharge and shallow watertables. This is especially the case in the irrigation districts of the Murray-Darling basin, and Western Australia. Saline streams and rivers are also a problem in these areas. This paper reviews the processes leading to the salinisation of land and waterways, effects of salinity, remediation and management techniques.

Soil salinity is caused by the domination of salt accumulation processes over leaching processes within the near surface layers of the regolith. Salt in soil comes from a variety of sources: it is released from soil and bedrock by chemical weathering; from previously marine sedimentary basins; it is deposited on the soil surface with rainfall and as dry fallout; and may be added with low quality irrigation water. Salt accumulates through evapotranspiration and the discharge of local or regional saline groundwater. In many farming areas, human activity has changed the salt balance, creating new salt movement pathways, enhancing existing salt movement and facilitating salt discharge. In particular, clearing of forested land for pasture or shallow rooting crops and the application of irrigation water have dramatically altered the water balance of both local and regional groundwater systems. The result has been enhanced recharge and subsequent watertable rise or discharge in low lying areas, at the break of slope or where changes in the permeability of soil, bedrock or sediments cause a build up of groundwater.

Excess salt affects plants and animals by increasing water demand and leading to poor growth, and death under severe conditions. Soil salinity often causes the replacement of adsorbed calcium and magnesium with sodium which increases dispersibility and the shrink swell capacity of the soil.

Salinity remediation techniques to reduce saline seepage and salt transport to rivers have focussed on reforestation, afforestation of recharge and discharge areas, drainage, interception, and irrigation management. *Total Catchment Management* may be the most fruitful method of approaching salinity problems where there are conflicting land use interests and landowners with different salinity problems.

Salinity research is focussing on saline area detection and the detection of groundwater movements. Novel integrated approaches using GIS and remote sensing may prove to be useful in salinity detection and management.

ACKNOWLEDGMENTS

I would like to thank my supervisor, Luke Connell, for inspiring this project, for his patience and encouragement, and for many fruitful discussions. Keith Collett of the Rural Water Corporation, and Hector Malano, of Dept. Civil and Environmental Engineering at University of Melbourne, offered many helpful criticisms in their reviews of the manuscript. Matt Gilfedder, Paul Fiekema and Sharon Davis offered encouragement, kept me interested in field work when all I was doing was writing, and lent me computers when the network was down. Thank you to Lance Mudgeway for the photograph for figure A1.

ABSTRACT

The salinisation of soil and water is a severe problem in many arid, semi-arid and temperate parts of Australia. Substantial areas of low lying prime agricultural land are affected by saline groundwater discharge and shallow watertables. This is especially the case in the irrigation districts of the Murray-Darling basin, and Western Australia. Saline streams and rivers are also a problem in these areas. This paper reviews the processes leading to the salinisation of land and waterways, effects of salinity, remediation and management techniques.

Soil salinity is caused by the domination of salt accumulation processes over leaching processes within the near surface layers of the regolith. Salt in soil comes from a variety of sources: it is released from soil and bedrock by chemical weathering; from previously marine sedimentary basins; it is deposited on the soil surface with rainfall and as dry fallout; and may be added with low quality irrigation water. Salt accumulates through evapotranspiration and the discharge of local or regional saline groundwater. In many farming areas, human activity has changed the salt balance, creating new salt movement pathways, enhancing existing salt movement and facilitating salt discharge. In particular, clearing of forested land for pasture or shallow rooting crops and the application of irrigation water have dramatically altered the water balance of both local and regional groundwater systems. The result has been enhanced recharge and subsequent watertable rise or discharge in low lying areas, at the break of slope or where changes in the permeability of soil, bedrock or sediments cause a build up of groundwater.

Excess salt affects plants and animals by increasing water demand and leading to poor growth, and death under severe conditions. Soil salinity often causes the replacement of adsorbed calcium and magnesium with sodium which increases dispersibility and the shrink swell capacity of the soil.

Salinity remediation techniques to reduce saline seepage and salt transport to rivers have focussed on reforestation, afforestation of recharge and discharge areas, drainage, interception, and irrigation management. *Total Catchment Management* may be the most fruitful method of approaching salinity problems where there are conflicting land use interests and landowners with different salinity problems.

Salinity research is focussing on saline area detection and the detection of groundwater movements. Novel integrated approaches using GIS and remote sensing may prove to be useful in salinity detection and management.

ACKNOWLEDGMENTS

I would like to thank my supervisor, Luke Connell, for inspiring this project, for his patience and encouragement, and for many fruitful discussions. Keith Collett of the Rural Water Corporation, and Hector Malano, of Dept. Civil and Environmental Engineering at University of Melbourne, offered many helpful criticisms in their reviews of the manuscript. Matt Gilfedder, Paul Fiekema and Sharon Davis offered encouragement, kept me interested in field work when all I was doing was writing, and lent me computers when the network was down. Thank you to Lance Mudgeway for the photograph for figure A1.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Humans have had to cope with salinised land and waterways for several millennia. Soils and waterways may be saline as a result of natural processes which are either augmented or unaffected by human activity. Natural saline areas such as salt scalds, seeps and salt lakes exist, as do saline rivers. The reports of Sturt on his expedition to the Darling river, in western New South Wales and beyond, noted that the Darling was salty long before any agricultural impact on the area (Close, 1990). Farming practices, however, including extensive irrigation and clearing, have been shown to greatly increase this salinity problem (Peck, 1978; Szabolcs, 1979; ACIL, 1983; Dyson, 1983). Agricultural practice in the Murray-Darling basin of Australia has resulted in over 1100 km^2 of land being classified as salt affected, and at least another 500 km^2 may be potentially salt prone (Murray-Darling Basin Ministerial Council, 1987a). The Murray-Darling Basin Ministerial Council (1987b) has estimated that the natural median salinity levels of the Murray river at Morgan (South Australia) are 0.4 $dS\ m^{-1}$, whereas the median salinity is now 0.62 $dS\ m^{-1}$. Salinity is thus clearly an extensive problem which affects not only agricultural productivity, but water quality, fish populations and wetland ecosystems (Maunsell and Partners, 1979; Salinity Committee, 1984; Hart *et al.*, 1990; Anderson, 1991).

This review attempts to describe the processes involved in natural and human induced land and river salinity. The paper looks at the local, regional and micro scales to identify processes for the movement of salt and water in the landscape. The review also looks at the effects of salinity on plants, animals and soil properties, remediation techniques and methods of identifying saline areas. It does not look at salinity resulting from present day marine processes, nor does it examine the economic issues that arise from salinity.

In part one of the review, salinity is introduced as a serious land management problem. Part two sets out the definitions of salinity, the parameters used to describe it, and the types of salinity found in Australia. Part three investigates the physical and chemical processes involved in salt transport which leads to both land and stream salinity. Part four focuses on the causes of salinity. The paper outlines the effects of salinity on animals, plants and soil chemical and physical properties in part five. Part six looks at remediation techniques for saline land, and methods of decreasing saline water input to streams and rivers. Part seven deals with contemporary measurement and detection techniques for both soil salinity and groundwater movement. Appendix A is intended as a guide to recognising salt affected land in the field.

2.0 DEFINITIONS AND TERMINOLOGY

2.1 What is Salinity?

All soils contain a certain quantity of water soluble compounds but this does not necessarily mean that they are salt affected. Consequently we must introduce the concept of a threshold above which soils should be regarded as salt affected or saline. The numerical value of this threshold may depend on the physical and chemical properties of the soil, and the reason for identifying soils as saline. Salt affected soils may be defined as "*...formations under the dominating influence of different electrolytes in solid or liquid phases which alter the physical, chemical, and biological properties, and eventually the fertility of the soil.*" (Szabolcs, 1989). Duchaufour (1982), however, notes that saline soils are really a subset of these salt affected soils. The sodium ion in saline soils does not give rise to alkalinity, though sodium ions may be associated with carbonate or bicarbonate with a consequent increase in pH, hence alkali soils. This review is limited to a discussion of saline soils and waterways where there is an accumulation of neutral sodium salts, and the pH is less than 8.5, alkali soils are not discussed (Duchaufour, 1982).

Soil salinity may be described either directly as a quantity of soluble salts in a given mass of dry soil, or indirectly as the electrical conductivity of the soil water (Marshall and Holmes, 1988). The electrical conductivity measurement is most commonly used, and is the primary technique for measuring salinity of waterways. This will be discussed further in section 7.1.

2.2 Methods for Describing Saline Environments

The USDA Salinity Lab Staff (1954) define salinity on the basis of a threshold level of electrical conductivity of soil water: EC > 4 mmhos cm^{-1} or 4 dS m^{-1} at 25°C where the exchangeable sodium capacity is less 15%. This threshold value is also used in Australia (ACIL, 1983). The UNESCO definition (in Szabolcs, 1979) of saline soils was thus devised: "[Soils] *having an electrical conductivity of more than 4 mmhos cm^{-1} in at least some part of the soil within 25 cm of the surface; if the pH (H_2O 1:1) is 8.5 or less an electrical conductivity of 15 mmhos cm^{-1} should occur within 125 cm in the case of coarse texture, 90 cm in the case of medium texture and 75 cm in the case of fine texture,* [of] *the surface.*"

Due to the dominance of sodium chloride in saline soils in Australia, Northcote and Skene (1972) proposed the use of percentage sodium chloride to indicate salinity. They devised 3 categories:

Category 0: Non-saline soils
Category 1: Surface salinity, ie soils containing in their A horizons, or in the surface 20 cm if either the A and B horizons are undifferentiated or the A horizon is less than 10 cm thick, more than 0.1% NaCl (loams/coarser soils) and more than 0.2% NaCl (Clay loams/clays).
Category 2: Subsoil salinity, ie soils lacking surface salinity but containing more than 0.3% NaCl in the B horizon, or below 20 cm if the A and B horizons are undifferentiated.

This definition of salinity is widely used in Australia (ACIL, 1983).

Salinity thresholds for waterways in Australia are based on the EC (electrical conductivity) of the water, but may also be expressed in terms of mg l^{-1} total dissolved salts. EC units (dS m^{-1}) may be approximately converted to mg l^{-1} of dissolved salt by multiplying by a factor of 600. The National Water Resources Council classification for saline waters is given in table 1 and the Western Australian Riverine Salinity Classification is given in table 2. The differences between the two classifications exemplify the difficulty of defining salinity. Parameters and thresholds defining salinity are chosen for administrative convenience as often as they are chosen on the basis of noticeable changes in effects of the salt.

Table 1 National Water Resources Council Salinity Classification.

Class of Water	Salinity	
	Total Dissolved Salts mg l^{-1}	EC dS m^{-1}
Fresh	Less than 300	Less than 0.5
Marginal	300-600	0.5-1.0
Brackish	600-1800	1.0-3.0
Saline	Greater than 1800	Greater than 3.0

Table 2 Western Australian Riverine Salinity Classification.

Class of Water	Salinity	
	Total Dissolved Salts mg l^{-1}	EC dS m^{-1}
Fresh	Less than 500	Less than 0.83
Marginal	500-1500	0.83-2.5
Brackish	1500-5000	2.5-8.3
Saline	Greater than 5000	Greater than 8.3

2.3 Types of Salinity

Salinity may be either a natural occurrence or human induced. Naturally occurring salinity, or *primary salinity*, is associated with saline groundwater in close proximity to the soil surface. Primary salinity may occur where a subsurface watertable of saline groundwater is sufficiently close to the surface to affect vegetative growth, or where saline groundwater is discharging onto the soil surface. Primary salinity may also occur when marine water intrudes on the near coastal groundwater. The term *secondary salinity* was introduced by Northcote and Skene (1972) to describe the influence of humans on natural groundwater processes. Hence, secondary salinity is human induced.

Unfortunately the terminology used to describe areas of salinity is confusing in its profusion. Terms such as *seepage salting, salt scald, dryland salting, wet-pan salting, hillside seepage, seepage salting, lowland salinity* and *valley salting* have all been used to describe various conditions under which saline soils are found (Peck, 1978). For the purpose of this review, the expression, *saline seep,* will be used to describe saline areas where the watertable is in close proximity or discharging onto the soil surface either naturally or as a result of human induced watertable fluctuations. In the case of erosion bringing the soil surface down to the subsoil watertable, the term, *salt scald*, will be used.

2.4 Saline Soils in Australia

In Australia, saline soils are closely associated with alkali soils and frequently with the gypsiferous soils of lunettes (Szabolcs, 1989). While the saline soils of the arid interior tend to be solanchaks, east of 134° East, desert loams and red or brown clays are the main saline soils (Isbell *et al.*, 1983). There is no strong correlation, however, between soil type and salinity; saline soils of all textures are found. In the Murray Darling Basin, medium and heavy clay saline soils are common, including those with high shrink swell capacities (Murray-Darling Basin Ministerial Council, 1987a). Figure 1 shows the distribution of saline and sodic soils in Australia.

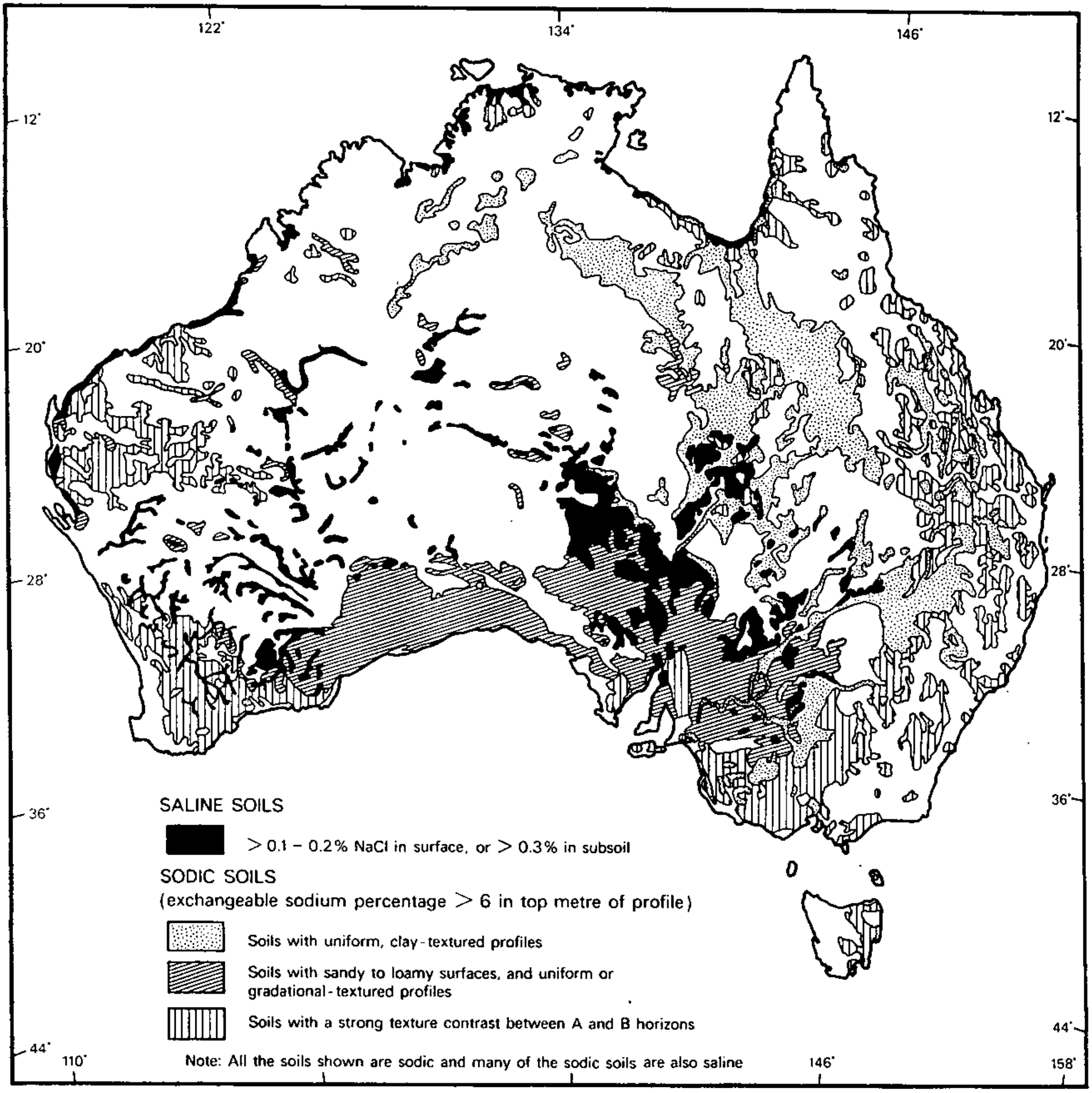

Figure 1 The distribution of Saline and Sodic Soils in Australia.
from Isbell *et al.* (1983).

