



1-3-1998

Groundwater trends in the agricultural area of Western Australia

R A. Nulsen

Follow this and additional works at: <https://library.dpird.wa.gov.au/rmtr>



Part of the [Agriculture Commons](#), [Natural Resources Management and Policy Commons](#), [Soil Science Commons](#), and the [Water Resource Management Commons](#)

Recommended Citation

Nulsen, R A. (1998), *Groundwater trends in the agricultural area of Western Australia*. Department of Primary Industries and Regional Development, Western Australia, Perth. Report 173.

<https://library.dpird.wa.gov.au/rmtr/158>

Important Disclaimer

No representations or warranties are made with respect to the currency, accuracy, reliability, completeness or suitability for any particular purpose of the information provided. The Chief Executive Officer of the Department of Primary Industries and Regional Development and the State of Western Australia accept no liability whatsoever by reason of negligence or otherwise arising from the use or release of this information or any part of it. Copyright © State of Western Australia (Department of Primary Industries and Regional Development), 2025.

Caution – Information in reports and other material could include inaccuracies, be outdated or be incomplete. Please ensure you verify any critical details with up-to-date sources before relying on the information.



ISSN 1039-7205
March 1998



Groundwater Trends in the Agricultural Area of Western Australia

**Catchment Hydrology Group
edited by Bob Nulsen**

Resource Management Technical Report No.173

Disclaimer

The contents of this report were based on the best available information at the time of publication. It is based in part on various assumptions and predictions. Conditions may change over time and conclusions should be interpreted in the light of the latest information available.

© Director General, Department of Agriculture Western Australia 2004

Table of Contents

Introduction - Bob Nulsen	1
Northern Agricultural Region - Russell Speed and Edwina Lefroy	4
Central Wheatbelt Region - Fay Lewis	13
Eastern Wheatbelt Region - Cecelia McConnell.....	29
South-West and Upper Great Southern Region - Richard George and Don Bennett	41
Western South Coast Region - Ruhi Ferdowsian, Don McFarlane and Arjen Ryder	58
Eastern South Coast Region - Rod Short, Gerry Skinner and Steven Gee	81

Introduction

Bob Nulsen

In 1994 it was estimated that salinity affected more than 1.8 million ha of agricultural land in Western Australia (Ferdowsian *et al.* 1996). This area was predicted to expand to over three million ha by about 2020 and, if nothing is done to stem the expansion, to eventually affect some six million ha, or 30% of the agricultural land in the state.

Damaging levels of salt accumulation in the root zone of both native and introduced plants can generally only occur when the groundwater levels are relatively close to the surface. Hence, the essence of addressing the problem is to prevent watertables rising which is occurring under most of the agricultural areas. The rates of rise vary from less than 5 cm/year to about 100 cm/year in extreme instances. Even under isolated patches of remnant vegetation watertables are rising, indicating that eventually these remnants will be affected by salinity.

The aim of this publication is to present a snapshot of the state of groundwaters under the agricultural areas of Western Australia. A series of 62 *hydrographs* (graphs of depth to the watertable with time) are presented showing the rates of watertable rise in various landscape positions and under different land uses and changing seasonal conditions. The hydrographs illustrate the variability of responses. Several depict episodic recharge (recharge as a result of either large storm events or a very wet year) and clearly show the need for long term monitoring of groundwater levels.

While the general picture of rising water levels is serious and emphasises the need for urgent action, there are examples where water levels are falling under specific land uses. These hydrographs should give hope as they are solid evidence that the salinity problem can be managed. If action is taken on a broad scale throughout the agricultural areas then we should be able to prevent a substantial proportion of the threatened six million ha from becoming saline.

Definitions and concepts

To appreciate what a hydrograph shows it is helpful to understand some of the basic concepts of how water is stored in and moves through the weathered mantle of the earth that is technically known as the *regolith* and is simply that material from the soil surface down to solid basement rock.

Groundwater aquifers

An *aquifer* is generally defined as a saturated permeable geological unit that can transmit significant quantities of water. An *aquiclude* is a saturated geological unit that is incapable of transmitting significant quantities of water. An *aquitard* is in between the two and may be permeable enough to transmit water in quantities that are significant in the study of regional groundwater flow, but the permeability is not

sufficient to supply water to a production well. These are typical of many systems in the agricultural areas of Western Australia.

A *confined aquifer* is one that is sandwiched between two aquicludes or aquitards. Confined aquifers occur at depth and when a *piezometer* is inserted into them the water level in the piezometer usually rises above the upper surface of the aquifer, or may even rise above the ground surface. This water level is called the *piezometric surface*.

An *unconfined aquifer* is one in which the upper surface is the watertable. The water level in an *observation well* inserted into an unconfined aquifer measures the watertable level. It does not rise above the surface unless the surface is flooded.

In the agricultural areas of Western Australia most of the deeper aquifers are semi-confined and there is some leakage either into them or, if they are under pressure, upwards towards the surface. Unconfined aquifers are typically the shallow aquifers associated with sandplain seeps and waterlogging.

Specific yield

When water is withdrawn from an unconfined aquifer the fall in the water level in the aquifer is many times greater than the depth of water that is withdrawn. The ratio between the depth of water withdrawn and the fall in the water level is termed the *specific yield* (S_y). A similar situation occurs when water is added to an aquifer. The reason for this is that immediately above the watertable most of the space is occupied by either solid material or films of water surrounding the solids and filling the small pores. Only the air filled spaces have to be filled with water to effect a relatively large rise in the watertable.

In most of the unconfined or watertable aquifers in the agricultural areas S_y is between 0.02 and 0.1. Thus, when $S_y = 0.02$ the watertable will rise by 50 mm for every mm of water added; when $S_y = 0.1$ the rise will be 10 mm for every mm added.

So if the annual rate of watertable rise is 300 mm, then the actual amount of recharge will be between 6 and 30 mm - not a lot of water but enough to eventually cause a major problem.

Groundwater flow

For a saturated soil (one in which all the pore spaces are filled with water), or an unconfined aquifer, the rate of water flow (v) is very simply described by Darcy's Law:

$$v = -K_s (\Delta H/\Delta z)$$

where K_s is the saturated hydraulic conductivity and $(\Delta H/\Delta z)$ is the hydraulic gradient - the slope of the watertable.

In most of our aquifers the saturated hydraulic conductivity is relatively low and rarely exceeds 1 m/day. The gradient of the watertable, or the hydraulic gradient, is also very low and is rarely greater than the topographic gradient (slope of the land

surface). So in a catchment with a hydraulic gradient of 1% (m fall in 100m) and $K_s = 1$ m/day the velocity of water flow (v) is:

$$v = 1 \times 0.01 = 0.01 \text{ m/day (or 1 cm/day)}$$

So in a year the water will travel about 3.6 m - not very far. Even if the estimate of K_s is out by a factor of 10 the velocity is very low. The factor that governs the rate of groundwater movement in most Western Australian catchments is the hydraulic gradient.

Preferential flow through cracks, old root channels and deeper fractured rock can also be significant for groundwater flow. Preferential flow paths are often observed in active saline seeps, where old root networks lead to 'seepage eyes'.

Water salinity measurements

There are several methods of measuring the salinity of water. The most common is to measure the electrical conductivity (EC) and express the result as millisiemens per metre (mS/m). The electrical conductivity is proportional to the concentration of dissolved salts in the solution. However, the composition of the dissolved salts varies and this affects the electrical conductivity. So there is no standard ratio available for converting EC to concentration. To get an estimate of the concentration of salts in milligrams per litre (mg/L) we use a ratio of 5.5:

$$\text{EC (mS/m)} \times 5.5 = \text{concentration (mg/L)}$$

The conversion ratio can vary between about four and nine so if the concentration is going to be critical for some intended use then it must be measured.

The concentration of total salts in a solution is usually measured by evaporating a sample to dryness. This can only be done in a laboratory.

Northern Agricultural Region

Russell Speed and Edwina Lefroy

Introduction

The Northern Agricultural Region encompasses the Geraldton, Three Springs and Moora advisory districts to the west and south of the clearing line (pastoral boundary) and covers an area of 6,243,540 ha.

There are three major geological provinces within the Northern Agricultural Region: the Yilgarn Craton to the east; the Perth Basin to the west; and the Northampton Block within the Perth Basin. The Darling Fault delineates the boundary between the Yilgarn Craton and the Perth Basin.

Yilgarn Craton

The majority of the Yilgarn Craton in the Northern Agricultural Region consists of crystalline basement; granitic and gneissic rock intruded by dolerite dykes. Quartz veins and dykes are common and often observed adjacent and parallel to the dominant strike of dolerite dykes.

The topography is generally subdued with gently undulating hills, often covered in sandplain, and with broad valley floors. Drainage is ill-defined and often terminates in closed depressions or salt lake chains. Much of the drainage aligns with dominant north-west/south-east and south-west/north-east structural trends clearly depicted on satellite imagery.

The climate is Mediterranean with mild wet winters and hot dry summers. Average annual rainfall varies from around 500 mm at New Norcia to 300 mm at Tardun in the north-east.

Salinity occurs mainly in the valley floors where its distribution is controlled by structural influences such as dolerite dykes. Sandplain seeps are common, particularly in the eastern region. In the eastern and north-eastern wheatbelt catchments an almost continuous line of sandplain seepage appears to be developing at the break of slope where soil type changes from sandplain to valley floor red loams and clays.

Groundwater salinity is typically greater than 2,000 mS/m, however, stock quality supplies can be located in upper landscape positions and groundwater quality in the midst of saline valley floors often approaches 6,000 mS/m (sea water) or worse.

Perched groundwater responsible for sandplain seeps is typically less than 1,000 mS/m and in some cases very fresh (< 50 mS/m).

From just south of Moora, north to a point level with Morawa, the western edge of the Yilgarn Craton is composed of an approximately 20 km wide strip of meta-sedimentary rocks dominated by chert and dolomite intruded by numerous dolerite dykes. Chert is very hard and brittle, hence very fractured and has enhanced secondary porosity through dissolution of the dolomite.

Within the chert country, topographic relief is more pronounced and salinity is largely restricted to narrow incised drainage lines. In areas of dolomite, topography is subdued and surface drainage ill-defined, often terminating in circular depressions the size of football ovals.

Groundwater quality and depth is highly variable within this region and tends to be divided into compartments or cells bounded by numerous dolerite dykes.

Perth Basin

The agricultural area of the Perth Basin in the Northern Agricultural Region covers more than three million hectares and comprises two distinct regions: the Irwin Sub-Basin and the main Perth Basin.

The Irwin Sub-Basin is bounded in the agricultural region by the Darling and Urella Faults. The Urella Fault splits from the Darling Fault at Coorow and traverses northward passing just east of Yuna. Permian sediments, notably the Nangetty Formation and Holmwood Shale, cover most of the basin. Topography ranges from extensive red loamy clay flats to gently undulating hills. Severe gully erosion occurs where surface water flows over degraded land.

Groundwater tends to be too saline for any use and hydrogeologically, the Irwin Sub-Basin appears to be isolated by bounding faults from the Yilgarn Craton to the east and Perth Basin to the west.

The Perth Basin, also referred to locally as the West Midlands Sandplain, contains significant groundwater resources. Surface formations are dominated by the Parmelia Formation in the east (sandstone, siltstone and shale), Yarragadee Formation in the middle (sandstone, siltstone and shale) and various Triassic and Jurassic sediments in the west overlain and fringed by the coastal Tamala Limestone.

The topography of the northern Perth Basin appears to be structurally controlled by faults. The tilted fault blocks expose a range of soil types in all landscape positions, for example, it is not uncommon to find crabhole clays on the crest of a hill.

Surface drainage is poorly developed throughout most of the basin with longitudinal valleys between fault scarps having little gradient and often sandy soils. Many drainage lines are topographically truncated, particularly in western areas, hence much drainage is probably internal.

Groundwater occurs in multiple layered sandy aquifers separated by silts and clays with regional aquifer systems being largely confined. An unconfined watertable occurs extensively in surficial materials.

Most of the groundwater is fresh with groundwater quality deteriorating towards the coast where it is still mostly suitable for stock. However, rising watertables and perched aquifers developing in surficial materials are causing salinity problems. Numerous lakes are developing in topographic lows which are often fresh in their initial development but high evaporation rates from shallow and outcropping watertables, particularly during summer, is increasing salinity of both water and soil. Seeps and springs appear to be becoming more active, particularly in western areas which may be the result of rising groundwater levels throughout the basin transmitting hydraulic pressure to low lying coastal areas.

Northampton Block

The Northampton Block is an inlier of granitic and gneissic basement rocks cut by swarms of dolerite dykes. It is partially capped with Mesozoic sediments, giving rise to flat topped hills, and patches of the Victoria Plateau sandplain.

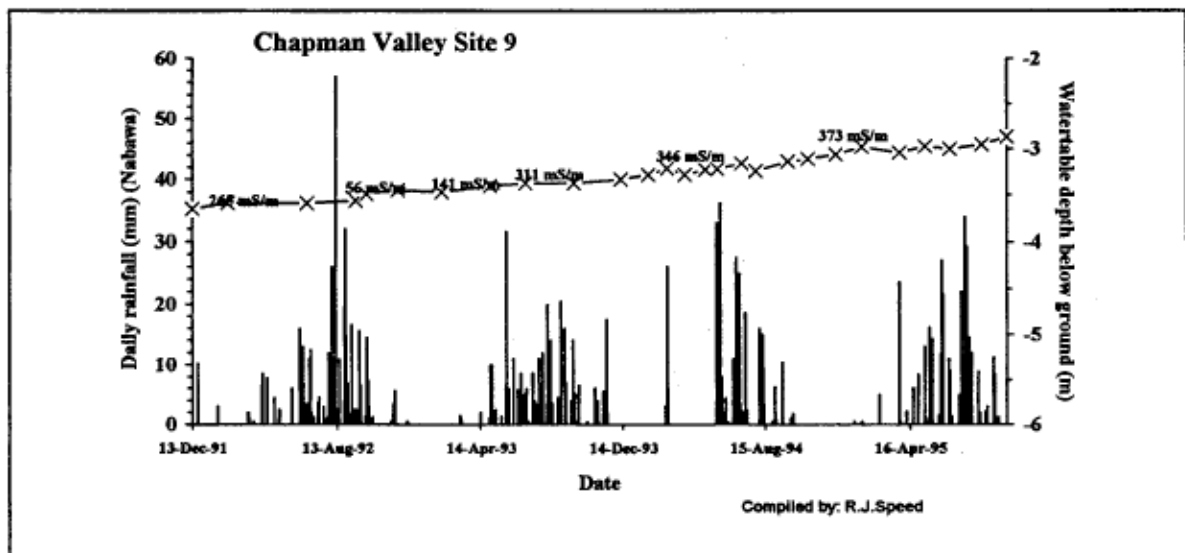
Deeply incised drainage lines, rounded granitic hills and flat topped ranges provide the characteristic topography of the Chapman Valley region in the midst of the Northampton Block.

Groundwater occurs in a range of settings, most of which can lead to salinity if unmanaged. The Victoria Plateau sandplain and numerous spillway sand deposits throughout the region contain perched aquifers invariably suited for stock but often with potable supplies. Scalding can occur by evaporative concentration of salt at the seepage zone.

Over much of the Northampton Block groundwater occurs in the weathered regolith of the crystalline basement. When the weathered profile becomes full, scalding and seeps develop, however, groundwater qualities are often suitable for mildly salt tolerant plants and much of the developing salinity could be averted by alternative management.

Fracture zones associated with dolerite dykes can trap water upslope of the dyke which is then transmitted along the fracture zone to topographic lows where seeps can develop behind the dyke.

The major river channels, particularly the Chapman River, appear to be deeply incised into the crystalline basement and infilled with beds of gravel and coarse sands. Groundwater contribution to base flow maintains surface water in sections of the Chapman River which is suitable for stock all year round. Potable groundwater resources have been located in the river bed aquifers. Groundwater within the river bed aquifers appears to be at hydrological equilibrium with enough contribution to base flow and lateral transmissivity through the coarse sediments to maintain a steady state watertable.



Location: Wathala Swamp, Northern Perth Basin east of the Northampton Block. 292300 mE, 6867200 mN.

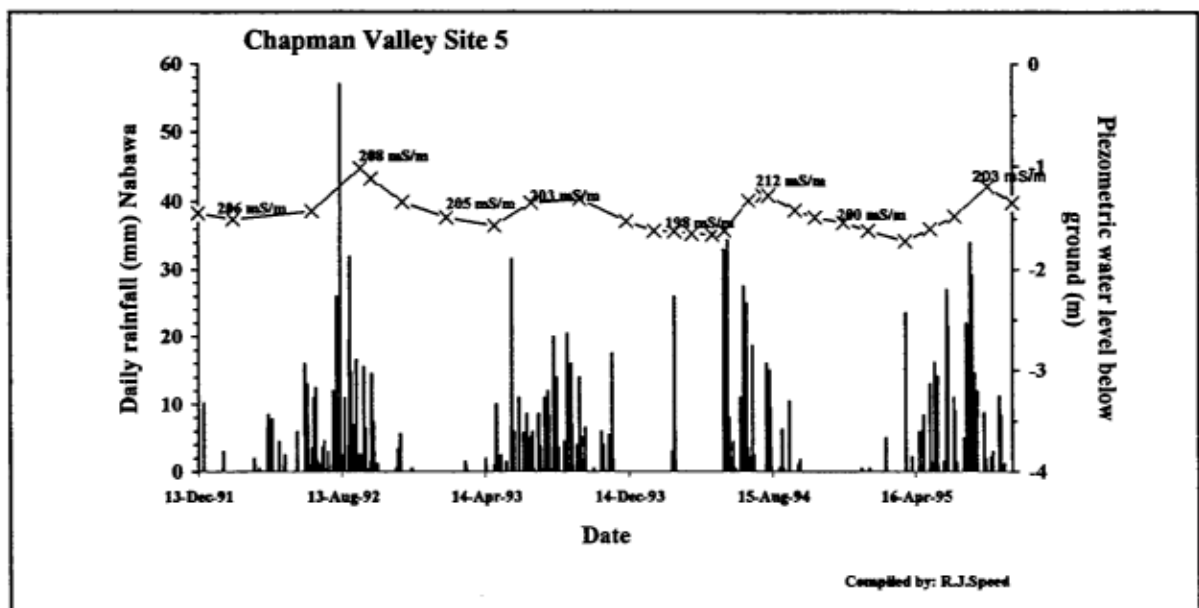
Landscape position: Base of a hollow in undulating sandplain country.

Land use: Cropping, predominantly wheat/lupin rotation with some stubble grazing.

General information: The site was drilled in December 1991. The hydrograph shows the watertable recorded in the observation bore.

A sandy soil profile with minor clays to 2 m overlies Tumblagooda Sandstone. Salt storage to a depth of 14 m at the site is 80 t/ha.

Interpretation: The watertable is steadily rising at 20 cm per year and the salinity is steadily increasing.

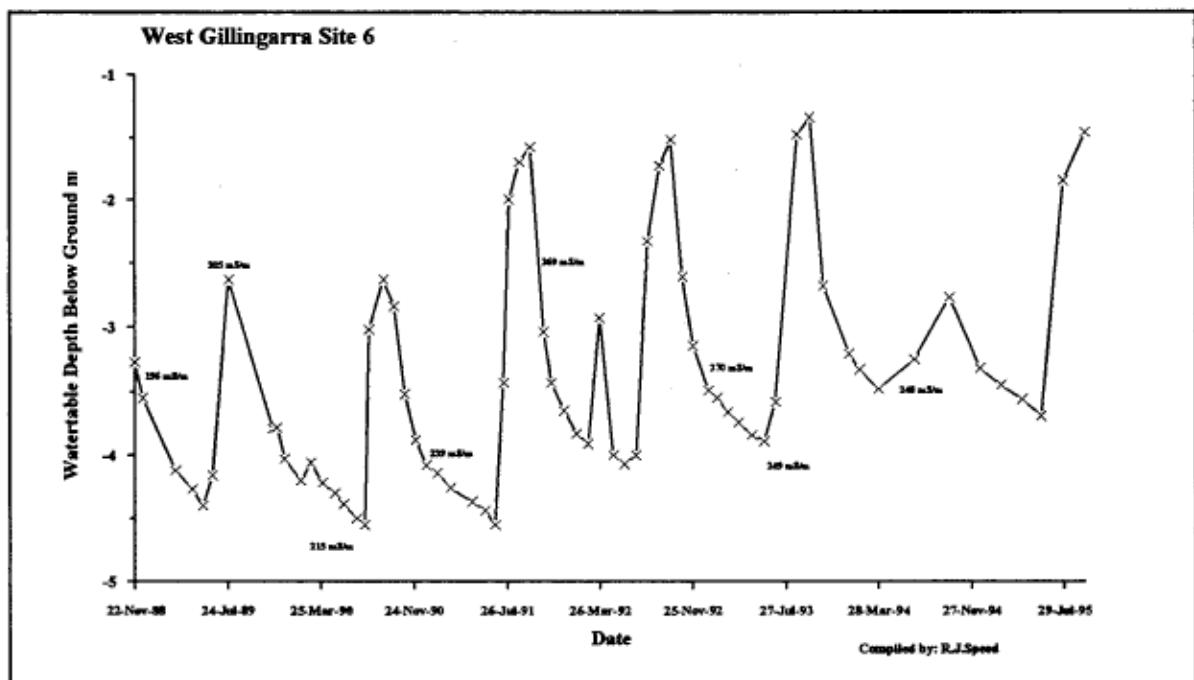


- Location:** Chapman Valley, 4 km north of Nabawa. 284500 mE, 6849650 mN.
- Landscape position:** Adjacent to the Chapman River.
- Land use:** Cropping, predominantly wheat/lupin rotation and sheep grazing.
- General information:** The site was drilled in December 1991. The hydrograph shows the piezometric water level from a screened interval

6.36-8.36 m below ground level. The top 2 m of the profile is red clay loam, below which coarse river sands and gravels were encountered to a depth of 10 m where drilling was stopped. Salt storage to 10 m is 80 t/ha.

Interpretation:

Seasonal fluctuations in the water level correspond to seasonal rainfall but there is no apparent longer term trend. That is, the river bed aquifer appears to be in hydrological equilibrium. The Chapman River channel appears to be deeply incised into the crystalline basement of the Northampton Block and infilled with beds of gravel and coarse sands. Groundwater contribution to base flow maintains surface water in sections of the Chapman River all year. Anticipated high permeability of the river bed aquifer together with groundwater contribution to base flow enables hydrological equilibrium to be maintained.

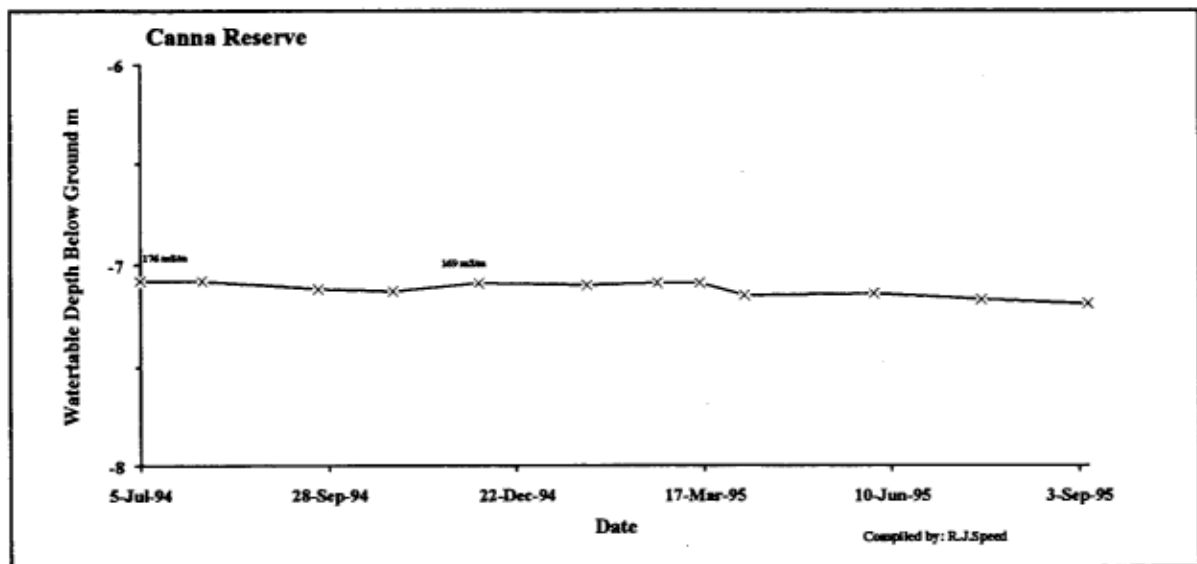


Location: West Gillingarra, overlying the eastern edge of the Perth Basin, approximately 1 km west of the Darling Fault.