3.0 SALT IN THE LANDSCAPE

Mineral salt is found in the landscape as a result of several processes and its distribution tends to be spatially heterogenous. In some areas salt is accumulating and in others depleting. Most importantly, the movement of salt in the landscape is a dynamic process and is driven by physical and biological mechanisms. Salt levels and salt compositions in an area vary with the seasons, landuse, and with longer term climatic and geomorphological change.

At the micro scale, mineral ions precipitate within the soil matrix, form adsorption complexes with clay minerals, exchange with other ions, are carried up the soil profile by evaporatively driven capillary rise, and moved down by recharge. Plants may act as sinks for many mineral ions, and by selective uptake, may change the chemical composition of soil. The identification of salt sources, micro scale processes and movement pathways is an important guide to the nature and sources of salinity in an area (Szabolcs, 1989).

3.1 Sources of Salt

For salinisation to occur there must be a source of mineral salt. Salts may be present in the landscape as a result of :

(i) weathering;
(ii) intrusion of marine water;
(iii) previous deposition of sediments in a marine environment (connate salt);
(iv) transport of salt as an aerosol in sea winds (meteoric or cyclic salt)
(Szabolcs, 1989; Sami, 1992).

The salts from these sources may be accumulated or transported by groundwater movement, evaporation, leaching, or biological activity.

3.1.1 Weathering

Parent rocks are subject to both physical and chemical weathering. Physical weathering may produce the larger soil particles, whereas chemical weathering produces soluble ions, colloidal gels and microcrystalline substances or clay minerals. The soluble ions may then be leached from the weathering complex, or become bonded to clay minerals (Duchaufour, 1982). Szabolcs (1989), however, points out that the chemical composition of most soils is not the same as the parent rocks they are derived from. The most easily extracted ions are also the most mobile and are found in lower quantities in most soils than the rocks they are derived from (Szabolcs, 1989). Highly mobile ions are typically the dominant ions involved in salinity (Szabolcs, 1989).

The chemical composition of groundwater can be related to the weathering products if the geology is well known (Szabolcs, 1989). The correlation between concentrations of anions and cations produced by chemical weathering should be strong if chemical weathering is the main source of dissolved salts in groundwater (Sami, 1992). The presence of chloride ions can also be used as an indication of the importance of weathering as they rarely originate from weathering processes (Sami, 1992; Herczeg *et al.*, 1993).

Dyson (1983) notes the frequent occurrence of deep weathering in saline areas. He suggests that this association exists because weathering increases the ability of the regolith to store ions. Furthermore, weathering produces cracks and joints which assist the development of deep rooted vegetation, thus increasing transpiration and the salinity of groundwaters (Dyson, 1983). The intensive leaching necessary for weathering to produce clay minerals, however, would remove the soluble ions associated with salinity. Salama *et al.* (1993a) suggest that weathering may contribute to salt accumulation through the uptake of water in chemical weathering reactions.

3.1.2 Marine salt

Marine salt, whether derived from contemporary processes (marine intrusion) or ancient marine sedimentation (connate salts), has a characteristic mineral ion composition. This composition is different for each body of sea water, but if the seawater compositions are known then proportional relationships may be derived to determine the relative contribution of these sources of salt to groundwater. If marine salt from recent intrusion or connate salt are the primary sources of salt in groundwater then the concentration of specific anions and heavy isotopes in the groundwater will vary according to the degree of mixing with recharge water. A plot of the concentration of ^{18}O versus ^{2}H or Cl^- should be positively correlated and should correspond to a mixing line between the composition of seawater and that of the least saline groundwater (Sami, 1992).

3.1.3 Meteoric Salt

Marine salt may be transported by the wind as an aerosol and deposited by rainfall or dry fallout (Bettenay *et al.*, 1964; Sami, 1992). This salt is often referred to as *meteoric* or *cyclic* salt. In near coastal areas particularly, this may be an important source of salt. The contribution of salt in this way is limited by distance from the sea (figure 2). Meteoric salt may fall out at a rate of 130-175 kg ha^{-1} yr^{-1} at near coastal areas and 27-67 kg ha^{-1} yr^{-1} in inland areas. Meteoric salt is characterised by an ion composition similar to that of the ocean from which it originated (Mazor and George, 1992). Hingston and Gailitis (1976) and Blackburn and McLeod (1983) provide detailed mineral ion ratios for rainfall and dry fallout for Western Australia and the Murray Darling Basin respectively.

The relative contribution of meteoric salt to groundwater may be estimated by examining the proportion of heavy isotopes of water (^{18}O and ^{2}H). Marine or connate water have heavy isotope levels similar to sea-water, so variations from this level can be associated with meteoric water isotope ratios to determine the relative contribution of meteoric salt to groundwater (Herczeg *et al.*, 1993).

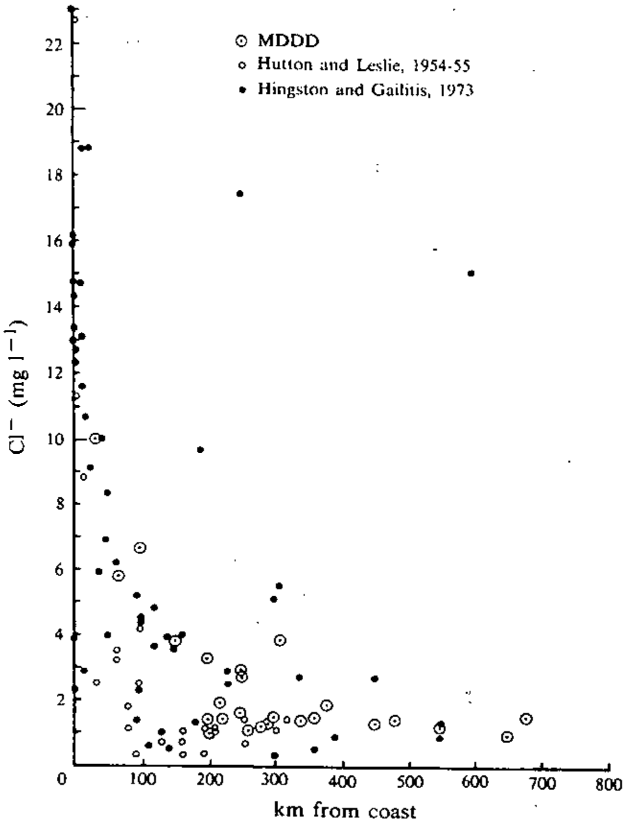

Figure 2 The relationship of distance inland from an oceanic salt source to deposition of meteoric chloride. Meteoric salt deposition follows a similar trend. From Blackburn and McLeod (1983).

MDDD refers to Murray-Darling Drainage Division.
NB: High chloride levels found in areas a long way inland may be associated with salt lakes.

3.1.4 Partitioning salt sources

The contribution to groundwater salt loads of meteoric, marine, sedimentary and weathering derived mineral ions can be determined from mineral ion ratios and a knowledge of the geology of the region (Bettenay *et al.*, 1964; Mazor and George, 1992; Sami, 1992). The relative importance of weathering contributions to the mineral ion population may be determined as a proportion of chloride to other ions as chloride is rarely a weathering product (Sami, 1992). Meteoric ions can be distinguished by their associated water which is likely to be enriched in the heavier isotopes of water (Sami, 1992). Bettenay *et al.* (1964), Peck (1978) and Salama *et al.* (1993a) suggest that the most important source of salt in Australian groundwaters is meteoric salt. Johnston (1987) and Turner *et al.* (1987) have combined mineral ion ratio and isotope analysis to determine sources of salt and water flow pathways in catchments.

3.2 Physics of Salt Movement

The movement of salt within the soil is essential to the understanding of salinity as salinisation is simply the accumulation of mineral ions. The mineral ion content of a soil is dependent not only on the sources of salt, large scale transport and transport by biotic agents, but also on micro scale processes such as cation exchange, precipitation and capillary rise (Raupach, 1983).

3.2.1 Adsorption and desorption: cation exchange

Adsorption is the accumulation of reacting species at the interface of solid and liquid or gaseous phases; desorption is the reverse process. Clay minerals consist of complex silicate lattices with sites of adsorption and desorption both within the lattice and on the surface which are suitable for cation or anion exchange. Adsorption of an ion consists of the formation of a weak electrostatic interaction between the ion and the outer or diffuse part of the double layer of a clay mineral or, alternatively, stronger bonds may be formed between the ion and the inner part of the double layer of a clay mineral (Marshall and Holmes, 1988). The cations involved in these weak bonds comprise the majority of the exchangeable cations of soils (Marshall and Holmes, 1988).

The cations bonded to clay minerals are often involved in replacement reactions where another cation replaces the first at the same site on a clay mineral. This is referred to as cation exchange.

Cation exchange follows a mass balance relationship:

$$K_{AB} = \frac{(A^{m+})^n (B_{ad})}{(B^{n+})^m (A_{ad})}$$

where (A_{ad}) and (B_{ad}) are the activities of A^{m+} and B^{n+} ions on the absorbent; (A^{m+}) and (B^{n+}) are the activities of the same ions in solution; m and n are the valence of the cations A and B respectively, and K_{AB} is the exchange constant (Szabolcs, 1989).

Cation exchange equilibrium is dependent on the activity of the cations and their valence. The replacing power of cations increases with valence, ie $M^{3+}>M^{2+}>M^{+}$. As soil water solutions become more dilute, the equilibrium shifts to favour the adsorption of cations with a higher valence, thus Ca^{2+} and Mg^{2+} would tend to replace Na^+, whereas Na^+ would tend to replace Ca^{2+} and Mg^{2+} as soil solutions become more concentrated (Szabolcs, 1989).

The most important cations involved in adsorption and cation exchange are: Na^+, K^+, Ca^{2+}, and Mg^{2+}. In practice, for saline soils, K^+ may be ignored as it is present in comparatively low quantities and many clay minerals have a high selectivity for potassium so that is unlikely to be disturbed by exchange reactions (Tucker, 1983). The Exchangeable Sodium Percentage (ESP) is used to quantify the effects of different relative ion concentrations. ESP equals the percentage of the Cation Exchange Capacity which is made up of exchangeable sodium (Salinity Lab Staff, 1954). Sodium Adsorption Ratio (SAR) is a similar measure which relates the concentrations of sodium to calcium and magnesium ions in the soil:

$$SAR = \frac{[Na^+]}{\sqrt{[Ca^{2+}] \cdot [Mg^{2+}]}}$$

The values of SAR do not differ greatly from corresponding ESP (Duchaufour, 1982). ESP and SAR have been used as indicators of soil stability (Salinity Lab Staff, 1954; Emerson, 1967; Lima *et al.*, 1990). Stability is a particular problem of saline soils as will be discussed later (Section 5.4).

3.2.2 Precipitation of mineral ions.

Mineral ions not bound to clay minerals in the soils are found either in solution or precipitated onto the surface of soil particles or on the ground surface. The distribution of mineral ions within a soil profile depends on their solubility and the dominance of accumulation and leaching processes. The most soluble salts will be the first to be dissolved and transported and the last to be precipitated. Thus highly soluble salts such as NaCl may move up and down the profile whereas salts with low solubility, such as $CaCO_3$, tend to accumulate in one soil horizon. In salt affected soils, precipitation is a dominant process, and the most important means of salt accumulation (Szabolcs, 1989).

3.2.3 Capillary rise and vapour rise

In many cases, soils are affected by salinity as a result of capillary rise of saline water from a near surface watertable and subsequent precipitation of mineral ions as the water evaporates. The process of capillary rise in soils is analogous to that within a capillary tube. The pressure applied in a capillary tube depends on the radius of the tube, and the nature of the tube material. Clay soils have a much finer pore structure and therefore impart stronger capillary forces. Water may be drawn up to two metres above the watertable in fine porous soil. However, the capillary rise in clay soils tends to be very slow and consequently the most effective capillary rise may occur in fine loamy soil of moderate porosity (Marshall and Holmes, 1988).

When the watertable is too deep for liquid flow to reach the surface at any given evaporation rate, water moves to the surface by vapour flow. This vapour flow does not bring salt to the surface, but may lower watertables as it is a form of discharge (Thorburn, *et al.*, 1992). This diffuse discharge depends on the evaporative power of the sun and is thus dependent on the degree of shading of the ground and the level of surface mulching (Thorburn *et al.*, 1992). Thorburn *et al.* (1992) suggest that even salt crusting may act as a surface mulching layer, preventing diffuse discharge.

3.3 Salt Balance Concept

Salt is neither created nor destroyed on Earth. There is a net balance of salt levels; however, for any region, salt input fluxes may exceed output fluxes or vice versa. Salt may be transported short distances within the soil profile, to nearby positions in the landscape, or may leave the local environment entirely. The quantity of salt in a volume of soil is thus dependent on processes which lead to the accumulation of salt, leaching processes and stability processes. Mineral ions are present in the landscape in huge quantities. ACIL (1983) estimates that between 3400 and 19 000 tonnes ha^{-1} total dissolved salt may be found within the regolith in saline areas. Figure 3 outlines the sources, sinks and pathways for salt movement including sources of salt external to the landscape, movement within the landscape and sources and sinks within a soil pedon. Micro scale processes described above operate at the scale of the soil pedon, whereas transport of salt within the landscape is accomplished by groundwater movement.

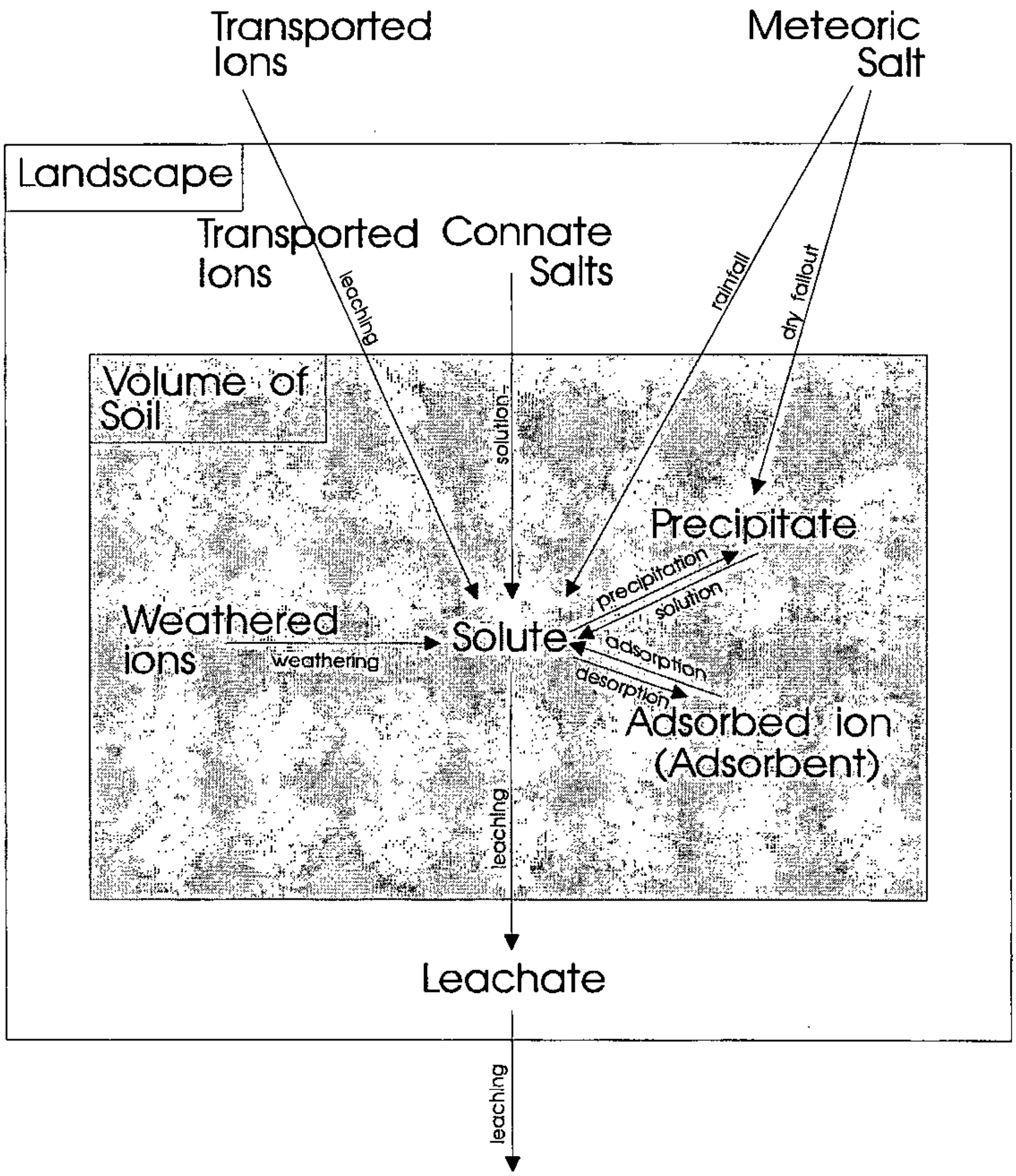

Figure 3 Sources, Sinks and Pathways For Salt Movement

4.0 CAUSES OF SALINITY

Soil salinity is caused by the domination of salt accumulation processes over leaching processes within the near surface layers of the regolith. Two models of salt transport and accumulation within the soil profile are commonly proposed. In the first model, salt is assumed to enter the soil profile with infiltrating water and encounter a low permeability subsoil or layer within the regolith. The salt then becomes concentrated in the unsaturated zone as water is removed by evapotranspiration (Marshall and Holmes, 1988; Charman and Junor, 1989; Salama *et al.*, 1993a). The second model assumes that the recharge water transports salt to discharge zones through confined and unconfined aquifers where the process of evapotranspiration again acts to concentrate salt in the soil (Peck, 1978; Dyson, 1983; Charman and Junor, 1989; Salama *et al.*, 1993a). The salinisation of soil may occur as a result of either or both of these models. Both of these models may also involve capillary rise from shallow watertables.