404950 mE, 6579775 mN.

Landscape position: Broad alluvial flat west of the Moore River at Gillingarra.

- Land use:** Sheep grazing on annual pasture.
- General information:** The site was drilled in November 1988. The hydrograph shows the regional watertable. An ephemeral perched watertable develops above the regional watertable in winter causing widespread waterlogging. The profile is sandy clay to 1.8 m overlying clayey sand to 5 m.
- Interpretation:** The watertable responds rapidly to winter rainfall and significant summer rainfall events (e.g. 1992) and then decays in an exponential manner. However, a rising trend of 18 cm per year is apparent and it is expected that extensive areas of alluvial flat will be degraded by salinity in the next few years compounding the current seasonal waterlogging problems.



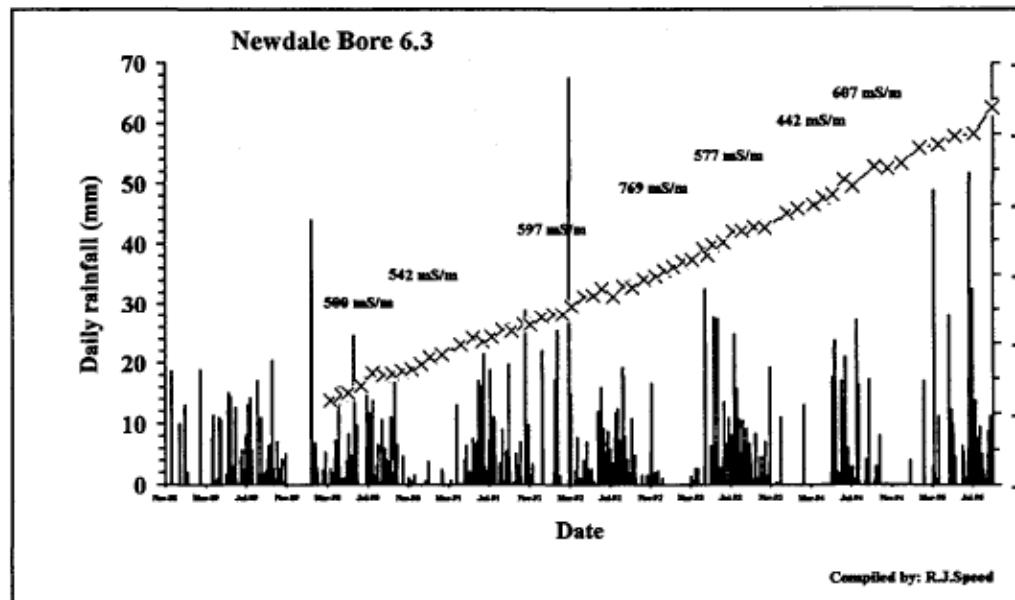
Location: Canna Reserve. 389800 mE, 6804800 mN.

Landscape position: Drainage depression in an upper landscape position.

Land use: Remnant native vegetation.

General information: The site, drilled in June 1994, is in a topographic and groundwater catchment that has 100% remnant native vegetation cover. The surface soil is a red/brown coarse loamy sand. From 0.3 m the profile is *in situ* weathered granitic rock which became too competent by 11 m for further drilling. Salt storage to 11 m is 57 t/ha. The hydrograph shows the watertable.

Interpretation: Only 16 months of data is available, however, the notable feature of the hydrograph is the near constant watertable level and lack of seasonal fluctuations.



Location: Newdale farm, New Norcia. 432600 mE, 6562650 mN

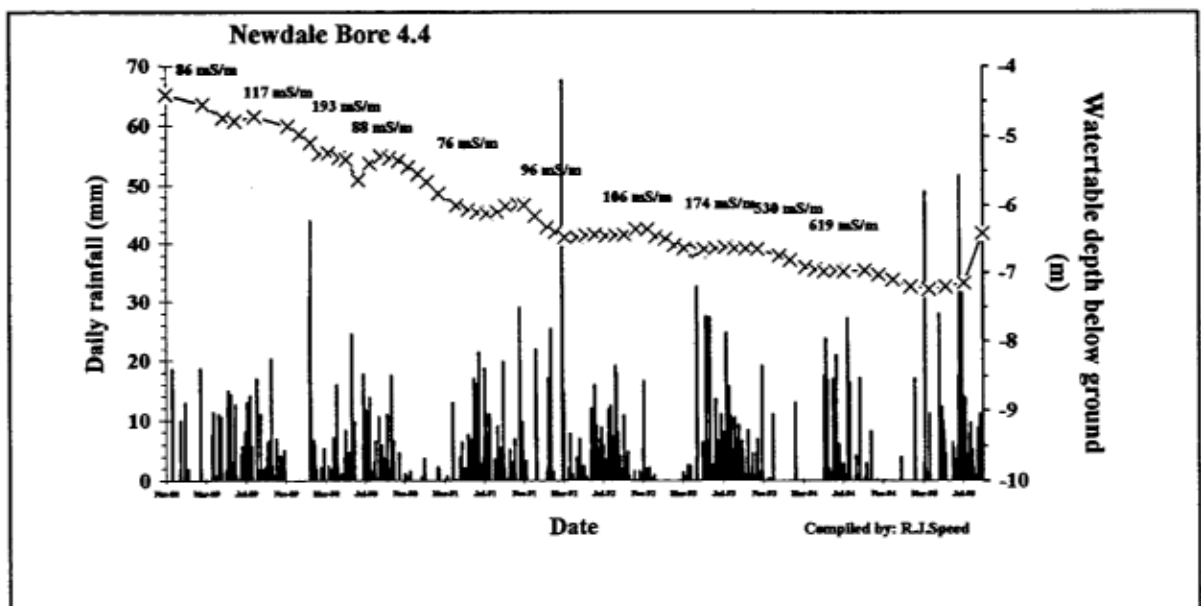
Landscape position: Break of slope.

Land use: Crop/pasture rotation.

General information: The site was drilled in March 1990. The hydrograph shows the regional groundwater level within *in situ* weathered granitic basement (pallid zone). The profile is yellow sand to 9 m overlying pallid zone clays.

Interpretation:

The groundwater level is rising steadily at 74 cm per year under an agricultural system based on annual crop and pasture rotations that fail to adequately utilise available rainfall. This monitoring site is north of the tagasaste plantation on the same hill line as Newdale Bore 4.4 and contrasts rising groundwater under traditional agriculture with a declining watertable beneath dense revegetation with tagasaste (see hydrograph of Newdale Bore 4.4).



Location: Newdale farm, New Norcia. 432600 mE, 6562150 mN.

Landscape position: Midslope.

Land use: Tagasaste plantation grazed by cattle.

General information: The site was drilled in November 1988. The profile is yellow sand grading to pale yellow sand at depth and is essentially a spillway sand deposit. A perched watertable exists within this spillway sand and the hydrograph shows the perched

watertable level. The tagasaste plantation was established in 1988 at a density of 2,000 stems per hectare by planting seed in rows along the contour with 5 m spacing between rows.

Interpretation:

The perched watertable level has declined by an average 40 cm per year beneath the tagasaste. Seasonal fluctuations in water level in response to rainfall indicate some recharge occurs, however, the amount of recharge is less than groundwater outflow and hence the watertable has declined.

Central Wheatbelt Region

Fay Lewis

Geology, landforms, aquifers and salinity

The geology of the Central Wheatbelt has been mapped by the Geological Survey of Western Australia at 1:250,000 and described in the accompanying memoirs (Wilde and Low, 1978 and 1980; Chin, 1986a and b). Myers (1990, 1993) re-interpreted the regional structural geology. In summary, the area is underlain by crystalline bedrock which formed more than 3,000 to 2,550 million years ago. The bedrock forms part of the Yilgarn Craton and in the Central Wheatbelt can be divided into three main groups of rocks. The oldest rocks, the Jimperding Gneiss Complex, underlie the Avon Valley and are the most complex and varied group. Predominant rock types are quartzite, felsic gneiss, schists, banded iron formation, mafic and ultramafic rocks, migmatites and small granitoid plutons. This group of rocks has been strongly deformed. The next oldest rocks are a group of gneisses, most of which are found around the boundaries of the Jimperding Gneiss Complex. The remainder of the area is underlain predominantly by younger plutons of granitoid rocks. All of the rock groups have been intruded by numerous mafic and quartz dykes.

The landscape in the region has been divided into three zones from west to east: the Darling Range Zone (DRZ); the Zone of Rejuvenated Drainage (ZRD); and the Ancient Drainage Zone (ADZ). Each zone has distinctive landforms and soils and these, together with the bedrock geology, influence the characteristics of the groundwater systems.

The agricultural parts of the DRZ are characterised by valleys with steep, gravelly and rocky sides and flat floors separated by undulating plateaux with shallow sheet laterite. Generally, the granitic bedrock has not been strongly deformed and is massive. However, zones of shearing and fracturing and quartz dykes are common and act as groundwater conduits. Between these zones groundwater forms an aquifer at the base of the regolith above the intact bedrock. Major valley floors are broad and flat and underlain by up to 40 m of weathered basement and alluvium. Below some valley floors the watertable is near the ground surface and causes salinisation. Groundwater discharge also occurs in seepage areas on slopes, commonly associated with shear zones which can be traced over several kilometres.

A characteristic of the ZRD is the shallow bedrock and associated rocky red soils forming from it. Because the bedrock is generally the Jimperding Gneiss Complex which has been strongly deformed, the bedrock is commonly densely fractured and sheared and acts as a fractured bedrock aquifer. The regolith is rarely deep and a high proportion of the groundwater movement takes place within the bedrock. At present, there is little broad scale salinity in this zone but the area affected along the main valley floors is increasing rapidly. Localised groundwater seeps occur, especially on hillsides.

The ADZ lies east of the Meckering Line which delineates the downstream boundary of the salt lake systems of the wheatbelt. It is a region of broad valleys with low gradients and commonly poorly defined drainage lines. Catchment slopes are long and gentle, although hills with shallow granitoid bedrock are common. Saline lake chains have developed along the main valley floors. The slopes are underlain by deep sandy and gravelly soils in many areas and clay soils predominate on valley floors. The granitoid bedrock is relatively underformed and the main bedrock aquifers are sheared and fractured zones and quartz dykes. At the base of the regolith, intact bedrock defines the bottom of the weathering rock zone aquifer, which is the most widespread type of aquifer. A feature of the ADZ are the perched aquifers which form in the sandplain soils which can provide good quality water resources. However, they may interact with the underlying saline groundwater and contribute to saline seeps. The broad flat valley floors are underlain in many cases by tens of meters of weathered bedrock and alluvium. Watertables are commonly near the ground surface below the valley floors causing broadscale salinity.

In all zones structural features such as fault zones, shear zones, and quartz and mafic dykes control the flow of groundwater by acting as either conduits or barriers, and are associated with groundwater discharge.

Climate

The average annual rainfall decreases from about 800 mm per year in the west to about 325 mm per year in the east of the region. Although agriculture is based on winter growing annual crops and pastures, the mean rainfall data illustrate that a significant proportion of the rain falls during the period when there is no significant pasture growth and before crops are sown (many crops are not sown until June). Even after the crops have been sown, their roots are not able to access stored water in the soil below a few centimetres depth for several weeks. So, if the soil water holding capacity of the final root zone is too low to store the large amount of rain which falls during June and July then this water will not be used by the crop and may percolate to the groundwater system.

Table 1. Mean rainfall for specified months and % of total mean rainfall for one location in each of the three zones

Location	1 November- 31 May (mm)	1 June- 31 July (mm)	1 August- 31 October (mm)	1 November- 31 May (% Total)	1 June- 31 July (% Total)
Bakers Hill (DRZ)	182	226	178	31	39
Northam(ZRD)	151	159	123	35	37
Kellerberrin (ADZ)	142	108	78	43	33

Because many crops are not sown until June, the amount of rain falling on bare land, or land with no actively growing plants, may be significantly higher than the '1 November to 31 May' total given above.

The Class A pan evaporation rate increase from about 2,100 mm per year at Bakers Hill to about 2,400 mm per year at Kellerberrin.

Current and predicted salinity

My estimates for the current percentage of land affected by agriculture-induced salinity are: DRZ 9%, ZRD 7% and ADZ 9-12%.

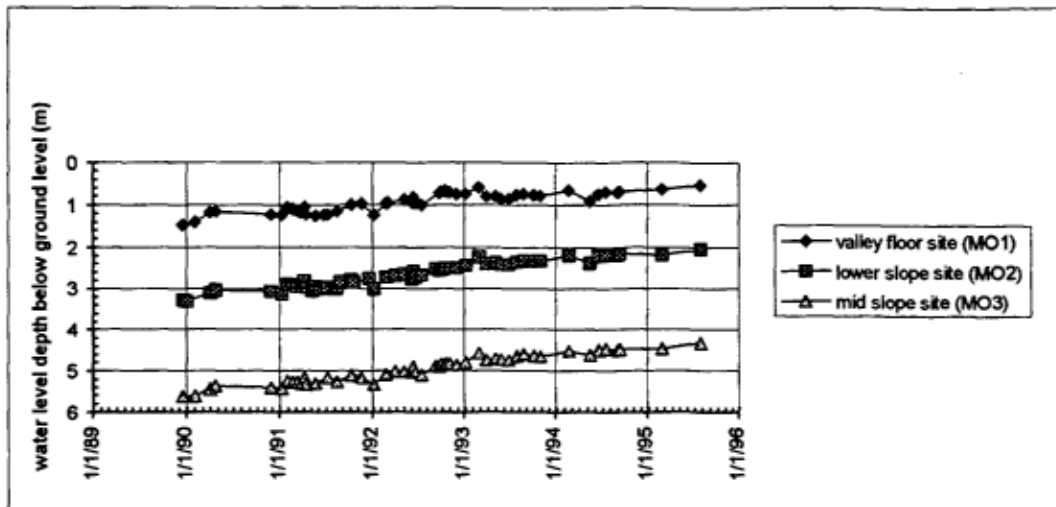
It is not appropriate to make predictions on a topographic catchment basis of how much land could eventually become saline if management practices are not improved. This is because groundwater catchments do not always coincide with topographic catchments. Commonly there are a number of groundwater compartments, which have varying degrees of interaction with each other, within a topographic catchment. It is conceivable that 100% of a specific groundwater compartment could become a discharge zone for part of the year, and part of it become a recharge zone for the other part of the year. Conversely, some compartments could be 100% recharge area if the watertable is sufficiently deep. Therefore, the idea of equilibrium discharge areas must be used cautiously.

It is not hard to visualise 50% of the cleared land in each zone having the potential to become zones of groundwater discharge, and I suspect that some catchments could have greater areas affected.

References

- Chin, R.J. (1986a). Corrigin, Western Australia. Western Australia Geological Survey, 1:250,000. *Geological Series Explanatory Notes*.
- Chin, R.J. (1986b). Kellerberrin, Western Australia. Western Australia Geological Survey, 1:250,000. *Geological Series Explanatory Notes*.
- Lantzke, N. and Fulton, I. (undated). Land resources of the Northam Region. Department of Agriculture, Western Australia. *Land Resources Series* No. 11.
- McArthur, W.M. (1992). Land resources of the Kellerberrin Region. Department of Agriculture, Western Australia. *Div. Resource Management Tech. Rep.* No. 134.
- Myers, J.S. (1990). Western Gneiss Terrane. In: *Geology and Mineral Resources of Western Australia. Geological Survey of Western Australia Memoir* 3: 13-32.
- Myers, J.S. (1993). Precambrian history of the West Australian Craton and adjacent orogens. *Ann. Rev. Earth Planet. Sci.* 21: 453-485.
- Salama, R.B., Farrington, P., Bartle, G.A., Watson, G.D. and Hawkes, G.E. (1994). Salinity investigations in selected wheatbelt catchments of Western Australia. 3. Base data for Wallatin Creek Catchment. *CSIRO Div. of Water Resources Technical Memorandum* No. 94/6.
- Wilde, S.A. and Low, G.H. (1978). Perth, Western Australia. Western Australia Geological Survey, 1:250,000. *Geological Series Explanatory Notes*.
- Wilde, S.A. and Low, G.H. (1980). Pinjarra, Western Australia. Western Australia Geological Survey, 1:250,000. *Geological Series Explanatory Notes*.

1. Steady rises, rates of rise decreasing downslope



Location: Morbinning Catchment

Grid references:
 MO1: 518975E, 6445500N
 MO2: 519150E, 6445250N
 MO3: 519200E, 6445 150N

Landscape position: MO1: Valley floor, not salt affected, adjacent to drainage line. Soil landscape unit: Mortlock (Lantzke and Fulton, undated).

MO2: Lower slope, about 100 m upslope from MO1. Soil landscape unit: Ewerts (Lantzke and Fulton, undated).

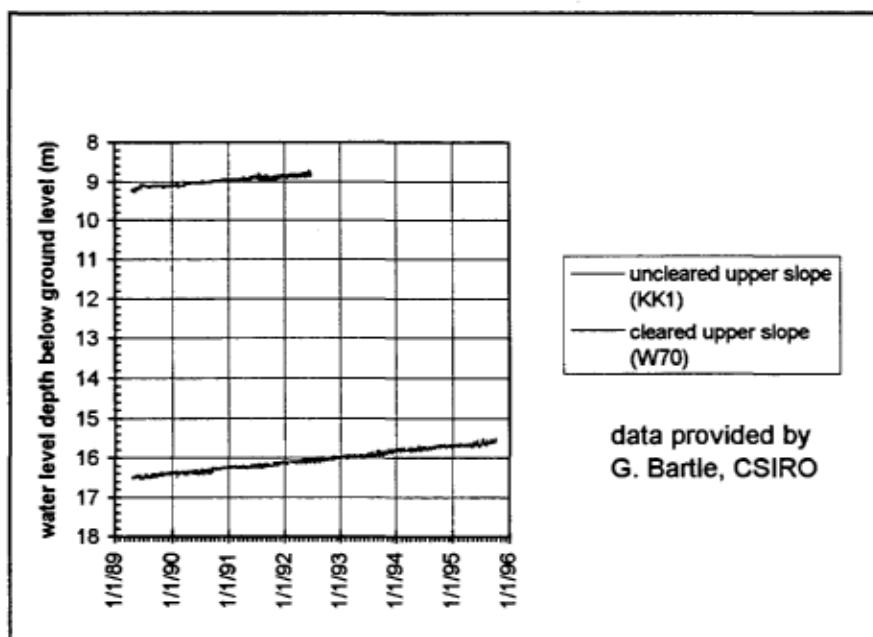
MO3: Midslope, about 50 m upslope from MO2. Soil landscape unit: Ewerts (Lantzke and Fulton, undated).

Land use: MO1: Laneway.

MO2 Firebreak between paddock of 1:2 cereal/pasture &
 MO3: rotation and road.

Features of the trend: The water levels in all three piezometers have rising trends, with the rate of rise increasing up slope from about 20 cm per year at MO1 to 30 cm per year at MO3. The water levels in all three piezometers rise about the same amount in response to rainfall but MO3 drains more slowly than the sites lower down the slope. In this case, the lower drainage rate below MO3 may be related to a groundwater barrier downslope inhibiting drainage to the valley floor.

2. Steady rises under both cleared and uncleared land, almost no seasonal fluctuations



Location: Wallatin Creek Catchment

Grid references: KIK1: Trayning 1:100,000; 745196 (Salama *et al.* 1994)

W70: 575500E, 6519000N (approximate only)

Landscape position: KK1: Upper slope.

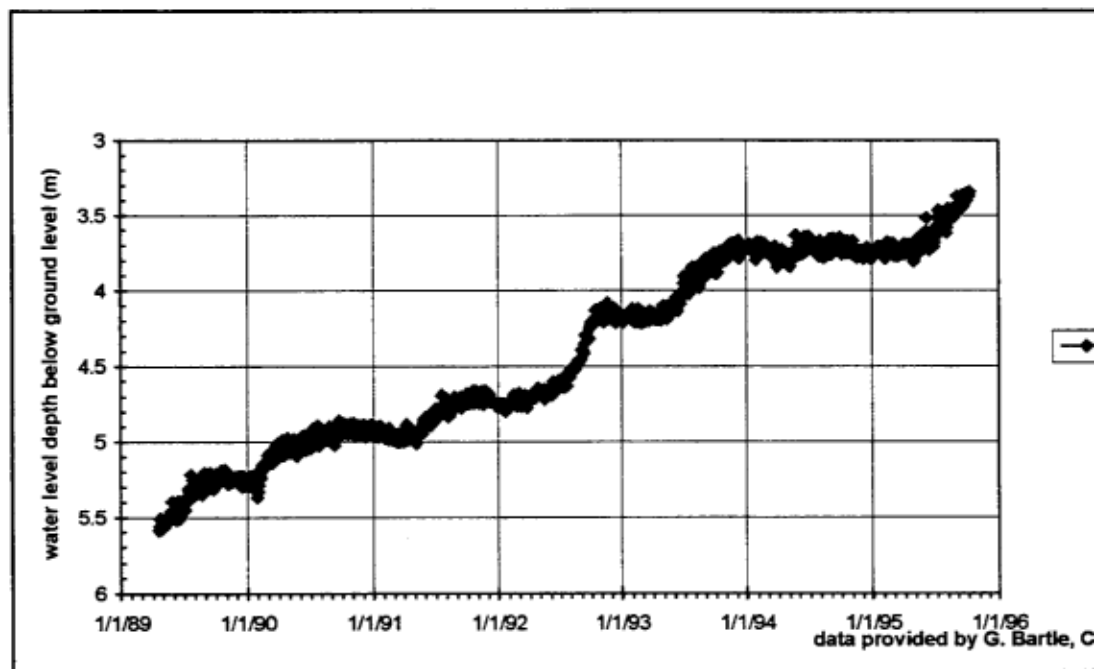
W70: Upper slope, approximately 100 m downslope of KK1. Soil landscape unit for both piezometer sites was mapped as Collgar (McArthur, 1992).

Land use: KK1: Uncleared reserve.

W70: Paddock under 1:3 cereal/pasture rotation.

Features of the trend: Even though the KK1 is in an uncleared area the groundwater level is rising at about 16 cm per year. The level in W70 is rising about 15 cm per year. It could be assumed that recharge at KK1 is from lateral groundwater flow because the site still has deep rooted trees. Both hydrograph patterns show a steady rise with minimal seasonal response. As the two hydrographs are so similar, it may be that W70 also receives recharge from lateral groundwater flow. Another possibility is that recharge to W70 is by slow vertical percolation of water that infiltrates at the site, and water from below the cleared land then flows laterally towards the uncleared area below the reserve.