Agricultural practices and associated clearing of land have altered the landscape water balance, and in places altered the movement of groundwaters thus affecting the position of watertables in recharge and discharge areas. Wood (1924) was one of the first to notice the effect of widespread clearing for agriculture and timber on salinity in Australia. Since that time, farming practices, especially irrigation, and extensive clearing of native forests have continued to change the water balance, alter groundwater movements and cause substantial erosion. The result has been extensive areas of watertable rise, and widespread salinity.

4.1 Water movement pathways and Groundwater Recharge

Within the regolith there are zones that are saturated with water, and unsaturated zones. The unsaturated zone or *vadose zone* is above the watertable but water may pass through it from above (infiltration), from below (capillary rise) or pass laterally through it (subsurface flow). At the junction of the saturated and unsaturated zones is the watertable. The saturated zone is composed of fractured rock, weathered rock, alluvial or colluvial sediments, groundwater and mineral ions. Soil may also be a part of the saturated zone where there are shallow watertables. Streams and rivers are often surface expressions of the watertable. Groundwater flows into these waterways from the adjacent aquifers. Water also enters rivers from surface runoff and subsurface flow.

Figure 4 shows a simplified natural hydrological cycle. In this cycle precipitation is the only source of water to the landscape. The soil surface, unsaturated zone and saturated zone are the three zones of water movement. At the soil surface, water can follow any pathway indicated by a single headed arrow; it is either evaporated, runs off, or infiltrates. Once water has infiltrated, it may follow a pathway denoted by a double headed arrow. It can be evaporated from the soil, taken up and transpired by plants, stored within the soil, transported laterally within the soil, or transported into the saturated groundwater zone. Groundwater may follow the triple headed arrow pathways, either upwards to the unsaturated zone, or the soil surface, laterally within the aquifer, into a waterway, or down to a deeper aquifer.

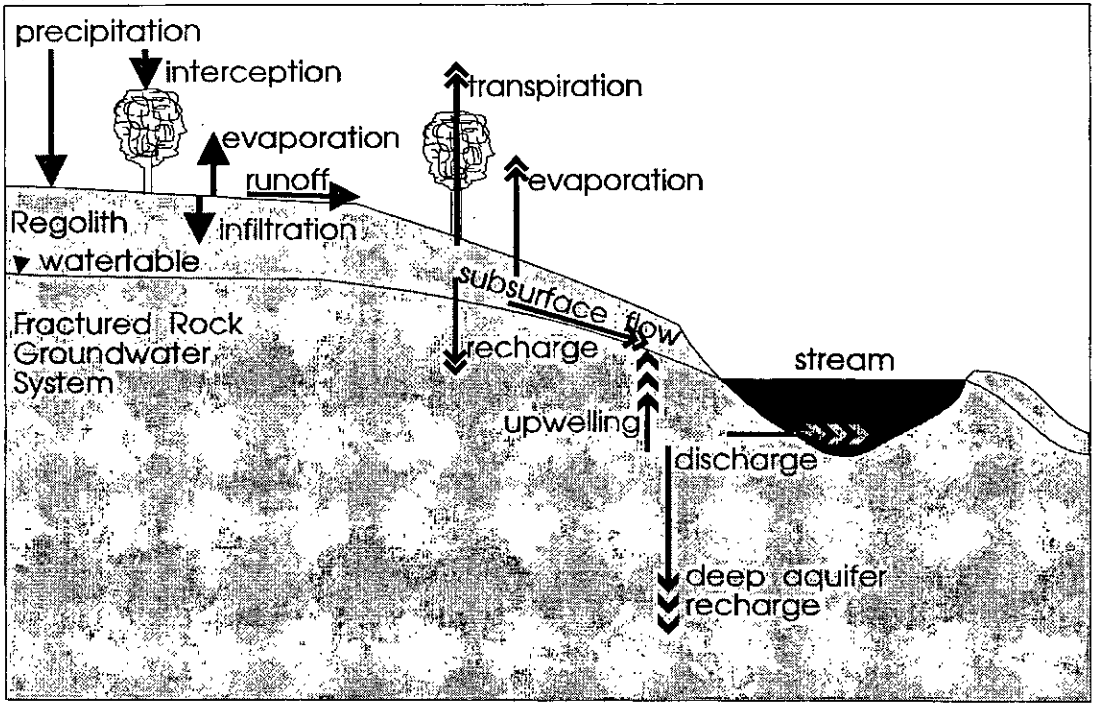

Figure 4 Simplified Hydrological Cycle - Unconfined Aquifer.
(Adapted from Salinity Committee, 1984)

The depth to the watertable is dependent on the groundwater flow paths outlined above, and on the water budget. Watertables tend to rise in the wet seasons of the year, and fall during the dry seasons. Watertables may also fluctuate according to longer term climate change. The concentration of salts in groundwater is dependent not only on the sources of salt and the storage capacity of the soil, but on evapotranspiration.

The water budget for an unsaturated volume of soil may be expressed as follows (modified from Cooke and Willatt, 1983; and Williamson *et al.*, 1987):

$$P + I = E + R + T + \Delta G + \Delta V$$

Where: P = Precipitation,
I = Irrigation
E = Evapotranspiration
R = Surface Runoff
S = Subsurface flow
ΔG = Change in groundwater storage
ΔV = Change in storage within the vadose zone

In groundwater recharge areas, precipitation exceeds evapotranspiration, runoff, subsurface flow and soil water storage, so ΔG is positive and water percolates to the watertable. In discharge areas, ΔG is negative, and groundwater storage reduces as water is brought to the surface where it is transpired, or it evaporates or runs off. For salt to accumulate in the soil profile, evapotranspiration must exceed the volume of leachate (P-R).

4.2 Groundwater Discharge

Water enters the groundwater system at recharge sites and exits at discharge sites. In a catchment of uniform geology and soil, aquifers are said to be unconfined, and groundwater movement is limited primarily by landscape morphology (Zecharias and Brutsaert, 1988). There is a reduction in hydraulic gradient at the break of slope. As a result, soils downslope cannot transport all of the water being fed from upslope; water builds up at the break of slope and may discharge to the surface forming a saline seep (fig. 5) (Nulsen, 1986). Groundwater encountering a break of slope or other obstruction may be forced downwards as well as seeping to the surface. Local discharge sites may thus act as recharge sites for local or regional deep aquifers (George, 1992).

In most catchments the geology and soils are not uniform. The permeability of soil, sediment and bedrock may be highly variable. The lateral movement of water in the regolith may be impeded by an impermeable layer of clay or rock, causing the water to rise to the surface higher on a slope than would be expected (Charman and Junor, 1989). Geological features such as basement highs and dykes may act as impediments to groundwater movement. This lack of uniformity means that groundwater movement and subsurface flow in a catchment may be much more complex than shown by figure 5 Figures 6-9 illustrate possible groundwater flow patterns in catchments with non-uniform geology.

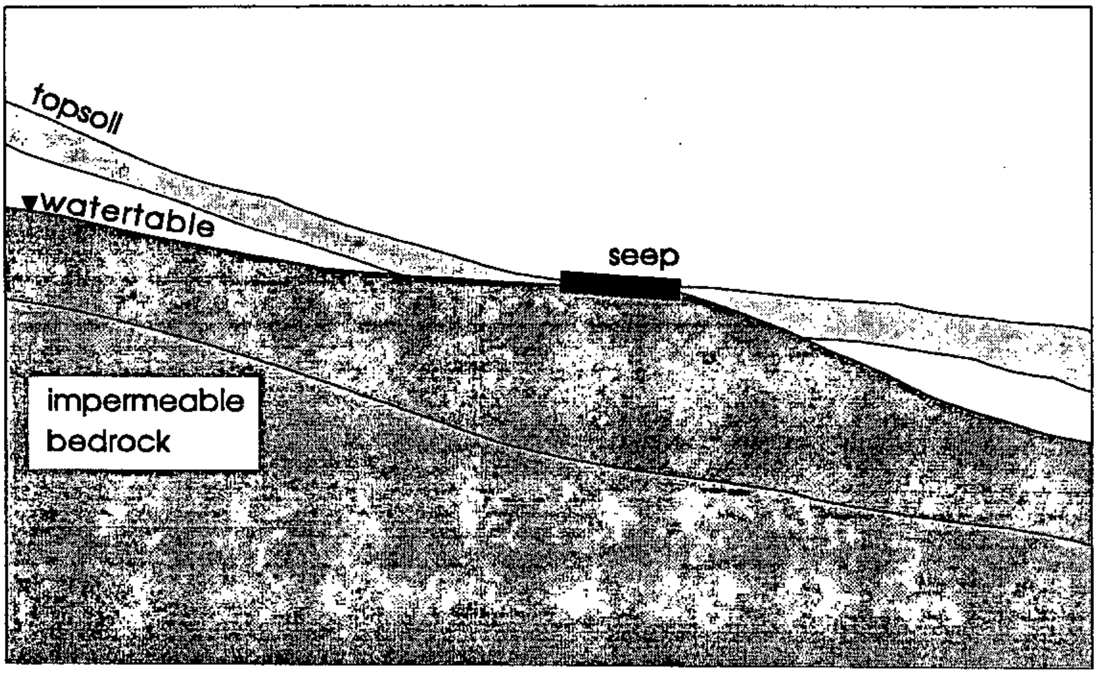

Figure 5 Simplified Hydrological Cycle - Salinity at Break of Slope.

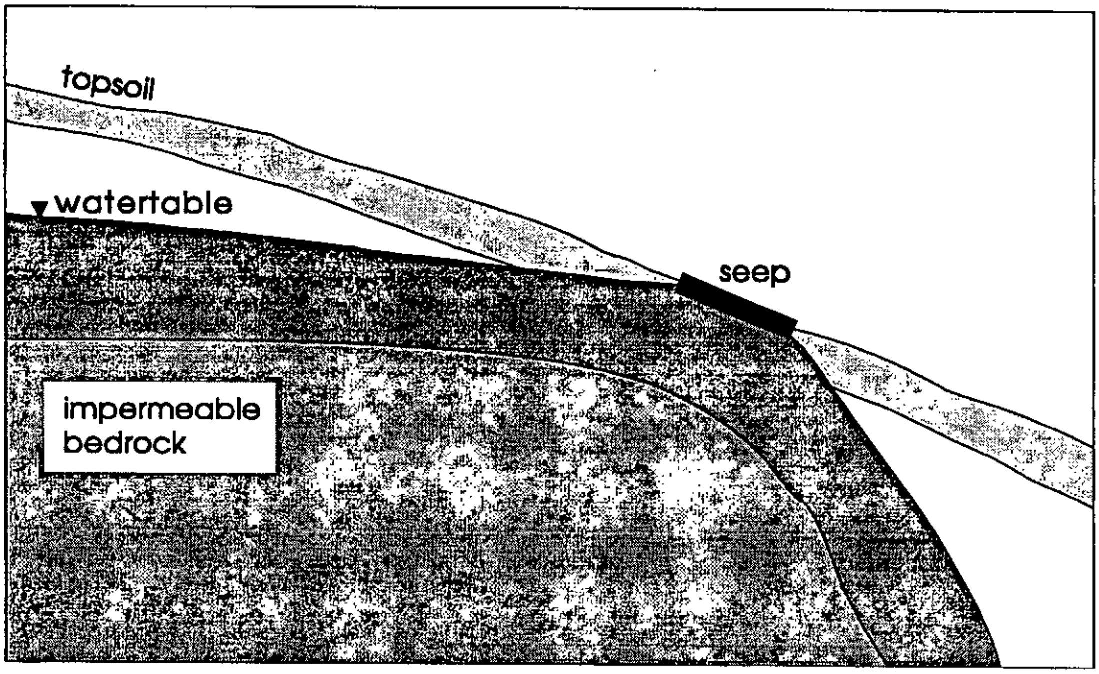

Figure 6 Simplified Hydrological Cycle - Basement High.
(Adapted from Nulsen, 1986 and Thorburn, 1991)

An irregular impermeable bedrock layer may near the surface at some point; this is referred to as a basement or bedrock high (fig. 6). Groundwater encountering a basement high is trapped behind it, and forced to rise towards the surface. Basement highs may be visible as rock outcrops; in this case a seep would form upslope of the basement high (Nulsen, 1986; Thorburn, 1991).

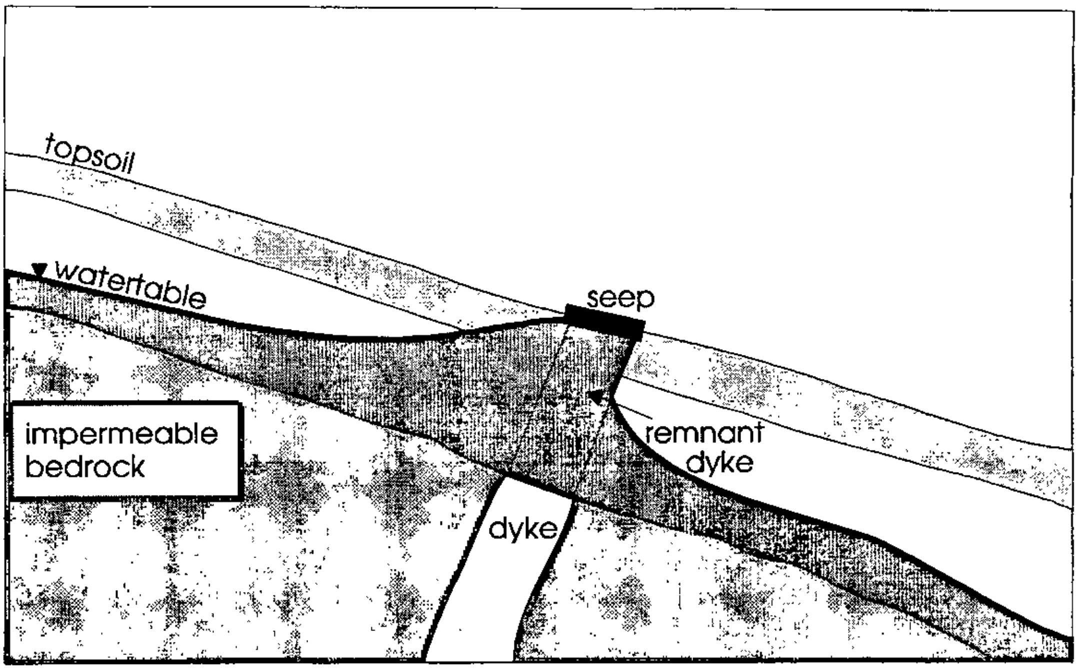

Figure 7 Simplified Hydrological Cycle - Dyke.
(Adapted from Nulsen, 1986)

At the junction of two rock types an intruded layer, or dyke, may be found (fig. 7). These dykes are often formed of material that is highly resistant to weathering and thus impermeable to water. Groundwater encountering a dyke is trapped behind it in a similar fashion to a basement high (Nulsen, 1986).