3. Steady rise with rainfall responses



Location: Wallatin Creek Catchment

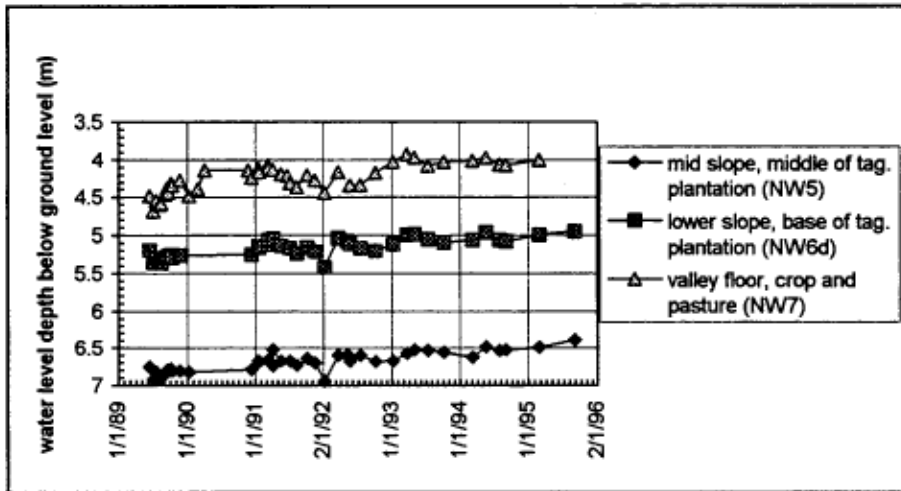
Grid references: W58: 573750E, 6522000N (approximate only)

Landscape position: W58: Near a poorly defined drainage line on a lower slope. Soil landscape unit is Collgar (McArthur, 1992).

Land use: W58: On a firebreak between a vegetated roadside verge and a paddock in a 1:2 cereal/pasture rotation.

Features of the trend: W58 shows a rising trend of about 30 cm per year. The water level responses reflect rainfall (compare to the steady rises of KKI and W70 on previous graph); for example, low winter rainfall in 1994, high winter rainfall in 1992 and over 110 mm rain in 2 days at the end of January in 1990.

4. Rising trend below 'high water use' agriculture



Location: North Wyola Catchment

Grid references: NW5: 5343 50E, 6506900N

NW6: 534250E, 6506850N

NW7: 534000E, 6506700N

Landscape position: NW5: Midslope, bedrock at 26.5 m.

NW6: Mid to lower slope, bedrock at 17.5 m.

NW7: Valley floor, bedrock at 7.5 m.

All piezometer sites have been mapped as Ulva soil landscape unit (Lantzke and Fulton, undated).

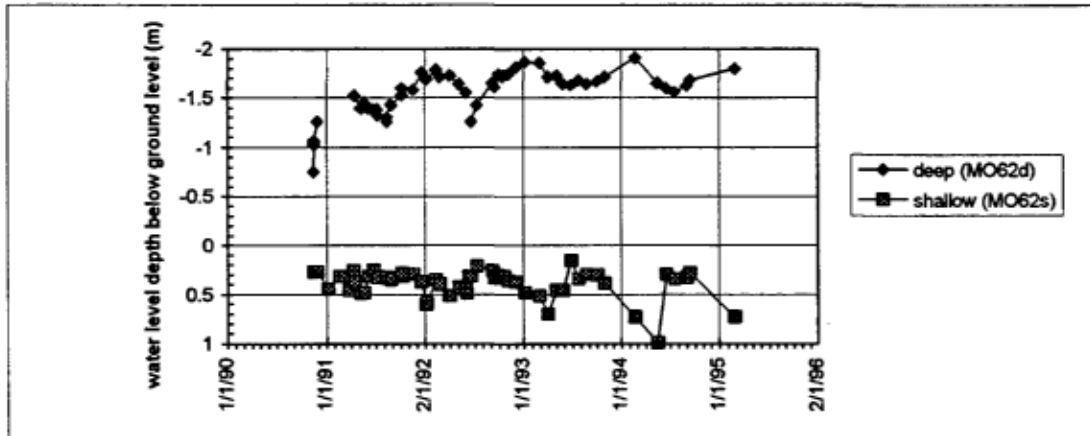
Land use: NW5: Middle of plantation of *Chamaecytisus palmensis* (tagasaste), where shrubs are growing particularly vigorously.

NW6: Downslope edge of tagasaste plantation.

NW7: 1:1 cereal/lupin rotation.

Features of the trend: The water levels in all piezometers are rising. That in the piezometer at NW5 in the middle of the plantation is rising at the greatest rate (25 cm per year). Probably the site is receiving recharge from groundwater flowing to the site from other parts of the catchment as well as the rain which falls at the site. Although the tagasaste is growing vigorously, it is probably unable to use all the inflowing recharge.

5. Stable shallow piezometer trend and rising deep piezometer trend, discharge site



Location: Morbinning Catchment

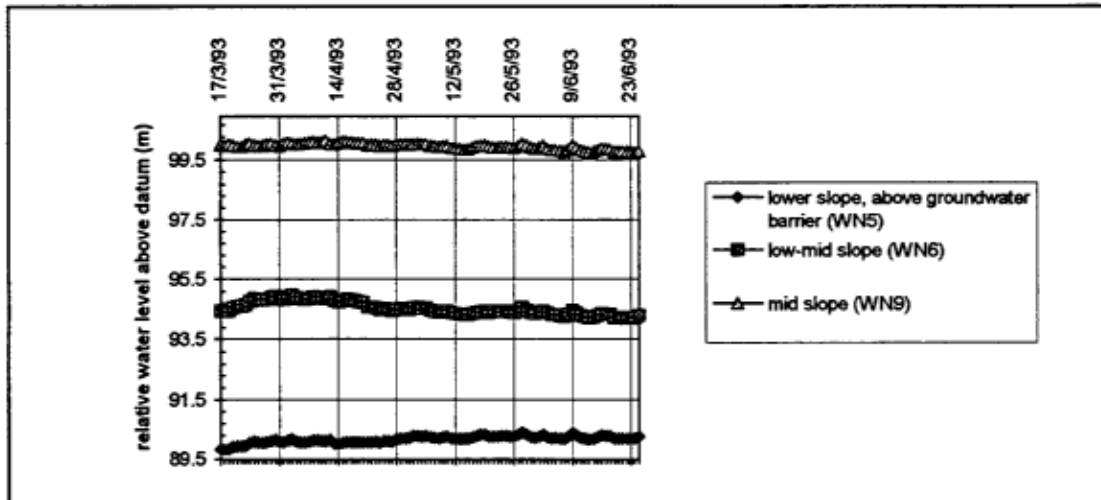
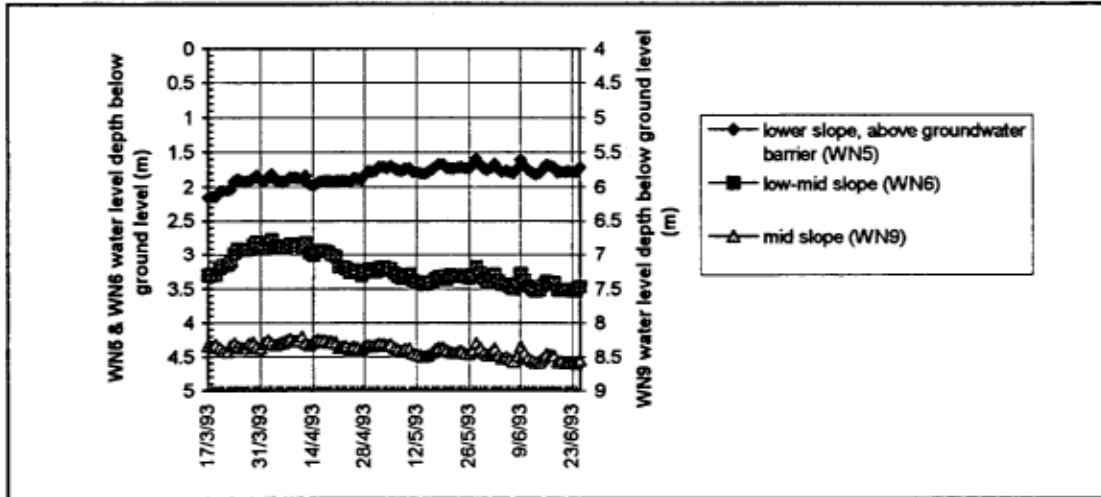
Grid references: MO62: 517450E, 6448750N

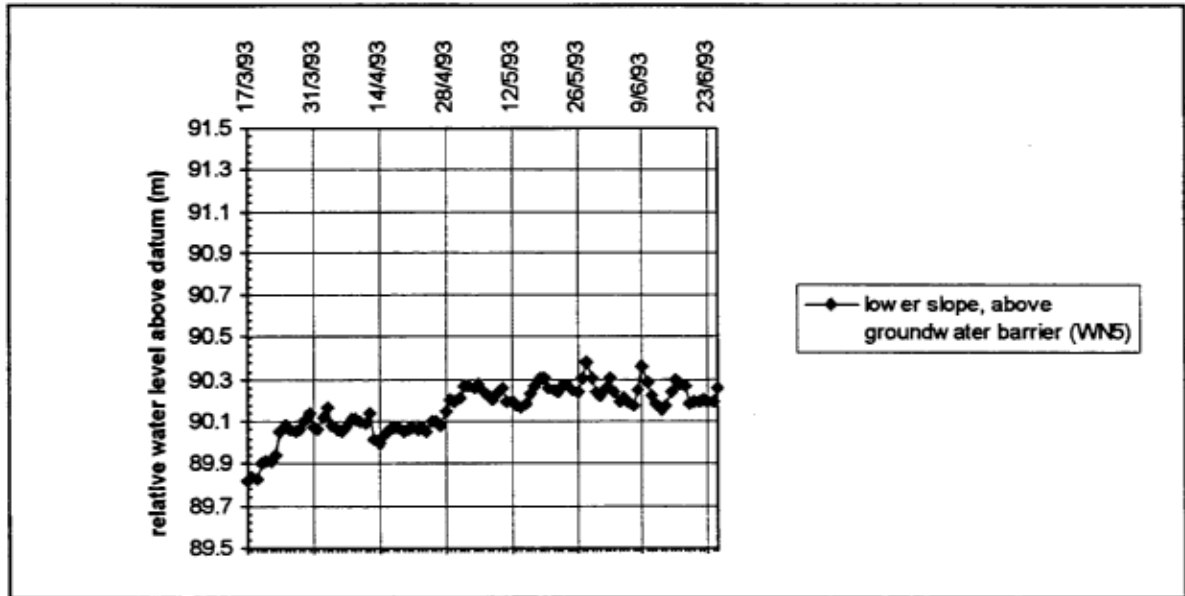
Landscape position: Valley floor discharge site, overlying a quartz dyke. Soil landscape unit was mapped as Mortlock (Lantzke and Fulton, undated).

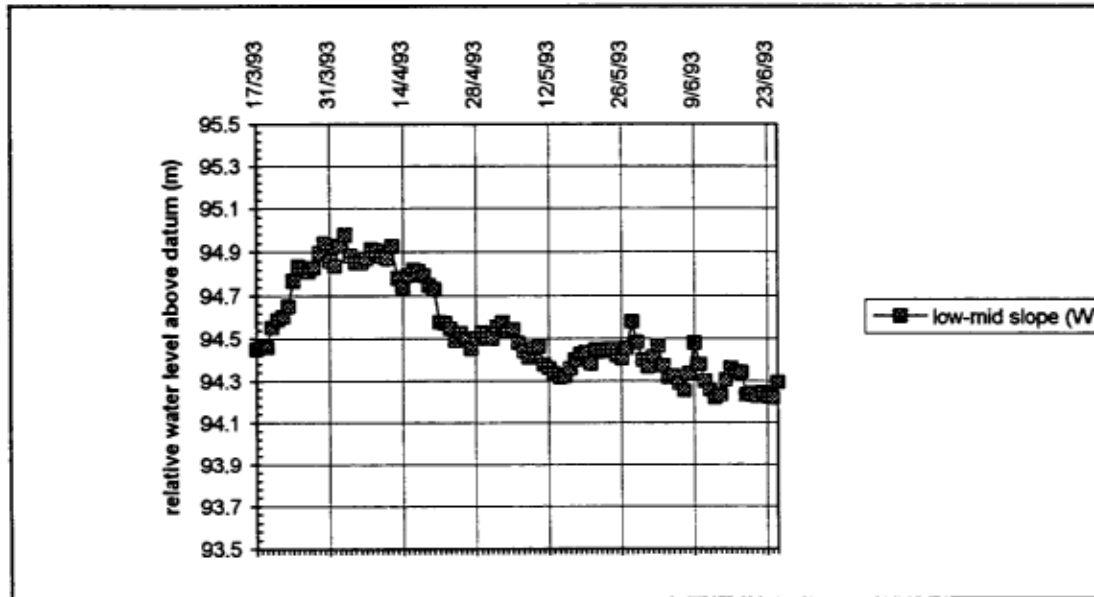
Land use: Severely degraded by salinity and waterlogging (was *Eucalyptus wandoo* (wandoo or white gum) woodland).