Fractured permeable rock may form the recharge zone of a catchment and relatively impermeable rock may be found lower in the landscape (fig. 8). At the junction of the two rock types, groundwater may be forced to the surface. A common example of this is where fractured upland basalt forms the recharge area and lowlands are comprised of less permeable sedimentary or granitic rocks (Thorburn, 1991; Kevin, 1993). Similarly, shallow groundwater moving through lightly textured soils may encounter heavier textured soils or subsoils. For example, coarse textured upland soils may lie adjacent to alluvial plains composed of heavier textured soils which are less permeable to water (Kevin, 1993).

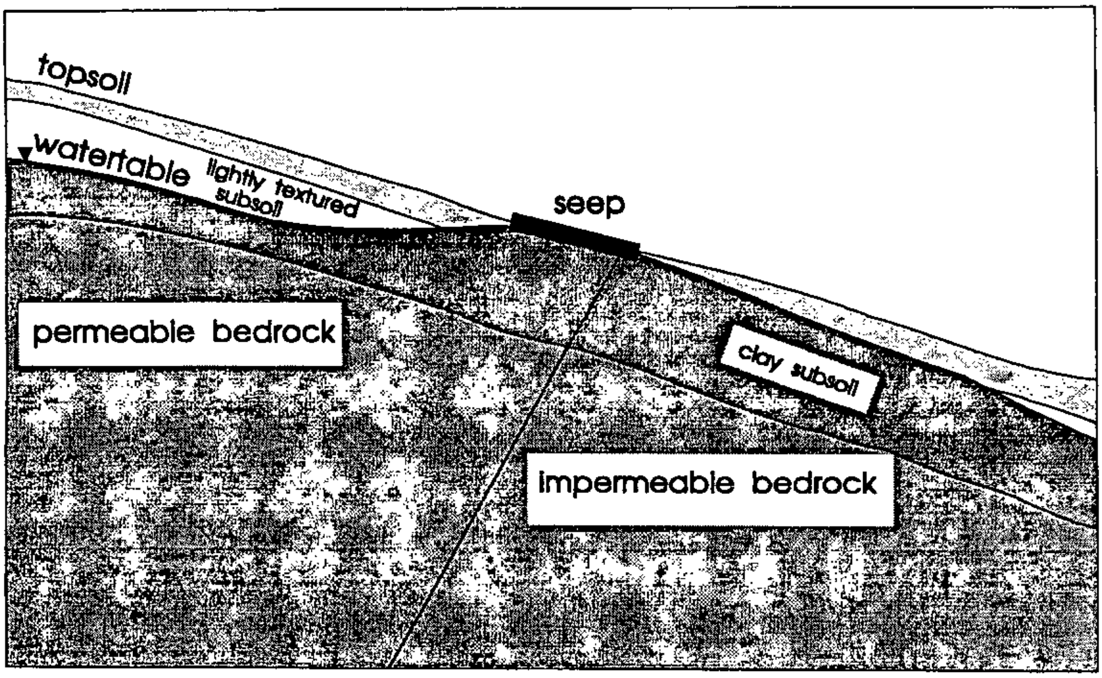

Figure 8 Simplified Hydrological Cycle - Change in Bedrock or Soil Type. (Adapted from Thorburn, 1991; and Kevin, 1993)

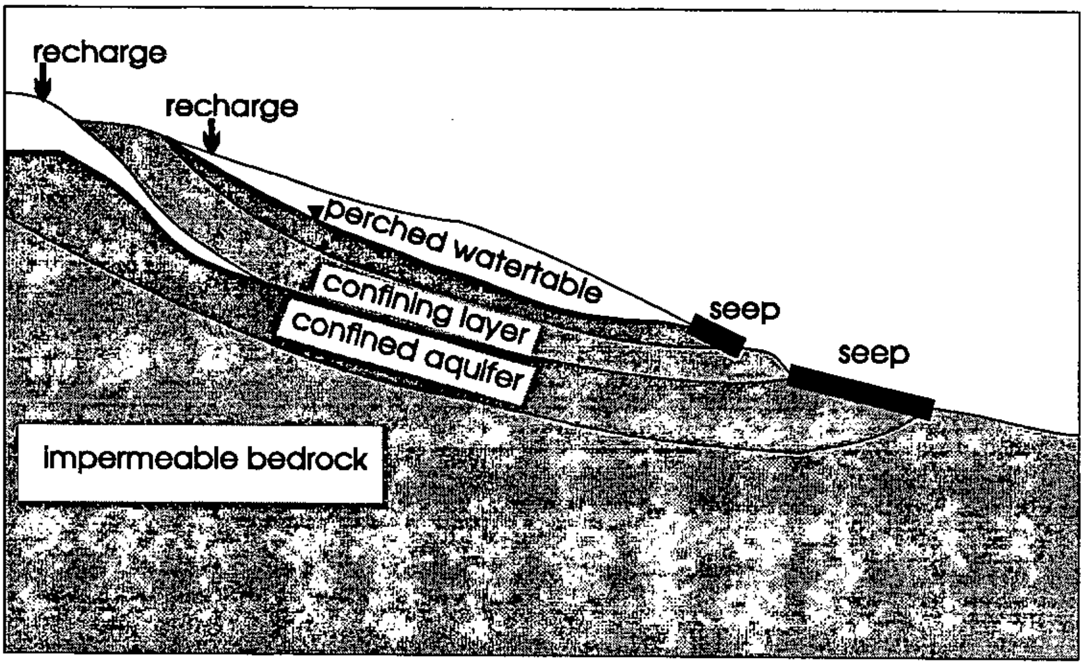

Figure 9 Simplified Hydrological Cycle - Confined Aquifer.

Clay or rock may form a confining layer both above and below an aquifer, thus limiting groundwater movement to lateral flow (fig. 9). Deep regional aquifers are often confined in this way. The recharge zones for these aquifers may be high in the landscape through joints, fractures and contact zones between the aquifer and rocky outcrops. Discharge zones are often distant from recharge areas, and in topographically low positions in the landscape (Salama *et al.*, 1993b). Groundwater recharge and discharge sites may also occur in close proximity where perched watertables are present.

4.3 Changes to Water Balance

The recharge and discharge of local and regional aquifers in Australia has been substantially altered by farming practices and forest clearing. Forested land has been replaced by broadacre cropping and orchards which transpire significantly less than the original vegetation. Irrigation fundamentally changes the water balance by adding half again or more the quantity of water that is received from rainfall. Farm dams and drainage and water supply channels leak into the surrounding soil and act as mini recharge zones. Farming practices such as fallow and tillage may also significantly contribute to excessive recharge to local aquifers. In the natural environment, recharge rates are often less than 1-10 mm y^{-1}, whereas in modified environments, recharge may exceed 1 m y^{-1} (eg Ruprecht and Schofield, 1991).

4.3.1 Clearing of native vegetation

Over half of the native forests and woodlands in Australia have been cleared since European settlement (Resource Assessment Commission, 1992). Observations by numerous researchers have shown that evapotranspiration in forests is greater than in grasslands under the same conditions (Peck, 1978; Greenwood *et al.*, 1985; Ruprecht and Schofield, 1991). Interception of rainfall has also been reduced by clearing native vegetation (Vertessy, pers. comm.). Land that was previously forested may now be under native pasture, improved pasture, cropping or orchards. With the exception of orchards, the plant species involved tend to be annuals which grow in Winter and Spring, and die down in Summer, leaving bare soils which evaporate even less than grassland (Peck, 1978). Evapotranspiration in Summer is therefore substantially less than under evergreen native forests. Many of the orchard plants are deciduous and thus transpire little during the winter months when the greatest recharge occurs. Charman and Junor (1989) suggest that "*...the clearing of trees from catchments is thus the primary catalyst for the hydrological disturbance which leads to soil salinisation.*" Figure 10 shows water balance before and after clearing of a small catchment.

The effect of clearing native vegetation on groundwater levels has been investigated in paired catchments (eg Peck and Williamson, 1987; Ruprecht and Schofield, 1991). Ruprecht and Schofield (1991) conducted an investigation of groundwater levels over a thirteen year period in the wheatbelt of Western Australia. For the first four years after clearing of the native vegetation, groundwater levels rose at 0.11 m y^{-1}. For the next five years the mean watertable rise was 1.45 m y^{-1}, and for the last 4 years, mean watertable rise was 2.3 m y^{-1}. Their results clearly show that removal of native vegetation leads to enhanced recharge. Peck and Williamson (1987) recorded similar findings. Regional aquifers may respond much more slowly to increased recharge, Charman and Junor (1989) suggest that there may be up to 50 years' delay between clearing and the development of salinity problems from the rising of watertables associated with regional aquifers.

Native vegetation may also be important in reducing the extent of discharge areas through evapotranspiration. Many halophytic plants such as the chenopod saltbushes grow on salt prone land. These plants may be responsible for preventing saline seepage (Peck, 1978; Malcolm, 1990).

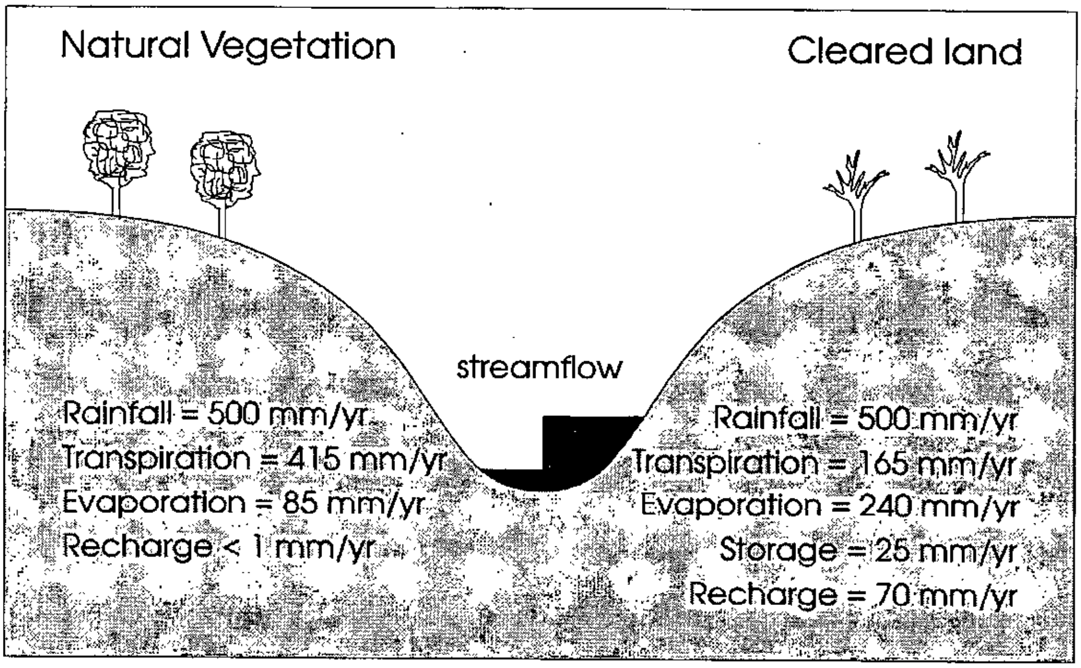

Figure 10 Water Balance Before and After Clearing of Native Vegetation.
(After Campaspe Weste Salinity Iplementation Group, 1992)

4.3.2 Irrigation

Irrigation results in the most significant deviation from the natural water balance of an area. In the Barr creek catchment, in Northern Victoria, for instance, mean annual rainfall is approximately 370 mm y^{-1}, and irrigation varies between 280 and 550 mm y^{-1} (Gutteridge Haskins & Davey *et al.*, 1985). As the water balance equation suggests (p. 15), irrigation is likely to result in surface runoff, subsurface flow and recharge. Irrigation is applied to serve two main purposes, namely: adequate water for plant growth and adequate leaching of the root zone. Unfortunately both of these objectives cause groundwater accessions as water supply is never metered perfectly to serve plant needs, and drainage systems do not collect all leachate.

While irrigation water may prevent the local accumulation of salt, the recharge and discharge cycle from irrigation water is often very short; neighbouring non-irrigated fields may suffer from salinity in the irrigation season (ACIL, 1983). Figure 11 shows a typical hydrological cycle under irrigation. Irrigation creates a groundwater mound, leading to groundwater transport to nearby regions and into local streams and drainage channels. Evapotranspiration from plants in the irrigation area also concentrate salts in areas of shallow watertables thus leading to soil salinity.

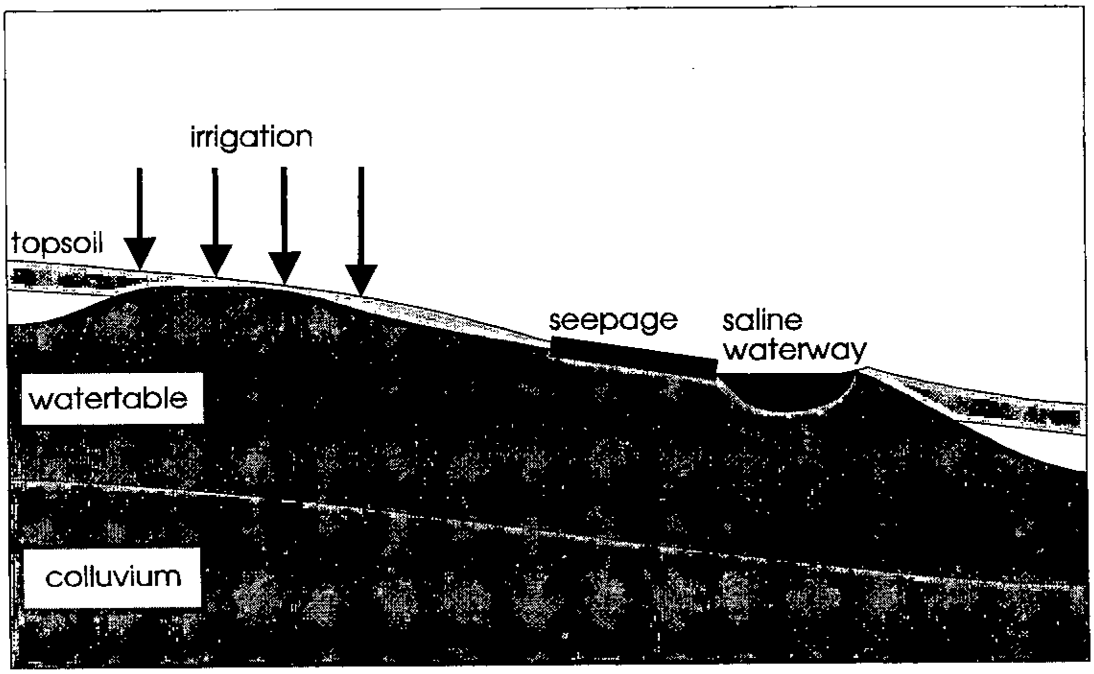

Figure 11 Hydrological Cycle Under Irrigation.

Irrigation areas are typically in topographically low areas with little relief, and soils are often deep and underlain by permeable fractured and weathered bedrock or alluvial sediments (Gutteridge Haskins & Davey *et al.*, 1985; Campaspe West Salinity Implementation Group, 1992). Saline seepage and soil salinity is thus usually a result of shallow watertables which are found in most of the irrigation districts in the Murray Darling Basin (ACIL, 1983; Murray-Darling Basin Ministerial Council 1987a). It is believed that irrigation accessions to the groundwater are the primary cause of these high watertables (Gutteridge Haskins & Davey *et al.*, 1985), but there are no hard data on irrigation accessions to groundwater (Turral, 1993).

In many irrigation districts in Australia, irrigation water contains quantities of mineral ions; these are concentrated within the root zone by evapotranspiration before drainage. The salt supply in irrigation water does not significantly increase the salt budget of areas with high saline watertables, but may increase the salinity of water in the root zone. In a well drained, efficient irrigation system, nine tenths of the irrigation water may be evaporated or transpired, so the salinity of the root zone water may be ten times that of the irrigation water when it reaches sub surface drains (Gutteridge, Haskins & Davey, *et al.*, 1985).

It has become common practice for farmers to re-use irrigation drainage water (see section 4.3.4). This practice increases available volumes for irrigation, and reduces costs. This drainage water, however, may have accumulated salt through evapotranspiration, so leaching with re-used water may thus be less effective than with new irrigation water (ACIL, 1983).