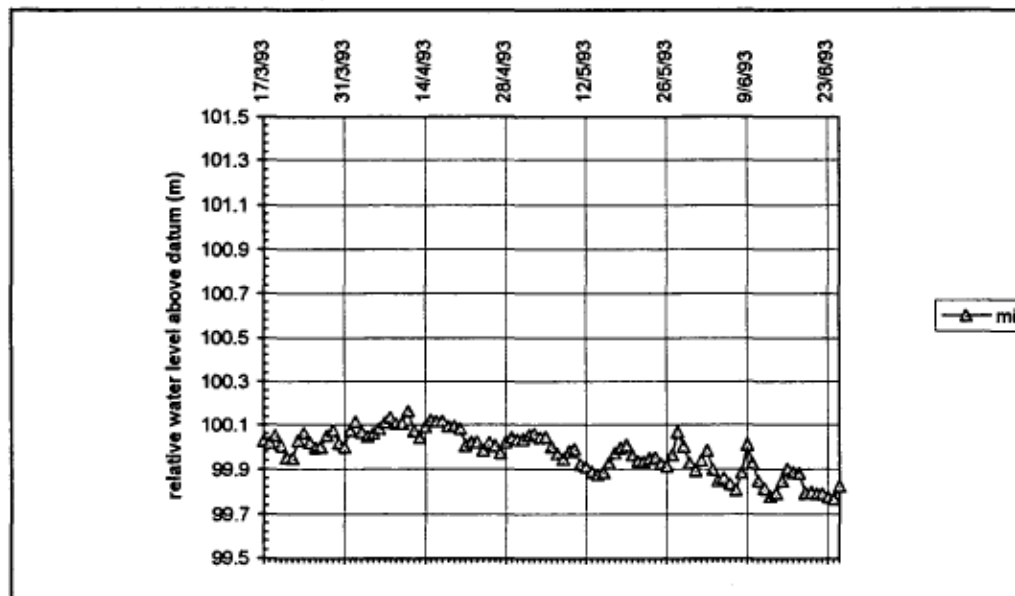
Features of the trend: The water level in the shallow piezometer responds to seasonal rainfall but does not have a rising trend. The deep piezometer shows a rising water level trend. This difference in behaviour between deep and shallow piezometers is common in sites where the groundwater causing the degradation problem is deep groundwater under upward pressure, which is recharged by groundwater flowing from elsewhere.

6. Summer recharge, accumulation downslope behind groundwater barrier









Location: Kettlerock Gully Catchment

Grid references: WN5: 456300E, 6430750N
 WN6: 456300E, 6430800N
 WN9: 456300E, 6430900N

Landscape position: WN5: Gully, lower midslope, just upslope of groundwater barrier (mafic dyke).
 WN6: Lower midslope, about 50 m upslope of WN5.
 WN9: Midslope, about 200 m upslope of WN6.

Soil landscape unit for all piezometer sites was mapped as Leaver (Lantzke and Fulton, undated).

Land use: Until 1993 the site was in a 1:2 cereal/pasture rotation. In 1993 a *Eucalyptus globulus* (Tasmanian bluegum) plantation was established.

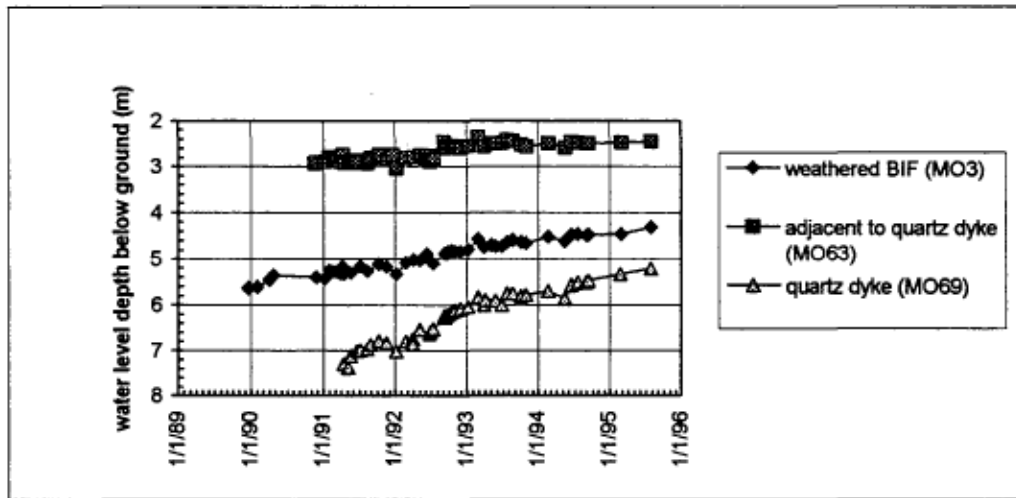
Features of the trend: The hydrographs show the water levels recorded by data loggers in the piezometers during and following a rainfall event on 19 March 1993 of about 60 mm. (They have been corrected for barometric pressure). At this time there was nothing actively growing on this site. At WN9 there is 5 m of 'buckshot' gravels overlying mottled clays. At WN6 and WN5 there are 1.5 m of gravels over clay. The 2 m slotted intake section of the piezometers is in the clay at all sites, at the following depths:

WN5 9-urn
WN6 9-lim
WN9 12-14m.

These three hydrographs illustrate the recharge following the rain event. Within 2 days WN6 had risen 15 cm and after 15 days reached its maximum rise of 45 cm. WN9 took longer to respond and eventually rose 10 cm. Within 2 days WN5 had risen 10 cm. The quick response at several meters depth occurred at a time of year when the soil profile would be expected to have a sufficient available water storage capacity to store the amount of rain that fell. There are many old tree root channels preserved in the gravel soils and the rapid rise in water levels could be explained by preferred pathways transporting water quickly to depth without wetting up the whole profile.

Subsequently, WN9 and WN6 drained but WN5 continued to rise and by the break of season was 44 cm higher than in early March. One way to explain this is to assume that the groundwater from up slope drained downslope towards the mafic dyke just below WN5 where it accumulated.

7. Episodic recharge compared to steady recharge



Location: Morbinning Catchment

Grid references: MO3: 51 9200E, 64451 50N
M063: 516450E, 6448050N
M069: 518500E, 6449550N

Landscape position: MO3: Midslope, regolith predominantly derived from *in situ* weathering of metamorphosed banded iron formation. Soil landscape unit: Ewerts (Lantzke and Fulton, undated).
M063: Midslope, regolith predominantly derived from *in situ* weathering of granite. Site is downslope of a quartz dyke. Soil landscape unit: Ewerts (Lantzke and Fulton, undated).
M069: Midslope, piezometer is within a quartz dyke. Soil landscape unit: Ewerts (Lantzke and Fulton, undated).

Land use: MO3 & M063: Firebreak between paddock (in 1:2 cereal/pasture rotation) and road.
M069: 1:1 cereal/lupin rotation (rotation started about 8 years ago with the intention of high water use).

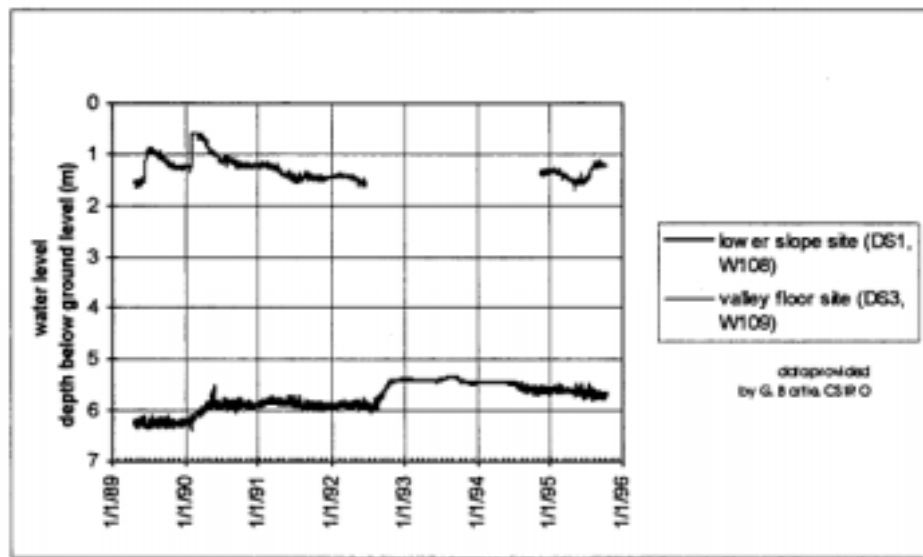
Features of the trend: The water levels in all three piezometers have rising trends. The rate of rise is greatest (50 cm per year) within the quartz dyke (M069). However, the type of trend varies. M03 is rising steadily and its rate does not increase dramatically in 'wet' years (e.g. 1992). The water level in M063 did not appear to

have a rising trend until the wet winter of 1992 when it stepped up to a new level and has not drained back to its original level. M069 has the greatest rate of water level rise of the 35 piezometers being monitored in the Morbinning Catchment. It was rising steadily until 1992 and then the rate increased and the former rate is now imposed on the elevated level.

These three sites may show that threshold values of recharge exist below which the seasonal increase in water level is not sustained. The rate of rise and type of rising trend appears to be predominantly controlled by the rate of drainage and to a lesser extent by the amount of recharge.

The hydrographs also illustrate the need for long term monitoring to define trends. M063 did not rise from 1990 to mid 1992, nor from late 1992 to 1995. But it rose 30 cm over a few weeks in 1992.

8. Episodic recharge and summer recharge



Location: Wallatin Creek Catchment

Grid references: W108: Kellerberrin 1:100,000, 838066 (Salama *et al.* 1994)
W109: Kellerberrin 1:100,000, 830063 (Salama *et al.* 1994)

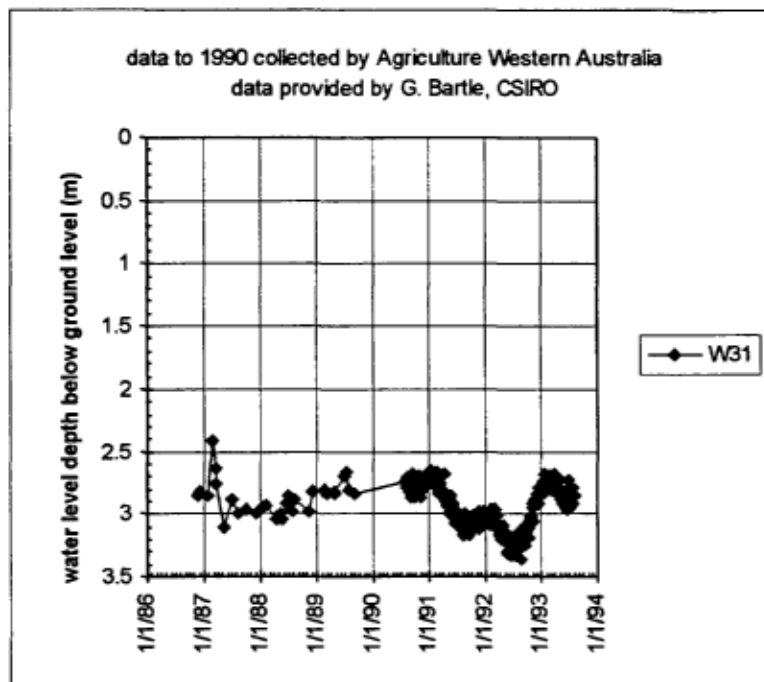
Landscape position: These two piezometers are part of a transect across the lower part of the Wallatin Creek Catchment. W108 is in a lower slope position (soil landscape unit is Collgar (McArthur, 1992)) and W109 is on the flat valley floor (soil landscape unit is Merredin (McArthur, 1992)).