4.3.3 Farming practices - tillage/fallow/infiltration

Fallowing, absorption banks and contour banks on gentle slopes are believed to lead to greater groundwater recharge by increasing infiltration (ACIL, 1983). McFarlane *et al.* (1990) report that level banks used to prevent waterlogging on low lying land may also act as sites of enhanced recharge thus leading to greater downslope salinity problems. Tillage may also increase groundwater accessions though Beke *et al.* (1993) report that deep tillage may help to reduce soil salinity as irrigation water via enhanced drainage.

4.3.4 Channel seepage and leakage

Irrigation water is supplied and drained from the land by networks of open channels. Water supply channels are often imperfectly sealed, and contribute to groundwater recharge through seepage through the channel walls and leakage through holes in the channel created by yabbies, water rats and other fauna (McLeod, 1993). These channels are typically very variable in quality; accessions may be high in short segments of a water supply channel, and otherwise minimal (ACIL, 1983). Gutteridge Haskins & Davey *et al.* (1985) suggest that approximately 25% of groundwater accessions from the Barr creek irrigation area come from water supply channel seepage and leakage. In an investigation of channel seepage and leakage, McLeod (1993) found that seepage was higher and leakage lower in areas with coarse textured soils as opposed to areas with fine soils. Overall, groundwater accessions from water supply channels were greater in areas with coarse textured soils (McLeod, 1993). Drainage channels may also contribute to recharge. However, in areas where watertables are close to the surface, groundwater is likely to discharge to the drains.

4.3.5 Farm dams and disposal basins

Farm dams are often poorly constructed, and particularly poorly sealed. Seepage from these dams may create a groundwater recharge ridge just below the dam. The water in this ridge is under pressure which results in a rise in groundwater levels down from the dam, possibly followed by saline discharge (Salama *et al.*, 1993b). The mass of water in a dam also creates elastic pressure whether the dam is properly sealed on not. This pressure also contributes to groundwater rise and discharge (Salama *et al.*, 1993b). Saline water disposal areas may act similarly to farm dams. Chambers *et al.* (1992) describe displacement of saline regional groundwater and subsequent discharge surrounding an irrigation waste water disposal basin.

4.3.6 Waste water disposal

Saline waste water is often created in salinity management and may exacerbate salinity problems. If it is not disposed of in an evaporative basin (see section above) it may be pumped into a river (see section 4.6.2) or it may be injected into deep groundwater aquifers, thus contributing to groundwater recharge.

4.4 Changes to Groundwater Movement

Groundwaters transport mineral ions. Human activities that alter the natural pattern of groundwater movement may thus contribute to salinity problems. The altered distribution of recharge and discharge zones, formation and destruction of aquifer confining layers, and the creation and destruction of obstacles to groundwater movement may also contribute to greater watertable rise and hence salinity.

4.4.1 Altered distribution of recharge and discharge zones

Changes to vegetation, and surface permeability have altered the spatial distribution of groundwater recharge zones. Natural discharge zones have increased in size, and new discharge zones have appeared as a result of human activity. New discharge zones have the capacity to intercept groundwater, and thus alter the downhill distribution of discharge. There appears to be a lack of research into this area which could prove to severely affect management plans for salinity remediation.

4.4.2 Formation and destruction of confining layers

Surface aquifers may be confined from below, resulting in a perched watertable. These aquifers are often involved in saline water discharge in close proximity to recharge areas. Poor soil management may lead to the formation of hardpans or indurated layers within the subsoil which act as confining layers.

Deep regional aquifers, sometimes referred to as deep leads, are often much more saline than the surface waters, but are prevented from reaching the surface by confining layers. The construction of wells, and possibly excavation work for the installation of deep drains and reservoirs may break through these confining layers and thus create localised sites of deep groundwater discharge.

4.4.3 Creation and destruction of obstacles to groundwater movement

Deep ripping and tillage often brings clay subsoil to the surface greatly reducing the permeability of the near surface soil, whereas the addition of gypsum and other minerals may improve soil permeability. These farming practices create heterogeneity in the soil water permeability which may force groundwater or subsurface flow to the surface. Similarly, farming practices or excavations which create or remove irregularities in the permeability of the regolith to water may alter groundwater movements.

4.5 Erosion of Topsoils

Scalds are formed when the topsoil is completely removed. In areas where the subsoil is already saline, a salt scald is formed. Many natural salt scalds exist in Australia, but clearing of native vegetation, overgrazing and cropping have increased erosion in many areas, contributing to the formation of these scalds. Erosion of topsoil is thus a method of bringing the watertable closer to the surface. Topsoil erosion is also a problem in many salt affected areas as it exacerbates soil fertility problems caused by excessive salt content.

4.6 Human Induced River Salinity

Salt accumulation in the soil and on the soil surface, groundwater salinity, and meteoric salts are all responsible for river salinity (ACIL, 1983; Schofield and Ruprecht, 1989). Schofield and Ruprecht (1989) suggest that river salinity is also a function of rainfall. River salinities vary inversely with annual rainfall, and hence the dilution of salt discharge (Schofield and Ruprecht, 1989). River salinity is thus caused by the same processes that causes soil salinity. However, farming practices may exacerbate river salinity while not in themselves contributing to soil salinity. Any farming practice that causes saline groundwater displacement in salt affected areas or produces saline drainage effluent is likely to increase stream and river salinity.

4.6.1 Clearing of native vegetation

Clearing of native vegetation may lead to increased stream flows and greatly increased surface runoff. Williamson *et al.* (1987) found that clearing of a previously forested catchment in Western Australia led to a 2.8 to 6.6 times increase in annual stream flow, and a 15 fold increase in direct runoff during a storm event. They also found that the chloride loading in the streams increased by a factor of 4.0 to 5.4. Thus some streams became more saline, and others less saline with clearing.

Clearing of native vegetation may lead to enhanced deep regional aquifer recharge and thus increased discharge by displacement of regional aquifer water into streams and rivers. The Parilla sands aquifer of the Victorian mallee, for instance, receives substantial recharge from previously forested land. However, it is uncertain whether clearing of native vegetation or irrigation has a greater effect on the discharge of this regional aquifer into the river Murray (Nyah to SA border Community Salinity Group, 1992).

4.6.2 Irrigation, drainage, pumping and waste water disposal

Irrigation water is usually collected in surface and subsurface drains. This water is often saline and must be disposed of, either in streams or rivers, holding tanks or evaporation basins. When irrigation water is disposed of in rivers it contributes to the salt load of the river. Irrigation water disposed of by deep aquifer injection may also displace highly saline groundwater into the river (Nyah to SA Border Community Salinity Group, 1992).

4.6.3 Reduced dilution flows

The use of irrigation water from the Murray and other rivers and the enhancement of evaporative loss of water from artificial weirs and dams reduces the total flow of water, and hence the dilution of salt. The result is that these rivers are more saline (Murray-Darling Basin Ministerial Council (1987b).

4.7 Conclusion

Soil salinity occurs when salt accumulating processes exceed salt leaching processes. Salt may be either transported to the system from meteoric sources and then concentrated by evapotranspiration or from groundwater discharge. Soil salinity has been induced by humans by increasing groundwater recharge through clearing of native vegetation, irrigation and other farming practices. Changing groundwater flow pathways has also enhanced groundwater discharge. Erosion of topsoils has created many saline scalds, effectively bringing the watertable to the surface by lowering the soil surface.

Salt enters rivers from runoff, subsurface flow and groundwater discharge. Soil salinity thus provides a ready source of soluble ions which are picked up by runoff and subsurface flow and delivered to streams. Clearing of native vegetation also contributes to river salinity directly by recharging the often more saline regional aquifers, and causing them to discharge into rivers and streams.

5.0 EFFECTS OF SALINITY

Salinisation of soil and waterways affects plants and animals on an individual level and an ecosystem level. Salt may lead to toxicity and may adjust the osmotic balance in the soil. Saline areas may possess unusual mineral ion compositions leading to changes in soil physical properties and soil formation. Saline waterways present a huge problem to irrigation agriculture and the provision of adequate water supplies for human and livestock consumption.

5.1 Effects on Animals

Saline water supplies are a problem to both humans and livestock. Over-consumption of mineral ions may lead to toxic effects, increased requirement for water and poor livestock growth (ACIL, 1983). Whilst few animals die directly from saline water consumption, there are many secondary effects. The most important secondary effect is the requirement of greater water consumption to metabolise or dilute the mineral salts. Animals supplied only with saline drinking water may be subject to heat exhaustion and heat stroke as they do not have enough available water for temperature regulation (Keaton and Gould, 1986). ACIL (1983) suggests saline water supply thresholds for different livestock; poultry may be limited to 1500-3500 mg l^{-1}, whereas adult sheep on dry feed can survive with water supplies of up to 14 000 mg l^{-1} total dissolved salts (ACIL, 1983).

High salt levels are toxic to fish, prevent their feeding, and may reduce oxygen levels causing asphyxiation (Anderson, 1991). Most adult fish in the Murray-basin area appear to be adapted to cope with salinity in the order of 9600 mg l^{-1}, however, there is little known about the salinity thresholds of fish eggs, larvae and juveniles (Hart *et al.*, 1990; Anderson, 1991)

The World Health Organisation and the National Health and Medical Research Council (Salinity Committee, 1984) have recommended that for health reasons the sodium content of water supplies for human consumption should not exceed 115 mg l^{-1} and should be reduced to half that level. In terms of total salinity units, these recommendations equate to 450 and 225 mg l^{-1} of total dissolved salt respectively.

5.2 Effects on Plants

Plants affected by salinity grow more slowly, and are hence stunted. Their leaves are smaller, often thicker, and deeper green or blue-green (glaucous) (Bernstein, 1975).

Salinity may stunt the growth of fruits, or prevent fruiting entirely. Salt may affect plants through the toxicity of specific ions which break down biochemical pathways, through nutritional depletion, and through osmotic effects of the saline root media (Bernstein, 1975; Levitt, 1980). Levitt (1980) describes the effect of salt on plants as a combination of *Salt Stress,* and *Drought Stress.* According to Levitt (1980), a stress is any environmental factor which is potentially unfavourable to living organisms, and hence stress resistance is the ability of an organism to tolerate the unfavourable factor.

Plants are very variable in their ability to tolerate saline conditions. Different plant species may be very tolerant to salt, others may be very susceptible. Plant salt tolerance also varies with their life history. Adult plants may be able to cope with or grow under salt levels that juveniles or seedlings find acute (Bernstein, 1975). Table 3 shows the salt tolerance of some common crop plants. Maas and Hoffman (1977) and Bressler *et al.* (1982) provide comprehensive lists of the salt tolerance and yield reduction of over 100 crops.

Table 3 Salt Tolerance of Some Common Agricultural Crops.
Source: Maas and Hoffman (1977).

Crop	Threshold Soil Salinity EC $\mu S\ m^{-1}$	Yield Decrease Beyond Threshold (% / 000 EC units)	Salt Tolerance Rating
Barley	8 000	5.0	Tolerant
Sugarbeet	7 000	5.9	Tolerant
Wheat	6 000	7.1	Mod. Tolerant
Perennial Rye	5 600	7.6	Mod. Tolerant
Tomato	2 500	9.9	Mod. Sensitive
Lucerne	2 000	7.3	Mod. Sensitive
Peach	1 700	21	Sensitive
Apricot	1 600	24	Sensitive
Clover	1 500	12	Sensitive
Beans	1 000	19	Sensitive

5.2.1 Nutritional depletion

High sodium levels in saline soils often result in exchange reactions with Ca and Mg. Consequently there may be a depletion of available Ca and Mg in the soil. Excessive sodium may also reduce the amount of available potassium in the soil. These ions are essential for a healthy plant metabolism as they are involved in many biochemical pathways, for protein synthesis, hormone production and transport, and in salt exclusion mechanisms (Bernstein, 1975).

Bernstein (1975) suggests that exchangeable sodium potential (ESP) is a guide to the level of secondary toxic effect or nutrient depletion. At an ESP of 10, beans and other salt sensitive plants start to become affected. Most crops are affected by salinity at an ESP of 25, and even salt tolerant plants such as tall wheat grass and beetroot are affected at an ESP of 50.

5.2.2 Osmotic effects

The addition of salt to soil water decreases its osmotic potential which leads to drought stress in plants. Plants take up water by maintaining a water potential gradient between their cells and the soil water (Salisbury and Ross, 1992). The water potential (Ψ_w) of a plant is made up of its osmotic potential (Ψ_s) and pressure potential (Ψ_p). The osmotic potential (measured in MPa) of a solution is the pressure that would be applied on the solution by pure water through a semi-permeable osmotic membrane. The pressure potential is the internal pressure of the cell.

Thus: $\Psi_w \text{ (plant)} = \Psi_p + \Psi_s$

The water potential of soil is made up of soil osmotic potential and matric potential (Ψ_m).

Thus $\Psi_w \text{ (soil)} = \Psi_m + \Psi_s$

The matric potential is defined as the pressure exerted on a reservoir of pore water through a semi-permeable membrane by a soil at a water content less than saturation. Matric potential is related to the size of the pore spaces in the soil, and is larger in fine grained soil for a given water content.

When Ψ_w of the soil is greater than Ψ_w of the plant then the plant loses water to the soil. A plant will suffer from drought stress if it cannot take up water at a similar rate to which it loses water by evaporation from its stem and leaves. Plants growing in saline conditions are thus subject to lower water potentials (pressure, osmotic, matric and water potential are all negative) than in non-saline conditions. Thus the greater the salinity, the greater the drought stress.

5.3 Effects on Ecosystems

Rising salinity may affect the relationships between plants and animals. The death of many trees in saline areas reduces the number of bird nesting sites, reduces food production, and alters the microclimate by reducing shade and wind protection (Anderson, 1991). Similarly, wetland vegetation may be substantially altered by saline water intrusion such that frog and fish populations no longer have appropriate breeding areas. This in turn affects the populations of insect larvae that are the food of frogs and fish, and affects the waterbird populations also. Ecosystems are characterised by their interconnectedness; food, habitat space, microclimate, and the presence of predators may all be affected by the removal or depletion of one species. Salinity may thus have wide-reaching effects on both aquatic and terrestrial ecosystems.

5.4 Effects on Soil Properties and Formation

In soils where salinisation is an active process, the most soluble salts (NaCl, $MgSO_4$, Na_2SO_4, Na_2CO_3, $MgCl_2$) are found nearest the surface (Szabolcs, 1989). In these soils the dominant processes are cation exchange, aggregate dispersion, surface sealing, loss of soil structure, and shrinkage and swelling (Duchaufour, 1982; Szabolcs, 1989).

5.4.1 Dispersion and surface sealing

Dispersion is the process by which aggregated soil material loses its internal consistency and falls apart. When water is added to a soil, its osmotic potential may be different to that of the soil water. If a strong osmotic gradient exists between the recently added water and the water within soil aggregates then the aggregates are likely to disperse, this is often referred to as osmotic explosion (Gafni and Salingar, 1992). Saline soils are thus susceptible to aggregate destruction from fresh rainfall (Gafni and Salingar, 1992).

Saline soils tend to have a much greater ESP and SAR than non-saline soils. As a result, sodium is exchanged for Ca and Mg. Soils with a greater sodium content disperse more easily as the sodium ions form a more extensive diffuse layer around the clay particles than the divalent Ca and Mg (Marshall and Holmes, 1988). The presence of this diffuse layer prevents clay particles coming into close enough contact to cohere.

Dispersion of aggregates within the soil, and particularly on the surface has the effect of forming a surface seal which may greatly decrease the permeability of the surface layer, and hence reduce the infiltration rate of water (Agassi *et al.*, 1981; Lima *et al.*, 1990). If soils are also dispersed at depth then they may develop a massive non-aerated structure (Duchaufour, 1982). Agassi *et al.* (1981) and Lima *et al.* (1990) investigated the affect of adding irrigation water of different salinities to saline soil. They both found that for any level of soil ESP or SAR, the infiltration rate will decrease as the salinity of the irrigation water decreases. Agassi *et al.* (1981) identified threshold levels of EC of the irrigation water for each level of soil ESP below which clay dispersion and sealing was likely to occur. They also found that where EC of irrigation water exceeded 5.6 dS m^{-1}, clay dispersion was virtually independent of the ESP of the soil. When distilled water was added (EC = 0 dS m^{-1}) infiltration reached a minimum of 1.2 mm h^{-1}. Between these extreme values, infiltration rate of water with a low EC value was greater in soil with a low ESP.

5.4.2 Shrink-swell

Heavy clay soils, especially those dominated by montmorillonite, are susceptible to shrinkage and swelling. The presence of sodium ions in the clay matrix rather than Ca or Mg reduces the resistance of the clay to swelling. These high shrink-swell soils absorb little moisture when in a swelled state, and produce deep cracks in the dry condition. Van der Tak and Grismer (1987) investigated the infiltration and drainage from these high shrink-swell soils and found that the cracks were the dominant feature in soil water transport. They found that the soil matrix had a permeability of less than 1 mm day^{-1} but they found responses to irrigation in drains over 350 metres from the irrigation source only six to eight hours after irrigation. Saline water input to naturally shrink swell soils may increase cracking and thus increase drainage of the soil.

6.0 REMEDIATION TECHNIQUES

Soil salinity may be caused by excessive groundwater recharge, alterations to groundwater movements, changes to the soil leaching regime, and erosion of topsoils overlying saline subsoils. River salinity is caused by a combination of the above processes and the transport of salt by subsurface flow, drainage, and groundwater flow to streams and rivers. Use of appropriate management techniques for the remediation of soil and river salinity depends on an accurate identification of the causes of salinity.

6.1 Soil Salinity and Changes to Water Balance and Groundwater Movement

Most remediation techniques to alleviate soil salinity manipulate water balances in the landscape. In discussing each of these remediation techniques, three hydrological options will be considered:

(i) reduce groundwater recharge,
(ii) increase groundwater discharge, or
(iii) intercept groundwater in transmission areas

(Thorburn, 1991). Management of saline land for saline agriculture is a further management option; it will not be considered here as it is not a remediation technique.

6.1.1 Drainage and pumping

Drainage and pumping may serve to lower the watertable in a given area. Both methods, however, create a waste water disposal problem (refer to sections 4.3.6 and 4.6.2). Drainage and pumping are typically used in discharge zones and as interception devices immediately above discharge zones. Recharge reduction is not typically achieved by drainage or pumping.

Drainage may take a number of forms; surface drains may intercept runoff, subsurface shallow drains may divert subsurface flow and shallow groundwaters, and deep drains may redirect groundwater. Drains may consist of open trenches or furrows, or may be porous piping laid down within the regolith (George and Nulsen, 1986). Pumping may be used to remove shallow or deep groundwater. It is particularly useful for lowering deep groundwater levels, causing less saline shallow groundwater to recharge deep aquifers.

The effectiveness of an individual drain depends on the soil hydraulic properties as well as the suitability of the drain for the soil water conditions. In soils with a low permeability to water, each drain will only lower the watertable in a small strip on either side of it (Thorburn, 1991). Low permeability soils thus need closely spaced drains. However, Grismer (1993) found that the most effective drains were deeper and more widely spaced in an irrigated area. He suggested that the deeper drains were draining more saline groundwater and causing surface water to percolate downwards, leaching the surface soils. Drainage is especially important in irrigation areas. Ideally, all irrigation water is either evaporated, transpired or enters the surface and subsurface drainage network, thus there is no groundwater recharge.

George and Nulsen (1986) present the results of a number of different drainage studies using tube drainage and pumped drainage of saline seeps. They suggest that drainage may need to be combined with soil structure improvement through the application of gypsum. The presence of shallow perched watertables may reduce the effectiveness of drainage as water will continually be trapped near the soil surface (George and Nulsen, 1986). MPW (1988) suggest the use of tile drains, which are subsurface drains layed between tree rows which enhance transpiration.

Doering and Sandoval (1976) and George and Frantom (1991) have investigated the use of interceptor drains immediately above dryland saline seeps. They found that open and buried drains were very effective at locally lowering the watertable and preventing discharge, particularly on gently sloping ground.

The effectiveness of pumping is strongly influenced by soil permeability as water is being drawn out from a point source (MPW, 1988). Pumping is typically used to lower groundwater levels in discharge areas but may also be used to intercept groundwater.

6.1.2 Reforestation

The potential of trees to control salinity depends on their ability to use more water than annual crops or pasture (Morris and Thompson, 1983; Greenwood *et al.*, 1985). Schofield (1990) states that "[The] *essential premise of all the reforestation techniques is that revegetated areas will evaporate more water per unit area than the original forest, and so only part of the cleared area will need to be reforested to restore the hydrological balance.*" Trees transpire throughout the year, drawing water from deep within the regolith. Trees also intercept rainfall leading to evaporation of water from their leaves. Rainfall interception by trees may amount to as much as 30% of annual gross rainfall (Vertessy, pers. comm.). Thorburn *et al.* (1991), however, has found that under conditions where potential evapotranspiration exceeds rainfall, and where soil is of low permeability, recharge under crops and perennial shallow rooted pasture may not be greater than under native vegetation. In this case, pasture should be maintained, and other means sought for recharge reduction.

Reforestation of recharge areas poses no special salinity problems. However, recharge areas are typically large, and it may be difficult to determine the optimum location for tree planting. Morris and Thompson (1983), Schofield (1990) and, Salama, Laslett and Farrington (1993) present models for determining reforestation area and distribution.

Discharge areas are often much more easy to identify, and smaller in extent. Tree planting in or near discharge areas may reduce surface discharge by evapotranspiration. Reforestation of these areas, however, is often difficult as salt levels may prevent seed germination and cause seedling death. These areas are also often waterlogged, which increases the plant stress. Furthermore, the removal of water by transpiration may increase groundwater salinity levels thus aggravating the problem (Morris and Thompson, 1983). Chenopod shrubs, such as saltbush and bluebush, which are much more salt tolerant than most tree species, may be used to revegetate saline seeps (Malcolm, 1990). Reforestation in discharge areas, however, will not reduce groundwater recharge and therefore will not affect the supply of salt which may eventually kill the trees (Salama, Laslett and Farrington, 1993).

George (1991) describes a reforestation project to intercept groundwater before it enters a discharge area. A plantation was established with a mix of trees and shrubs that could cope with changes in the salinity regime and changes in their performance throughout their life history. Plants were established in belts of increasing salt tolerance with increasing proximity to the seep.

Evapotranspiration and salinity tolerance data are available for a wide variety of native Australian tree species, exotic tree species, saltbushes, and salt sensitive and salt tolerant crops (Greenwood and Beresford, 1979, 1980; Greenwood *et al.*, 1981, 1982, 1985; Morris and Thompson, 1983; Malcolm, 1990; George, 1991).

6.1.3 Cropping management and Perennial pasture

Judicious cropping management, the planting of deep rooted perennial pasture instead of annual pasture, and improvement of soil structure may decrease recharge and increase leaching of salts from the upper layers of the soil profile (Cooke and Willatt, 1983; MPW, 1988; Charman and Junor, 1989). MPW (1988) suggest that shortening the fallow, and increasing the area under perennial pasture may reduce groundwater accessions. Perennial pasture species such as lucerne, and phalaris are identified as suitable. There appears to be a general lack of information on the water balance under annual and perennial pastures (Webb, 1993). Webb (1993) suggests that there is no evidence that perennial pastures are effective at lowering groundwater levels. He implies that they may be effective at stopping recharge reduction under normal climatic conditions but are just as ineffective as annual pasture at stopping recharge resulting from significant storm events. Charman and Junor (1989) note that soil amendment with gypsum or other ameliorants to improve drainage may increase leaching and thus remove salt and allow vegetation establishment. Unfortunately, leaching means remobilisation of the salt, which must accumulate elsewhere in the landscape or contribute to river salinity.

6.1.4 Irrigation management

Irrigation management may reduce groundwater accessions and therefore reduce salinity. Irrigation water is used to supply plants with adequate fresh water for growth, and to leach salt from soil. Management of irrigation may involve the timing of irrigation; methods for the supply of irrigation water, including sprinkler systems, water flow patterns and the size and nature of irrigation bays; landforming, including lasergrading; and the construction of furrows (Fouss *et al.,* 1990; Hoffman *et al.,* 1990; Turral, 1993). An ideal irrigation system will be managed such that crops receive adequate water supply for maximum yields and the competing interests of minimising groundwater accessions and obtaining adequate leaching of the root zone are achieved.

The simplest type of irrigation is probably flooding. This is normally very inefficient because of inadequate surface levelling and should not be used where salinity is a problem as it involves substantial accessions to groundwater (Hoffman *et al.,* 1990). Modifications to this method of irrigation reduce water usage and in most cases reduce groundwater accessions. Landforming, including lasergrading, produces a level surface which reduces the requirement for excess water to be added in flood irrigation to ensure that all areas receive a minimum quantity of water (MPW, 1988).

The introduction of furrows may also reduce water consumption and hence accessions, but while the furrows are usually adequately leached, salt may accumulate in the seed beds leading to poor germination and reduced crop yields (Hoffman *et al.,* 1990).

Water supply for flood or furrow irrigation can be by continuous flow or surge flow. Turral (1993) has investigated surge flow, where water is supplied to irrigation bays in a series of surges instead of a continuous stream. Surge flow can reduce groundwater accessions if the surges are timed such that the soil surface dewaters and infiltration falls below the steady state rate between surges (Turral, 1993). The result of using surge flow is that more water reaches the far end of the field. Less water is therefore required to adequately irrigate those areas furthest from the water source. Irrigation by microsprinklers rather than overhead broadcast sprinklers can also reduce groundwater accessions as the water can be supplied to the plant roots where it is more likely to be taken up rather than in open spaces between plants (MPW, 1988).

Irrigation scheduling to meet the needs of crop plants can also greatly reduce groundwater accessions (MPW, 1988; Fouss *et al.,* 1990). The erratic spatial and temporal distribution of rainfall, however, needs to be taken into account in irrigation scheduling. It may be very difficult to maintain soil moisture content at optimum levels for crop growth when weather is unpredictable (Fouss *et al.*, 1990). Many crop plants grown in areas with shallow water tables derive some of their water supply from the groundwater. It is very difficult to quantify this groundwater contribution, but if it is not taken into account, irrigation may occur too frequently, leading to groundwater accessions (Fouss *et al.,* 1990).

6.1.5 Proactive techniques

Total Catchment Management (Charman and Junor, 1989) or *Integrated Catchment Management* (Llewellyn, 1985) are concepts which seek to integrate land degradation control and remediation with land management planning. This form of management may be successful in balancing resource utilisation with resource conservation. Catchment management is proactive as it seeks to prevent problems from occurring, as well as deal with existing land degradation problems. Irrigation reduction schemes and forestry department consultation with water boards, where works occur in regional recharge areas, may be essential elements in plans to avoid further salinity problems.

6.2 Soil Salinity and Erosion

Erosion of topsoils is a widespread problem not limited to saline affected areas. The same control measures can be used to reduce topsoil erosion on saline and non-saline land. Vegetation growing on salt affected land, however, may be less robust, and thus more susceptible to overgrazing. Furthermore, livestock may congregate at salt affected sites to consume salt on the soil surface. Charman and Junor (1989) suggest that these sites may need to be fenced off and revegetated with salt tolerant grasses and shrubs to prevent further erosion.

6.3 River Salinity

River salinity may be reduced by adopting local and regional measures to reduce accessions to groundwater and reduce groundwater discharge to the soil surface or to irrigation drains (Gutteridge, Haskins & Davey *et al.*, 1985). The remediation techniques for reduction of recharge, and interception as discussed in section 6.1 are also appropriate for reduction of river salinity. Some remediation techniques particularly appropriate to river salinity warrant further attention here.

6.3.1 Pumped bore interception

Groundwater pumping can be used to intercept flows to rivers in much the same way that it is used to intercept groundwater above saline seeps (section 6.1.1). Unfortunately these schemes produce a saline water disposal problem. Pumped bore interception schemes are in operation and more are planned for the river Murray (Murray-Darling Basin Ministerial Council, 1987b).

6.3.2 Drainage diversion

Irrigation water captured in the irrigation drainage system may be re-used. If salinity levels of the drainage waters are monitored, and kept below a threshold level of 5.0 dS m^{-1} then drainage diversion of this nature can be put into practice with no effect on the vegetation (Gutteridge, Haskins & Davey *et al.*, 1985). This practice will reduce the salt output via drainage discharge to streams and rivers, however, it may result in greater salt storage within the soil.

6.3.4 Dilution flows

Regulated rivers such as the Murray have a large capacity for water storage. This water may be released to dilute saline discharges during drier periods, or to maintain minimum water flows (Gutteridge Haskins & Davey, 1983). Unfortunately this means that the water is unavailable for irrigation or other water supply purposes. It also means that the natural flooding regimes are altered with consequent effects on the floodplain ecosystems.

6.4 Disposal of Saline Water

Drainage water, and water pumped out of saline aquifers needs to be disposed of in a way that does not contribute to salt loading elsewhere. Drainage effluent is a large source of river salinity (Gutteridge, Haskins & Davey, 1985). This saline water may be disposed of in evaporative basins, in deep aquifers or removed from the system by piping it to the sea. Saline water may also be de-salinised.

6.4.1 Evaporative basins

Evaporative basins may be used for disposal of saline waste water. Saline effluent is pumped into these basins and left to evaporate. Since the basins have no outlet, the salt is confined to the basin itself. Unfortunately, evaporative basins are not completely reliable. Some leakage of hypersaline water occurs into the local aquifer, and in heavy rains, evaporative basins may overflow. The water within evaporative basins also exerts pressure on the underlying groundwater which may force it towards the surface in the surrounding area (Chambers *et al.*, 1992).

6.4.2 Deep aquifer injection

Saline water may be injected into deep aquifers by pumping through sealed boreholes. This method may be effective at getting rid of a problem in the short term but it either contributes to aquifer recharge or causes displacement of groundwater into waterways. In the Mallee region of Victoria it has been found that deep aquifer injection may lead to an equivalent volume of highly saline groundwater being displaced into the river Murray (Nyah to SA border Community Salinty Group, 1992).

6.4.3 Pipeline to the sea

Saline water can be removed from the area entirely by construcing a pipeline to the sea. Such a project requires a saline water collection system, a pipe network, and possible pumping stations. Gutteridge, Haskins & Davey *et al.* (1990) have investigated the feasibility of constructing a pipe from the Murray irrigation region and suggest that it is not feasible for economic reasons.

6.4.4 De-salination

Soluble salts can be removed from solution by distillation, electrodialysis or by reverse osmosis. All three methods require the expenditure of substantial quantities of energy. De-salination produces two streams of water, one is fresh, and the other highly saline. This highly saline stream must still be disposed of so de-salination is only a method of reducing the volume of saline water.

7.0 SALINITY MEASUREMENT AND DETECTION TECHNIQUES

Many techniques are used to quantify soil water salinity and detect saline areas. Field measurements and remote sensing have perhaps the most application in salinity detection and remediation. This section will concentrate first on the use of field techniques for salinity detection and the determination of soil water electrical conductivity, an analogue of salinity. Detection of salinity and groundwater recharge and discharge areas by remote sensing will also be examined. This section will not look at laboratory techniques, which may be found in many adequate references such as Salinity Lab Staff (1954), Klute (1986) and Page (1986).

7.1 Field Detection and Measurement

Field measurements may be used to determine the salinity of soil water, to detect saline areas, and to determine the location of groundwater recharge and discharge areas within a catchment. This section covers some of the most commonly used field techniques for detecting and quantifying salinity on the soil surface and at depth.

7.1.1 Soil water conductivity

The salinity of soil water can be determined in the field by measuring the electrical conductivity (EC) of soil water extractions at 1:1 or 1:5 dilutions, or directly on a saturated soil paste. Salinity Lab Staff (1954) outline methods for both of these techniques. Rhoades *et al.* (1989a) recommend the use of the soil paste method. They have derived a new calibration for determining the EC of soil water from EC of the soil paste.

7.1.2 Resistivity measurement

Rhoades and Ingvalson (1971) have developed a method for determining soil salinity by using four electrodes set in a straight line with equal separation to measure soil resistance. The technique is quick and simple to use, requiring no lab time (Rhoades and Ingvalson, 1971). Halvorson and Rhoades (1976) have used the technique to accurately map discharge areas, shallow flowing saline groundwaters, and recharge areas.

7.1.3 Electromagnetic induction devices

Fixed frequency electromagnetic instruments (Geonics EM31, EM34 and EM38) have been used to determine the electrical conductivity, and hence salinity, of soil water at different depths within the soil (Engel *et al.*, 1989; Rhoades *et al.*, 1989b; Richardson *et al.*, 1992). These devices measure the depth-weighted mean bulk electrical conductivity, which is mainly dependent on salt storage, soil texture and water content (Richardson *et al.*, 1992).