Land use: Both piezometers are on firebreaks between roads and paddocks in 1:2 cereal/pasture rotations.

Features of the trend: The response of the water level in W108 to rainfall is generally subdued, but the January rainfall in 1990 and the wet winter of 1992 appear to have exceeded a threshold and episodic recharge occurred. Following these events, drainage has been too slow for the water level to recover its former depth. Whether it will do so depends on the frequency of events which exceed the 'threshold' value.

W109 appears to respond to lower rainfall events than W108, e.g. winter 1989 and the beginning of winter 1995. However, winters with low rainfall (e.g. 1990 and 1991) only cause small rises. This site also responded markedly to the summer rain in 1990. Maybe the most important difference between the two sites is that W109 appears to drain back to a stable level following recharge episodes. If it did not, then the long term rate of rise at this site would be greater than that at W108.

9. Drawdown as a result of pumping, and subsequent recovery



Location: Wallatin Creek Catchment

Grid references: W3 1: 569500E, 6520750N (approximate only)

Landscape position: W3 1 is near a minor drainage line near the topographic catchment divide. The soil landscape unit is Collgar (McArthur, 1992).

Land use: The piezometer is on a site which was pumped using a windmill powered pump as part of a CSIRO experiment in 1991 and 1992. Trees are also planted at the site.

Features of the trend: Although the water level fell approximately 0.5 m during pumping, it rose once pumping stopped. There is no drawdown due to trees in evidence yet.

Eastern Wheatbelt Region

Cecelia McConnell

Geology

The Eastern Wheatbelt covers the area from Kellerberrin to Southern Cross, Beacon to Narembeen. It is located on the Southern Cross Province of the Yilgarn Craton which is predominantly Archaean granites and gneisses with migmatites, greenstones and intrusive Proterozoic dolerite dykes present in some areas.

The western section features the Kellerberrin Batholith, consisting of homogeneous seriate and porphyritic adamellite. There are numerous dolerite and diorite dyke intrusions that occur in parallel swarms mostly on an east-west trend.

To the north, over half the outcrop is comprised of seriate medium and coarse grained biotite granite and adamellite. Elongate greenstone belts have a northerly trend and consist of metamorphosed layered sequences of ultramafic, mafic and felsic volcanic rocks (Geological Survey of Western Australia (GSWA), 1990). Dolerite infills fractures, joints and some fault planes which trend east/north-east.

The greenstone belts in the east are a dominant geologic feature of the Southern Cross Province. Deformation of the granite greenstone terrain is complex with evidence of multiple folding. All rocks show a north/north-east trend however faults and shear zones trend north/north-west and are generally located at granite-greenstone contacts. Greenstones, gneiss and granitoids of the Southern Cross Province all range in age from 3.1-2.5 thousand million years (GSWA, 1990).

Topography

Elevations range from 200 m above sea level near Kellerberrin to 456 m east of Southern Cross. Generally the topography is gently undulating, broken only by occasional hills. The remains of a laterite surface, most of which was eroded during the Quaternary, is preserved along the drainage divides. Valleys are broad and flat with low gradients. They have been extensively infilled by alluvium during past arid climate phases. To the east and north of the district extensive sandplain has developed as a result of natural erosion processes.

The landscape has deeply weathered lateritic profiles up to 60 m thick. These consist of upland sand and gravel overlying mottled and pallid zones, above weathered rock (saprolite grits) and fractured rock zones. The sand plain, which overlies the mottled and pallid weathered zones ranges in depth from 1-9 m. Below this zone, extensively weathered alluvial sediments have infilled valleys. The depth of sediment ranges from 6 to 21 m in the small tributaries to over 40 m in the major paleodrainage zones (George, pers. comm.). These sediments consist of coarse sands to dense clays and are a mixture of alluvial, colluvial and aeolian deposits.

Water courses form part of the Swan Avon paleodrainage system and become more defined to the west. This system is thought to have developed during the Late Cretaceous, however by the mid Miocene regular flow had ceased in inland areas. The main drainage lines are now marked by strings of clay pans and salt lakes. These are surrounded by alluvial flats of saline and gypsiferous clays (Chin, 1986). Low lunette systems have developed around the eastern and south-eastern sides of lakes. These paleochannels flow westward toward the Avon river but water does not generally reach the river. It evaporates or becomes recharged.

Climate

The Eastern Wheatbelt has a Mediterranean climate with hot dry summers and cool wet winters. Rainfall ranges from 360 mm per year in the west to less than 290 mm per year in the east. Approximately 70% of rain falls between May and October with the remainder falling in summer storm events. There is a decreasing rainfall trend from south-west to north-east across the region for the winter rainfall. Temperature for winter ranges from 4-5°C to 16-17°C and in summer from 17-18°C to 33-34°C. Class A pan evaporation ranges from 2,400 mm at Narembeen to 2,900 mm at Wialki.

Soils and landforms

Within the Eastern Wheatbelt landscape management units have been identified. These are based on work by Bettenay and Hingston in the early 1960s. The eight major landscape units are described below.

Table 1. Major soil landforms of the Eastern Wheatbelt (modified from Bettenay and Hingston, 1964)

Soil/landform association name	Description	Approx. area as % of Eastern Wheatbelt
Danberrin	Skeletal arkosic soils, upper slopes, (clay sands to sandy clay barns)	5
Ulva	Residual lateritic surface, upper slopes, (gravelly sands to clay sands)	25
Norpa	Depositional surface from the Ulva, midslope, (deep yellow clay sands to earths)	15
Booraan	Exposed pallid and mottled zones, midslope, (erosional and depositional phases - clay texture)	10
Collgar	Duplex profiles below all above in small valleys, (sand over clay - often indurated subsoil)	10
Merredin	Heavy textured sediments on large valley floors, (red sandy clay barns to sandy clays)	15
Belka	Alluvial systems with mixed soils on large valley floors, (mixed sand to clayey soils - deposits)	10
Nangeenan	Heavy textured, often gilgai and saline morrell soils, (red clay barns to sandy loams/near Stirling Association)	3
Stirling	Salt lakes, discharge zones and primary saltland, (lunettes, lakebeds and associated parna)	7

Research by George (pers. comm.) on five sub catchments in the Eastern Wheatbelt has allowed salt storages estimates to be derived for each of these units.

Landscape unit	TSS* (t/ha)	<i>Depth to bedrock (m)</i>
Danberrin	296	8.25
Ulva	273	23.33
Norpa	423	26.42
Booraan	1,199	13.09
Collgar	1,160	25.00
Merredin	2,233	20.00
Belka	2,363	17.17
Stirling**	19,537	55.00

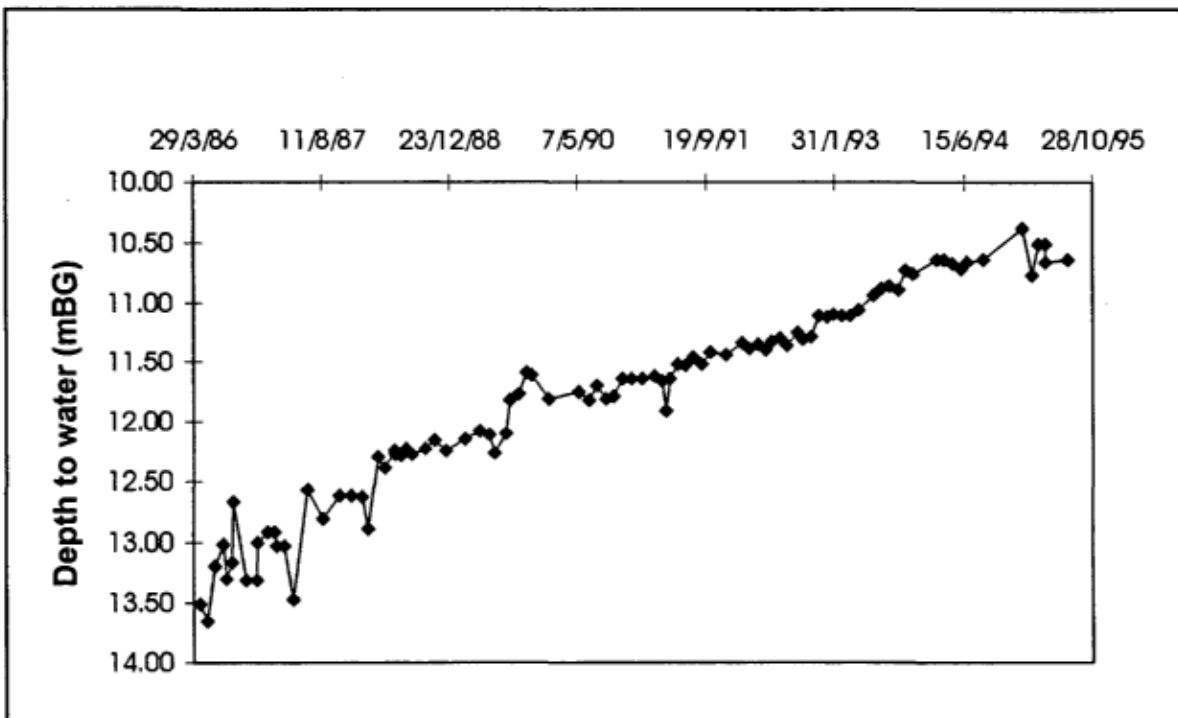
* Total soluble salts.

** Only one data point.

Primary salinity occurs throughout the salt lake chains. Spread of salinity in adjacent valley soils is the predominant form of secondary salinity impacting the Eastern Wheatbelt. Other expressions of secondary salinity are seen as sandplain seeps and other geologically controlled seeps sites. Some salinity is developing due to geomorphic constraints such as the convergence of tributaries and main drainage ways where transmissivity is inadequate to carry groundwater flow.

Rates of groundwater rise are generally lower for the valley floor units than for land units in the surrounding higher catchment areas. During the last nine years groundwater data has been collected in the Merredin catchment. Data suggests that groundwater is rising at rates of 0.11 m per year (mm = 0.03 m; max = 0.268) on the valley floor whilst on the slopes it is rising at rates of 0.28 m per year (mm = 0.199 m; max = 0.36 m).