These frequency-domain electromagnetic induction devices consist of a transmitter coil and a receiver coil held at a known separation in either vertical or horizontal orientation. The transmitter coil produces a primary electromagnetic field which induces a secondary field in the subsurface (soil) material. The receiving coil measures both the primary and secondary EM fields. The ratio of the two fields provides a measure of the apparent depth-weighted electrical conductivity of the soil in dS m^{-1}. The reading on the receiver coil is depth-weighted such that the surface layers in a homogenous soil contribute most of the secondary field. The greater the spacing between the coils, the greater the depth to which the field penetrates. The orientation of the coils also affects the effective depth of the secondary magnetic field. Coils in the vertical orientation provide electromagnetic measurements to greater depth.

There are many different EM devices, however three of these are particularly used for salinity based studies: Geonics EM31, EM34, and EM38. The EM31 has coils at a fixed spacing of 3.66m. The device measures most effectively within 5 metres of the surface. The EM34 consists of two separate coils, and is used for electromagnetic detection to a depth of 7.5-60 m. The EM38 is a fixed coil device for use in shallow soils of up to 1 to 1.5 metres in depth. All three devices have been used successfully in the mapping of salinity in the field and for the detection of recharge and discharge zones.

Researchers have derived numerous empirical relationships for equating apparent conductivity to actual conductivity (Williams and Baker, 1982; Rhoades *et al.*, 1989b). These relationships rely on the ability to assume that one or more factors contributing to the apparent conductivity is constant throughout the survey area.

7.2 Detection of Salinity by Remote Sensing

Photographic and photogrammetric interpretation are effective tools for mapping the presence of soil salinity (Nothrop, 1982; Harker, 1989). Salinity is detected through remote sensing by direct observation of soil salting, and by associated soil and vegetation reflectance patterns that have been identified to indicate salinity. Salinity may be obvious, but may also be difficult to detect due to the wide range of spectral reflectance caused by different soil, water and vegetation conditions. Remote sensing is thus often augmented by field work to check the validity of remote sensing data interpretation (Hill, 1992).

Harker (1989) considers that there are three main elements to a successful remote sensing program:

(i) establishment of appropriate mapping terms of reference,
(ii) determination of mapping criteria including salinity classes, and
(iii) appropriate use of interpretation aids.

Establishment of appropriate terms of reference and mapping criteria enable the worker to identify the type of remote sensing required, the degree of specificity in data analysis, and the resolution of the survey. Determination of mapping criteria is essential to limit data interpretation to a manageable dataset, and to provide consistent interpretation based on agreed salinity classes. Appropriate use of interpretation aids is essential to the recognition of salinity.

Aerial photography, video imagery, and satellite imagery are the primary remote sensing vehicles in use today. Images are commonly taken using visible light or infra red; the Landsat thematic mapping bands cover from near infra red to ultra violet. Le Vine *et al.* (1991) suggest that microwave radiometry, which is now being used for the measurement of soil moisture and ocean salinity, may also be applicable to the detection of land salinity. Video imagery in the infra red (composite colour) and narrow band red wavelengths has proven to be successful in detecting saline soils in both agricultural and rangeland environments (Everitt *et al.*, 1988). Each of these images requires different interpretation.

Indicators such as landscape location, field boundaries, high watertable signs, plant growth patterns, and changes in soil colour may be used to interpret visual light images (Harker, 1989). Geological features associated with recharge or discharge zones such as lineaments, basements highs, dykes and veins may be readily mapped because of their contrast with the surrounding landscape (Salama *et al.*, 1993c), however, weed infestation, eroded soils, land levelling scars and soil boundary changes may confuse visual light image interpretation. Infra red images show plant activity. Plant stress levels associated with saline areas may be readily identified as paler pink areas in CIR (artificially coloured infra red) photographs within dark red areas of healthy growing plants. Nothrop (1982) describes the use of Landsat for detection of irrigation area salinity. Band reflectance algorithms to identify saline land have been derived for the multi spectral scanning radiometer (Nothrop, 1982).

Remote sensing, however, may not prove to be sufficient for the identification of saline land or recharge and discharge areas. Hill (1992) suggests an integrated image analysis and GIS approach incorporating field mapping to verify land classification algorithms.

8.0 CONCLUSION

The salinisation of soil and water is a severe problem in many regions of Australia. Substantial areas of low lying prime agricultural land are affected by saline groundwater discharge and shallow watertables. This is especially the case in the irrigation districts of the Murray-Darling basin, and Western Australia. Saline streams and rivers are also a problem in these areas.

Salt exists in huge quantities throughout the landscape. Salt is released within the soil and bedrock by chemical weathering, from previously marine sedimentary basins, and is deposited on the soil surface by rainfall and dry fallout. It may be brought to the soil surface or transported into rivers and streams by natural processes. In Australia, there are many natural examples of soil and water salinity. However, human activity has changed the salt balance, creating new salt movement pathways, enhancing existing salt movement and facilitating salt discharge.

European settlement of Australia has resulted in a new or altered ecology over extensive regions of the continent. Conversion of forests and woodlands to agricultural land, in particular, has dramatically altered the water balance of both local and regional groundwater systems. Many previously forested upland regions now have enhanced recharge. This excess groundwater dissolves salt and transports it to lowland regions where it often discharges onto the soil surface or into streams and rivers.

Excess salt adversely affects plants and animals, eventually leading to their death. The salinisation of wetlands and waterways particularly may have substantial effects on these ecosystems, changing the populations of both resident and migratory birds and fishes.

Research into salinity remediation has resulted in the development of many techniques to reduce saline seepage and salt transport to rivers. These techniques have focussed on recharge and discharge areas, and on groundwater interception using such techniques as reforestation, afforestation, drainage and interception. Recently, research has been directed towards *Total Catchment Management.* This approach may be most fruitful in reducing salinity where there are conflicting land use interests and landowners with different salinity problems. Salinity research is also focussing on saline area detection and the detection of groundwater movements. Novel integrated approaches using GIS and limited field appraisal of remote sensing data interpretation algorithms may prove to be useful in salinity detection and management.

An integrated approach to salinity management and the management of saline waterways incorporating catchment planning is likely to be the most effective method of dealing with salinity problems. Salinisation must be seen as a land management and planning problem which transcends local and property boundaries. Further research is particularly needed on designing catchment plans to reduce recharge, contain discharge, and lower watertables.

APPENDIX A: EARLY WARNING SIGNS & RECOGNITION OF SALINITY IN THE FIELD.[1]

The initial signs of salinity may be difficult to detect. Areas mildly affected by salinity or incipient salting can be identified by reduced yields or a lack of vigour of the more sensitive crop plants such as subterranean clover. Plants may adopt a stunted growth form and experience leaf tip burn and a yellowing of leaves commonly seen in nitrogen deficient crops. This may be followed by the replacement of more productive species with sea barley grass (*Hordeum maritimum*) and buck's horn plantain (*Plantago coronopus*) (Matters and Bozon, 1989). The increase in salinity is also likely to be accompanied by the growth and spread of salt tolerant reeds and sedges such as spiny rush (*Juncus acutus*) and toad rush (*J. bufonius*).

Further salting may be observed by the presence of salt stains on the dry soil surface, small bare areas, and the development of small scalds. The leaf colour of vegetation may change from a healthy green to a slightly yellow or orange. Clover is usually absent. (Matters and Bozon, 1989). Salt sensitive species are likely to be completely replaced by salt tolerant species including salt bushes (*Atriplex sp.*) or ruby salt bush (*Enchyaena tomentosa*) (Matters and Bozon, 1989).

Salting may also be recognised by the progressive dieback of trees. Trees typically have much deeper roots than pasture or crop species and as a result they draw water from deeper within the regolith. Tree species are thus likely to encounter rising saline groundwaters before other plant species (ACIL, 1983). Paperbark species such as *Melaleuca ericifolia* or *M. halmaturorum* may continue to grow when other tree species die back.

Areas severely affected by salinity may have a characteristic suite of vegetation, often minimal ground cover, and surface salt crusting (fig A1). Often only two to three species will dominate the area. Typical species include the beaded glasswort (*Sarcocornia quinqueflora*) and samphire (*Haloscaria pergranulata*) (Matters and Bozon, 1989).

---

[1] Species mentioned are suitable for Victorian field identification only.

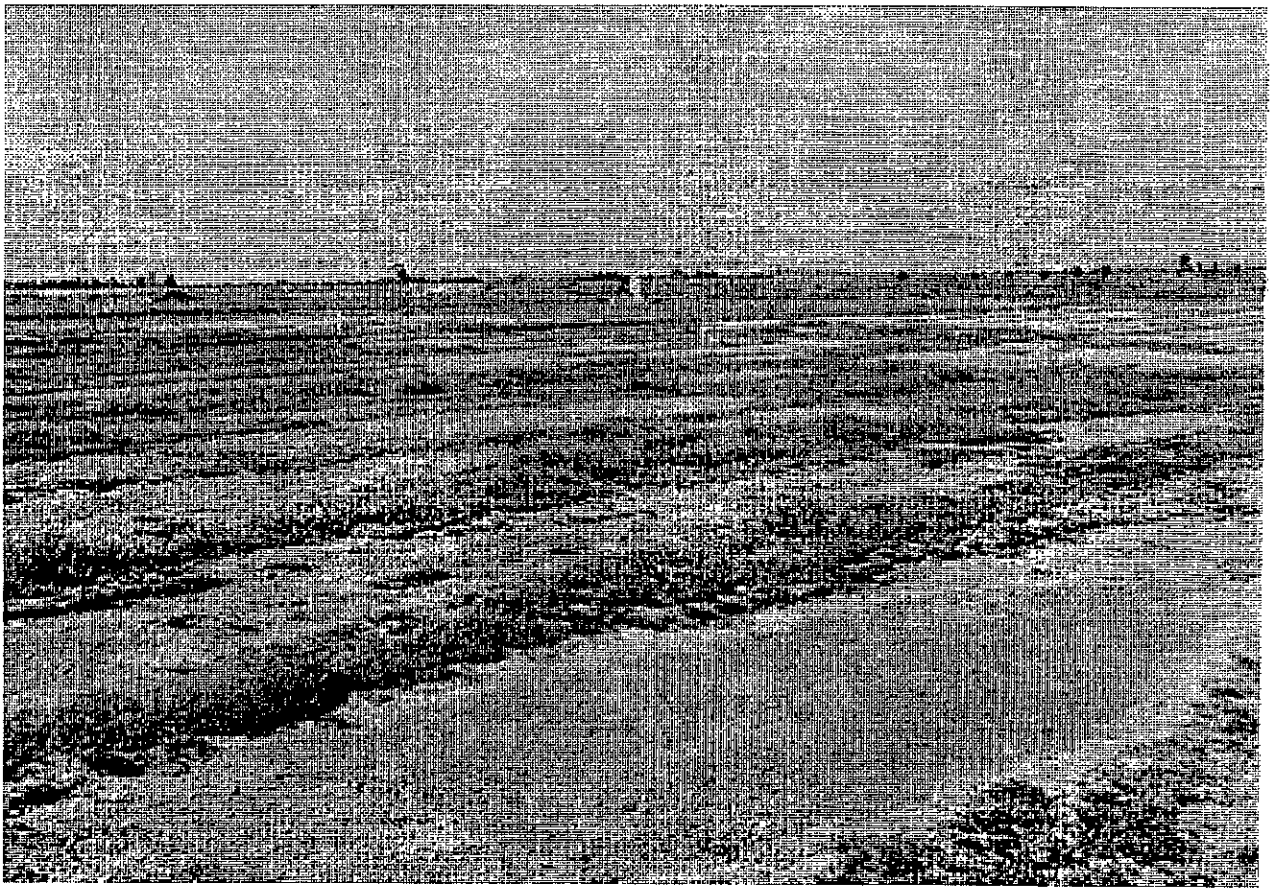

Figure A1: Poor vegetative growth and scalding indicating salt effected land.

High EC levels can be expected in saline soil, salt may also be visible in the soil profile as individual crystals, particularly lining cracks and small voids within the soil. The soil may have a characteristic fluffy appearance when dry. Other common soil features are a mottling or gleyed colour indicating the reduction of iron in the soil due to the persistence of high watertables (Thorburn, 1991).

A useful field guide to the identification of saline areas in the field in Victoria is: *Spotting Soil Salting* (Matters and Bozon, 1989).

REFERENCES

ACIL Australia (1983) *Causes, Extent and Effects of Salinity in Victoria.* Salinity Committee, Victorian Parliament: Melbourne.

Agassi, M., Shainberg, I. and Morin, J. (1981) Effect of Electrolyte Concentration and Soil Sodicity on Infiltration Rate and Crust Formation. *Soil Sci. Soc. Am. J.*, **45**: 848-851.

Anderson, J.R. (1991) *The Implications of Salinity and Salinity Management Initiatives, on Fish and Fish Habitat in the Kerang Lakes Management Area.* Arthur Rylah Institute for Environmental Research Technical Report No. 103. Dept. Conservation & Environment: Melbourne.

Beke, G.J., Entz, T. and Graham, D.P. (1993) Long-Term Quality of Shallow Ground Water at Irrigated Sites. *J. Irrig. Drain. Eng.*, **119**: 116-128.

Bernstein, L. (1975) Effects of Salinity and Sodicity on Plant Growth. *Ann. Rev. Phytopath.*, **13**: 295-312.

Bettenay, E., Blackmore, A.V. and Hingston, F.J. (1964) Aspects of the Hydrologic Cycle and Related Salinity in the Belka Valley, Western Australia. *Aust. J. Soil Res.*, **2**: 187-210.

Blackburn, G. and McLeod, S. (1983) Salinity of Atmospheric Precipitation in the Murray-Darling Drainage Division, Australia. *Aust. J. Soil Res.*, **21**: 411-434.

Bressler, E., McNeal, D.L. and Carter, D.L. (1982) *Saline and Sodic Soils, Principles-Dynamics-Modelling.* Springer-Verlag: Berlin.

Campaspe West Salinity Implementation Group (1992) *Campaspe West Draft Salinity Management Plan.* Salt Action.

Chambers, L.A., Williams, B.G., Barnes, C.J. and Wasson, R.J. (1992) The Effects of Irrigation Waste Water Disposal in a Former Discharge Zone of the Murray Basin, Australia. *J. Hydrol.*, **136**: 303-332.

Charman, P.E.V. and Junor, R.S. (1989) Saline Seepage and Land Degradation - a New South Wales Perspective. *BMR J. Aust. Geol. Geophys.*, **11**: 195-203.

Close, A. (1990) River Salinity. In: *The Murray.* N. Mackay, and D. Eastburn (Eds), Murray-Darling Basin Commission: Canberra. pp 127-144.

Cooke, J.W. and Willatt, T.S. (1983) Land Management, Water Use and Salinity Prevention, *Proc. R. Soc. Vic.*, **95**: 117-121.

Doering, E.J. and Sandoval, F.M. (1976) Hydrology of Saline Seeps in the Northern Great Plains. *Trans. Am. Soc. Agric. Engrs.*, **19**: 856-861.

Duchaufour, P. (1982) *Pedology, Pedogenesis & Classification.* Trans. T.R. Paton. George Allen and Unwin: London.

Dyson, P.R. (1983) Dryland Salting and Groundwater Discharge in the Victorian Uplands, *Proc. R. Soc. Vic.*, **95**: 113-116.

Emerson, W.W. (1967) A Classification of Soil Aggregates Based on their Coherence in Water. *Aust. J. Soil Res.*, **5**: 47-57.

Engel, R., McFarlane, D.J. and Street, G.J. (1989) Using Geophysics to Define Recharge and Discharge Areas Associated with Saline Seeps in South Western Australia. In: *Groundwater Recharge. Proc. Symp. on Groundwater Recharge,* M.L. Sharma (Ed). A.A. Balkema: Rotterdam. pp 25-39.

Everitt, J.H, Escobar, D.E., Gerbermann, A.H. and Alaniz, M.A (1988) Detecting Saline Soils With Video Imagery. *Photogrammetric Engineering & Remote Sensing*, **54**: 1283-1287.

Fouss, F.L., Skaggs, R.W., Ayars, J.E. and Belcher, H.W. (1990) Watertable Control and Shallow Groundwater Utilization. In: *Management of Farm Irrigation Systems,* G.J. Hoffman, T.A. Howell and K.H. Solomon (Eds). ASAE: St Joseph, MI. pp 783-824.

Gafni, A. and Salingar, Y. (1992) Hydraulic and Salinity Regime of Two Affected Sites in the Yizre'el Valley, Israel. *Hydrol. Processes*, **6**: 55-65

George, P.R. and Nulsen, R.A. (1986) Saltland Drainage: case studies. *J. Agric. W. Aust.*, **26**: 115-118.

George, R.J. (1991) Reclaiming Sandplain Seeps by Planting Trees, *J. Agric. W. Aust.*, **32**: 18-23.

George, R.J. (1992) Groundwater Processes, Sandplain Seeps and Interactions with Regional Aquifer Systems in South Western Australia. *J. Hydrol.*, **134**: 247-271.

George, R.J. and Frantom P. (1991) Drainage of Sandplain Seeps for Salinity Control and Stock Watersupply. *J. Agric. W. Aust.*, **32**: 88-93.

Greenwood, E.A.N. and Beresford, J.D. (1979) Evaporation from Vegetation in Landscapes Developing Secondary Salinity Using the Ventilated Chamber Technique. I. Comparative Transpiration from Juvenile *Eucalyptus* above Saline Groundwater Seeps. *J. Hydrol.*, **42**: 369-382.

Greenwood, E.A.N. and Beresford, J.D. (1980) Evaporation from Vegetation in Landscapes Developing Secondary Salinity Using the Ventilated Chamber Technique. II. Evaporation from *Atriplex* Plantations Over a Shallow Saline Watertable. *J. Hydrol.*, **45**: 313-319.

Greenwood, E.A.N., Beresford, J.D. and Bartle, J.R. (1981) Evaporation from Vegetation in Landscapes Developing Secondary Salinity Using the Ventilated Chamber Technique. III. Evaporation from a *Pinus radiata* Tree and the Surrounding Pasture in an Agroforestry Plantation. *J. Hydrol.*, **50**: 155-166.

Greenwood, E.A.N., Beresford, J.D., Bartle, J.R. and Barron, R.J.W. (1982) Evaporation from Vegetation in Landscapes Developing Secondary Salinity Using the Ventilated Chamber Technique. IV. Evaporation from a Regenerating Forest of *Eucalyptus wandoo* on Land Formerly Cleared for Agriculture. *J. Hydrol.*, **58**: 357-366.

Greenwood, E.A.N., Klein, L, Beresford, J.D. and Watson, G.D. (1985) Differences in Annual Evaporation Between Grazed Pasture and *Eucalyptus* species in Plantations on a Saline Farm Catchment. *J. Hydrol.*, **78**: 261-278.

Grismer, M.E. (1993) Subsurface Drainage System Design and Drain Water Quality. *J. Irrig. Drain. Eng.*, **119**: 537-543.

Gutteridge Haskins & Davey (1983) *Application of Salinity Control Techniques in Victoria.* Victorian Parliament: Melbourne.

Gutteridge Haskins & Davey, ACIL Australia, D. Naunton and Co. (1985) *Study of Future Management of Barr Creek and Catchment.* Rural Water Commission: Melbourne.

Gutteridge, Haskins & Davey, ACIL Australia and Australian Groundwater Consultant (1990) *A Pipeline to the Sea - Pre Feasibility Study.* Report to Murray-Darling Basin Commission.

Halvorson, A.D. and Rhoades, J.D. (1976) Field Mapping Soil Conductivity to Delineate Dryland Saline Seeps with Four-Electrode Technique. *Soil Sci. Soc. Am. J.*, **40**: 571-575.

Harker, D. (1989) Basic Factors Essential to the Consistent Detection and Mapping of Saline/Waterlogged Lands. In: *IGARSS '89. 12th Canadian Symposium on Remote Sensing*, Vol 5. IEEE: New York. pp 2742-2746.

Hart, B.T., Bailey, P., Edwards, R., Hortle, K., James, K., McMahon, A., Meredith, C., Swadling, K. (1990) Effects of Salinity on River, Stream and Wetland Ecosystems in Victoria, Australia. *Water Res.*, **24**: 1103-1117.

Herczeg, A.L., Simpson, H.J. and Mazor, E. (1993) Transport of Soluble Salts in a Large Semiarid Basin: River Murray, Australia. *J. Hydrol.*, **144**: 59-84.

Hill, S. (1992) Report on the Application of Modern Technology to the Mapping of Recharge Areas, to Assist Salinity Management and Planning. *Aust. J. Soil & Water Cons.*, **5**: 29-34.

Hingston, F.J. and Gailitis, V. (1976) The Geographic Variation of Salt Precipitated over Western Australia. *Aust. J. Soil Res.*, **14**: 319-335.

Hoffman, G.J., Rhoades, J.D., Letey, J. and Fang Sheng (1990) Salinity Management. In: *Management of Farm Irrigation Systems,* G.J. Hoffman, T.A. Howell and K.H. Solomon (Eds). ASAE: St Joseph, MI. pp 667-715.

Isbell, R.F., Reeve, R. and Hutton, J.J. (1983) Salt and Sodicity. In: *Soils: An Australian Viewpoint*, Division of Soils, CSIRO. CSIRO:Melbourne/ Academic Press: London. pp 107-117.

Johnston, C.D. (1987) Distribution of Environmental Chloride in Relation to Subsurface Hydrology. *J. Hydrol.*, **94**: 67-88.

Keaton, W.T. and Gould, J.L. (1986) *Biological Science*, 4th edn, W.W. Norton: New York.

Kevin, P.M. (1993) *Groundwater and Salinity Processes in the Uplands of the Loddon River Catchment.* Centre for Land Protection Research Technical Report No. 5. Dept. Conservation & Natural Resources: Melbourne.

Klute, A. (Ed) (1986) *Methods of Soil Analysis, Pt 1: Physical and Mineralogical Methods*, 2nd edn. Am. Soc. Agronomy: Madison, Wis.

Levitt, J. (1980) *Responses of Plants to Environmental Stresses, Vol II: Water, Radiation, Salt and Other Stresses*, 2nd edn. Academic Press: New York.

Lima, L.A., Grismer, M.E. and Nielson, D.R. (1990) Salinity Effects on Yolo Loam Hydraulic Properties. *Soil Sci.*, **150**: 451-458.

Llewellyn, P.V. (1985) *A multi-criteria analyis of salinity control in the Wellington catchment in South Western Australia.* MSc Thesis, Faculty of Agric., Uni. W.Aust.: Perth.

Maas, E.V. and Hoffman, G.J. (1977) Crop Salt Tolerance - Current Assessment. *J. Irrig. Drain. Div. Proc. ASCE*, **103**: 115-134.

Malcolm, C.V. (1990) Saltland Agronomy in Western Australia, an overview. In: *Revegetation of Saline Land.* Proc. Workshop Inst. Irrig. and Salinity Research, Tatura. B.A. Myers, D.W. West (Eds). Dept Agric. and Rural Affairs: Tatura. pp 27-35.

Marshall, T.J. and Holmes, J.W. (1988) *Soil Physics*, 2nd edn. Cambridge Uni. Press: Cambridge.

Matters, J. and Bozon, J. (1989) *Spotting Soil Salting*. Dept Cons. Forests & Lands: Melbourne.

Maunsell and Partners (1979) *Murray Valley Salinity and Drainage, Volume 1: Report.* Murray Valley Steering Committee.

Mazor, E. and George, R.J. (1992) Marine Airborne Salts Applied to Trace Evapotranspiration, Local Recharge and Lateral Groundwater Flow in Western Australia. *J. Hydrol.*, **139**: 63-77.

McFarlane, D., Engel, R., Ryder, A. and Eales, M. (1990) Level Banks Used to Decrease Waterlogging Can Increase Salinity. *J. Agric. W. Aust.*, **31**: 74-77.

McLeod, A.J. (1993) *Measurement and Modelling of Irrigation Channel Seepage in Northern Victoria.* Unpublished PhD thesis: Uni. Melb.

Morris, J.D. and Thompson, L.A.J. (1983) The Role of Trees in Dryland Salinity Control. *Proc. R. Soc. Vic.*, **95**: 123-131.

MPW Australia (1988) *Physical Control Options*, State Salinity Strategy Background Report No. 24. Dept Water Resources: Melbourne.

Murray-Darling Basin Ministerial Council (1987a) *Murray-Darling Basin Environmental Resources Study.* State Pollution Control Commission: Sydney.

Murray-Darling Basin Ministerial Council (1987b) Salinity and Drainage Strategy Background Paper. MDBMC.

Northcote, K.H. and Skene, J.K.M. (1972) *Australian Soils with Saline and Sodic Properties*. CSIRO Soil Publ. No. 27. CSIRO: Melbourne.

Nothrop, L.J. (1982) *Landsat Detection of Irrigation Area Salinity.* Aust. Water Res. Council Occassional Papers No. 4. AGPS: Canberra.

Nulsen, R.A. (1986) Hillside Seepages, *J. Agric. W. Aust.*, **26**: 128-129.

Nyah to South Australian Border Community Salinity Group (1992) *Background Report, Draft Salinity Management Plan from Nyah to the South Australian Border*. Rural Water Comm. & Dept. Food and Agric.: Sunraysia.

Page, A. (Ed) (1986) *Methods of Soil Analysis, Pt 2: Chemical and Microbiological Properties*, 2nd Edn. Am. Soc. Agronomy: Madison, Wis.

Peck, A.J. (1978) Salinization of Non-Irrigated Soils and Associated Streams: A Review. *Aust. J. Soil Res.*, **16**: 157-168.

Peck, A.J. and Williamson, D.R. (1987) Effects of Forest Clearing on Groundwater. *J. Hydrol.*, **94**: 47-65.

Resource Assessment Commission (1992) *Forest and Timber Inquiry, Final Report, Volume 2A*. AGPS: Canberra.

Raupach, M. (1983) Soil Solution and Silicate Clay Mineral Reactions. In: *Soils: An Australian Viewpoint*, Division of Soils, CSIRO. CSIRO:Melbourne/ Academic Press: London. pp 389-400.

Rhoades, J.D. and Ingvalson, R.D. (1971) Determining Salinity in Field Soils with Soil Resistance Measurements. *Soil Sci. Soc. Am. Proc.*, **35**: 54-60.

Rhoades, J.D., Lesch, S.M., Shouse, P.J. and Alves, W.J. (1989b) New Calibrations for Determining Soil Electrical Conductivity-Depth Relations from Electromagnetic Measurements. *Soil Sci. Soc. Am. J.*, **53**: 74-77.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J. and Alves, W.J. (1989a) Estimating Soil Salinity from Saturated Soil-Paste Electrical Conductivity. *Soil Sci. Soc. Am. J.*, **53**: 428-433.

Richardson, S.B., McCarthy, D.G., Henschke, C.J. and Narayan, K. (1992) Determining the Potential of Recharge Reduction for Control of Dryland Salinity. In: *Hydrology and Water Resources Symposium*. Inst. Eng. Aust. Nat. Conf. Publ. 93/14. pp 67-73.

Ruprecht, J.K. and Schofield, N.J. (1991) Effects of Partial Deforestation on Hydrology and Salinity in High Salt Storage Landscapes. *J. Hydrol.*, **129**: 19-38.

Salama, R.B., Farrington, P, Bartle., G.A. and Watson, G.D. (1993a) The Chemical Evolution of Groundwater in a First-Order Catchment and the Process of Salt Accumulation in the Soil Profile. *J. Hydrol.*, **143**: 233-258.

Salama, R.B., Farrington, P, Bartle., G.A. and Watson, G.D. (1993b) Distribution of Recharge and Discharge Areas in a First-Order Catchment as Interpreted from Water Level Patterns. *J. Hydrol.*, **143**: 259-277.

Salama, R.B., Farrington, P, Bartle., G.A. and Watson, G.D. (1993c) The Role of Geological Structures and Relict Channels in the Development of Dryland Salinity in the Wheatbelt of Western Australia. *Aust. J. Earth Sci.*, **40**: 45-56.

Salama, R.B., Laslett, D. and Farrington, P. (1993) Predictive Modelling of Management Options for the Control of Dryland Salinity in a First-Order Catchment in the Wheatbelt of Western Australia. *J. Hydrol.*, **145**: 19-40.

Salinity Committee (1984) *Salt of the Earth: Final Report on The Causes, Effects and Control of Land and River Salinity in Victoria.* Victorian Parliament: Melbourne.

Salinity Lab Staff (1954) *Diagnosis and Improvement of Saline and Alkali Soils.* USDA Agriculture Handbook No. 60. USDA: Washington.

Salisbury, F.B. and Ross C.W. (1992) *Plant Physiology*, 4th edn. Wadsworth: California.

Sami, K. (1992) Recharge Mechanisms and Geochemical Processes in a Semi-Arid Sedimentary Basin, Eastern Cape, South Africa. *J. Hydrol.*, **139**: 27-48.

Schofield, N.J. (1990) Determining Reforestation Area and Distribution for Salinity Control. *Hydrol. Sci J.*, **35**: 1-19.

Schofield, N.J. and Ruprecht, J.K. (1989) Regional Analysis of Stream Salinisation in Southwest Western Australia. *J. Hydrol.*, **112**: 19-39.

Szabolcs, I. (1979) *Review of Research on Salt-Affected Soils.* UNESCO: Paris.

Szabolcs, I. (1989) *Salt-Affected Soils*. CRC Press: Florida.

Thorburn, P. (1991) Occurence and Management of Dryland Salinity on the Darling Downs, Queensland. *Aust. J. Soil and Water Cons.*, **4**: 26-32.

Thorburn, P.J., Cowie, B.A. and Lawrence, P.A. (1991) Effects of Land Development on Groundwater Recharge Determined from Non-Steady Chloride Profiles. *J. Hydrol.,* **124**: 43-58.

Thorburn, P.J., Walker, G.R., Woods, P.H. (1992) Comparison of Diffuse Discharge in Shallow Watertables in Soils and Salt Flats. *J. Hydrol.*, **136**: 253-274.

Tucker, B.M. (1983) Basic Exchangeable Cations. In: *Soils: An Australian Viewpoint,* Division of Soils, CSIRO. CSIRO:Melbourne/ Academic Press: London. pp 401-416.

Turner, J.V., Arad, A. and Johnston, C.D. (1987) Environmental Isotope Hydrology of Salinized Experimental Catchments. *J. Hydrol.*, **94**: 89-107.

Turral, H. (1993) *The Evaluation of Surge Flow in Border Irrigation (With Special Reference to Cracking Soils).* Unpublished PhD thesis: Uni. Melb.

van der Tak, L.D. and Grismer, M.E. (1987) Irrigation, Drainage and Soil Salinity in Cracking Soils. *Trans. Am. Soc. Agric. Engrs.*, **30**: 740-744.

le Vine, D.M. , Hillard, L.M., Swift, C.T., Ruf, C.S. and Garrett, L.B. (1991) A Synthetic Aperture Microwave Radiometer to Measure Soil Moisture and Ocean Salinity from Space. In: *IGARSS '91. Remote Sensing: Global Management for Earth Management,* Vol 2. IEEE: New York. pp 975-978.

Webb, A. (1993) *Review of the Status of Technical Options for Salinity Control in Southern Victoria.* Salt Action.

Williams, B.G. and Baker, G.C. (1982) An Electromagnetic Induction Technique for Reconnaissance Surveys of Soil Salinity Hazards. *Aust. J. Soil Res.* **20**: 107-118.

Williamson, D.R., Stokes, R.A. and Ruprecht, J.K. (1987) Response of Input and Output of Water and Chlorine to Clearing for Agriculture. *J. Hydrol.*, **94**: 1-28.

Wood, W.E. (1924) Increase of Salt in Soil and Streams Following the Destruction of the Native Vegetation. *J. R. Soc. West. Aust.*, **10**: 35-47.

Zecharias, Y.B. and Brutsaert, W. (1988) The Infuence of Basin Morphology on Groundwater Outflow. *Water Resources Res.*, **24**: 1645-1650.

The Cooperative Research Centre for Catchment Hydrology is a cooperative venture formed under the Commonwealth CRC Program between:

Bureau of Meteorology

CSIRO Division of Water Resources

Department of Natural Resources and Environment

Goulburn-Murray Water

Melbourne Water

Monash University

Murray-Darling Basin Commission

Southern Rural Water

The University of Melbourne

Wimmera-Mallee Water

Associates
CSIRO Division of Soils
State Forests of NSW

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Centre Office
Department of Civil Engineering, Monash University, Clayton, Victoria 3168, Australia.
Telephone: (03) 9905 2704 Facsimile: (03) 9905 5033 International: +61 3 9905 2704
http://www-civil.eng.monash.edu.au/centres/crcch/