Trends in Eastern Wheatbelt



Bore ID: MDX (617147E, 6516158N)

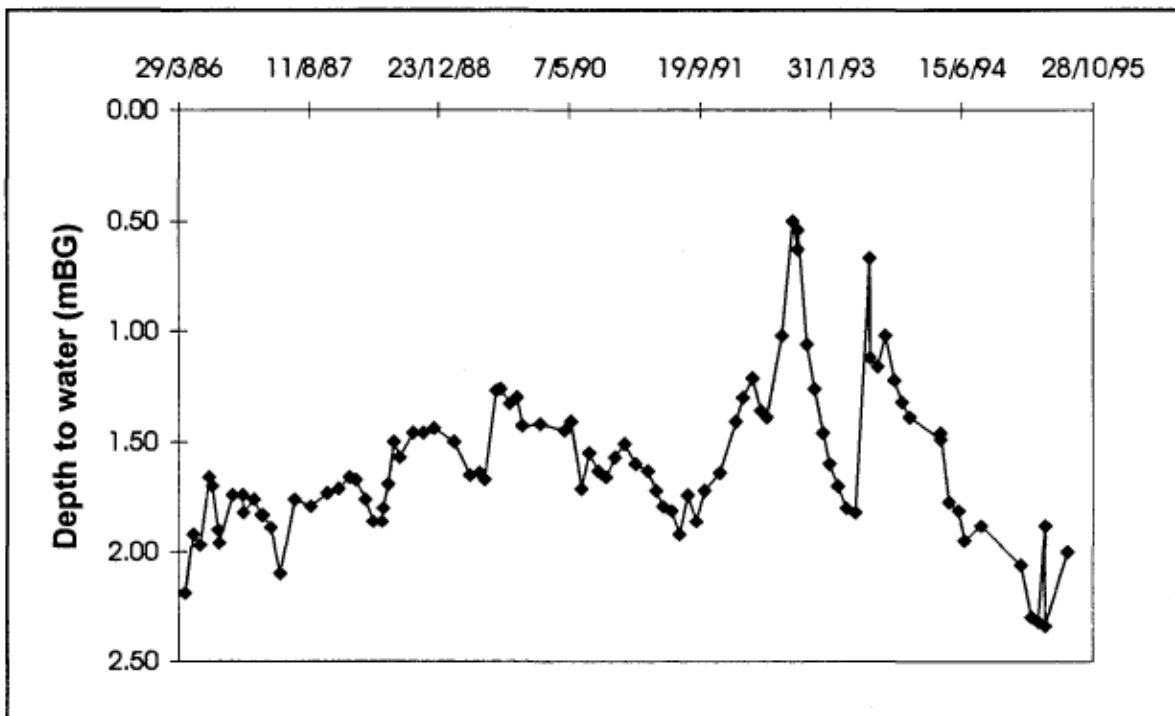
Location: Merredin (Dryland Research Institute)

Landscape position: Valley floor. Land unit: Merredin.

Land use: Wheat/pasture or wheat/grain/legume rotation.

Features: Valley floor. Sandy clay loams. Little runoff occurs although soil structural decline may produce local redistribution and ponding. Groundwater yields high but of poor quality. Seasonal variations to groundwater levels are minimal. Watertable rising steadily at about 25 cm per year.

This site is drilled in parkland surrounding the Dryland Research Institute, but reflects the groundwater conditions in the surrounding farmland.



Bore ID: MD03 (618753E, 6517988N)

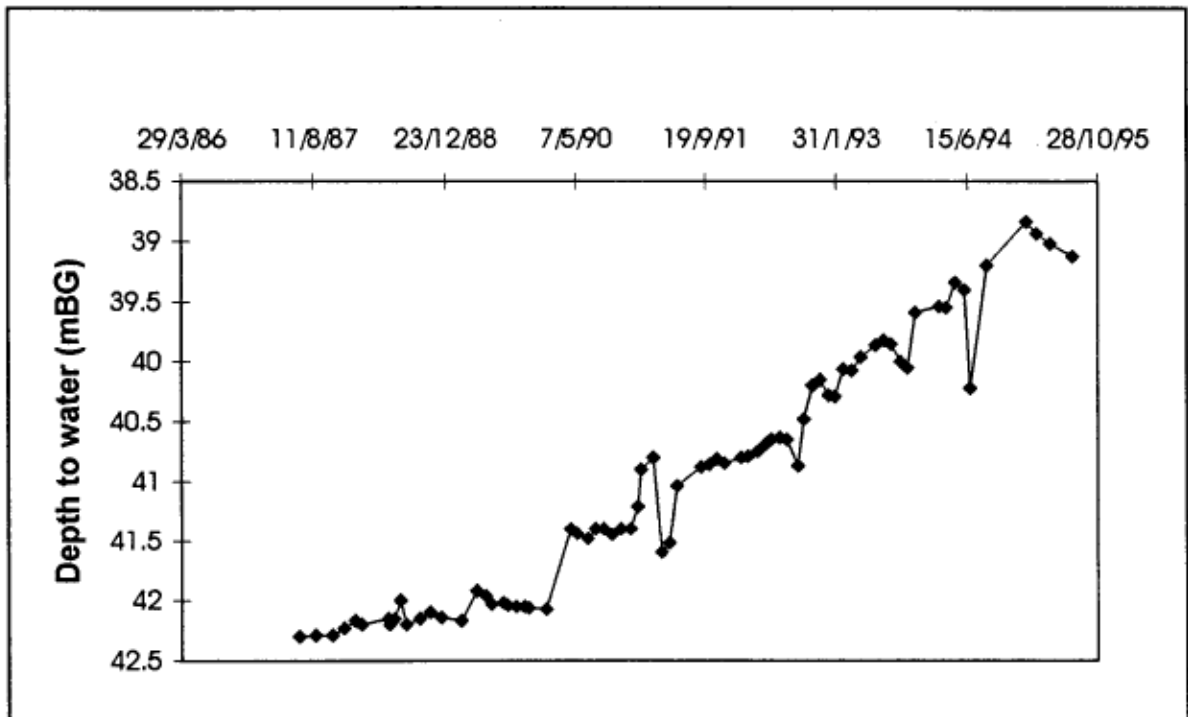
Location: Merredin

Landscape position: Minor drainage line, valley floor. Land unit: Merredin.

Land use: Wheat/pasture or wheat/legume (peas, fabas).

Features: Valley floor adjacent to minor drainage lines. Sandy clay loams. Little runoff occurs although soil structural decline may produce local redistribution and ponding. Groundwater yields high but of poor quality. Watertables close to surface (within 1-2 m) and saline. Watertable changes influenced by streamflow with large seasonal variation. Minimal rise (approximately 3 cm per year).

The reduction in the watertable after 1991 can be attributed to the effect of 70 ha of trees planted downstream from the bore.

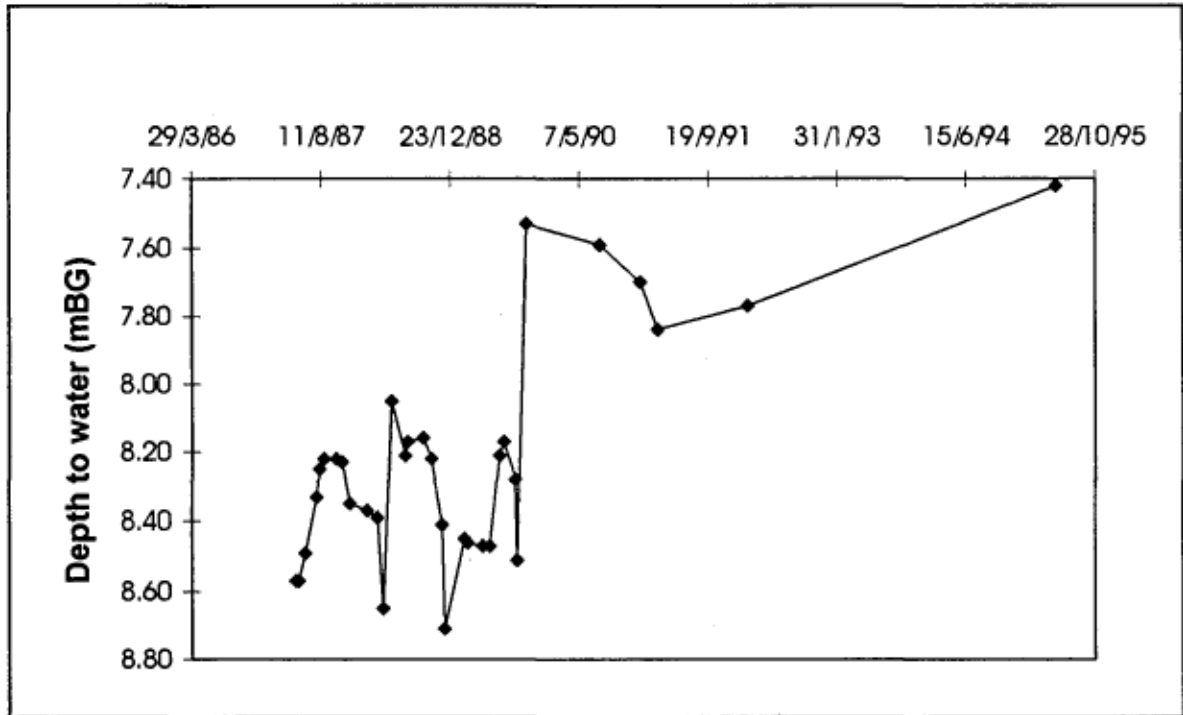


Bore ID: MDA (625042E, 6514218N)

Location: Merredin

- Landscape position:** Near catchment divide adjacent to sandplain. Land unit: Norpa.
- Land use:** Wheat/lupin, Triticale/serradella (acid).
- Features:** Located in upper slopes of catchment. Deep sands (1-8 m), well drained. Acidic (<pH 5 CaCl). Often contain perched watertables. Watertables deep and rising rapidly, approximately 25-30 cm per year due to poor water use of annual based agricultural system.

Episodic events



Bore ID: B06 (732032E, 6482800N)

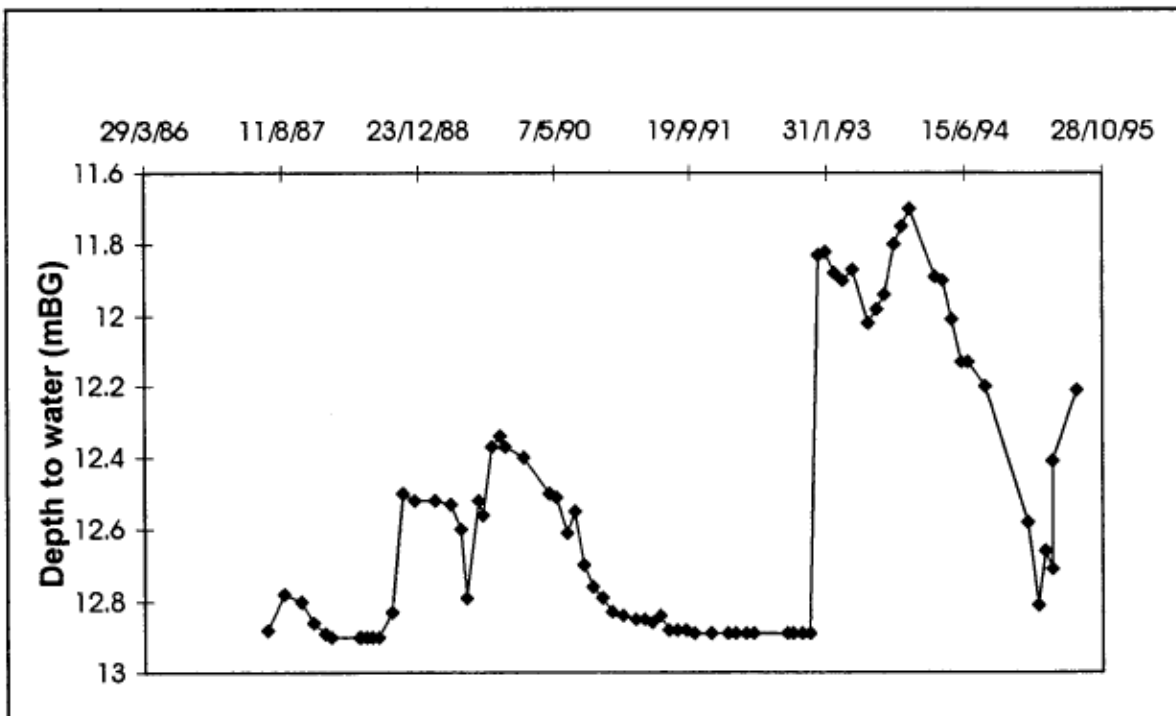
Location: Skeleton Rocks, Holleton

Landscape position: Valley floor. Land unit: Collgar.

Land use: Wheat/pasture rotation.

Features: Valley floor location on the edge of a small claypan. Sandplain and gravelly soils upslope. Groundwater system poorly developed; landscape cleared since 1980. Seasonal recharge prior to 1988 flowed to adjacent groundwaters.

Episodic recharge due to a rainfall event at the end of winter (October 1988) caused a large rise in the watertable. Drainage from this area did not occur sufficiently to resume previous water levels. Any future recharge event will probably be cumulative.



Bore ID: MDB (623460E, 6514238N)

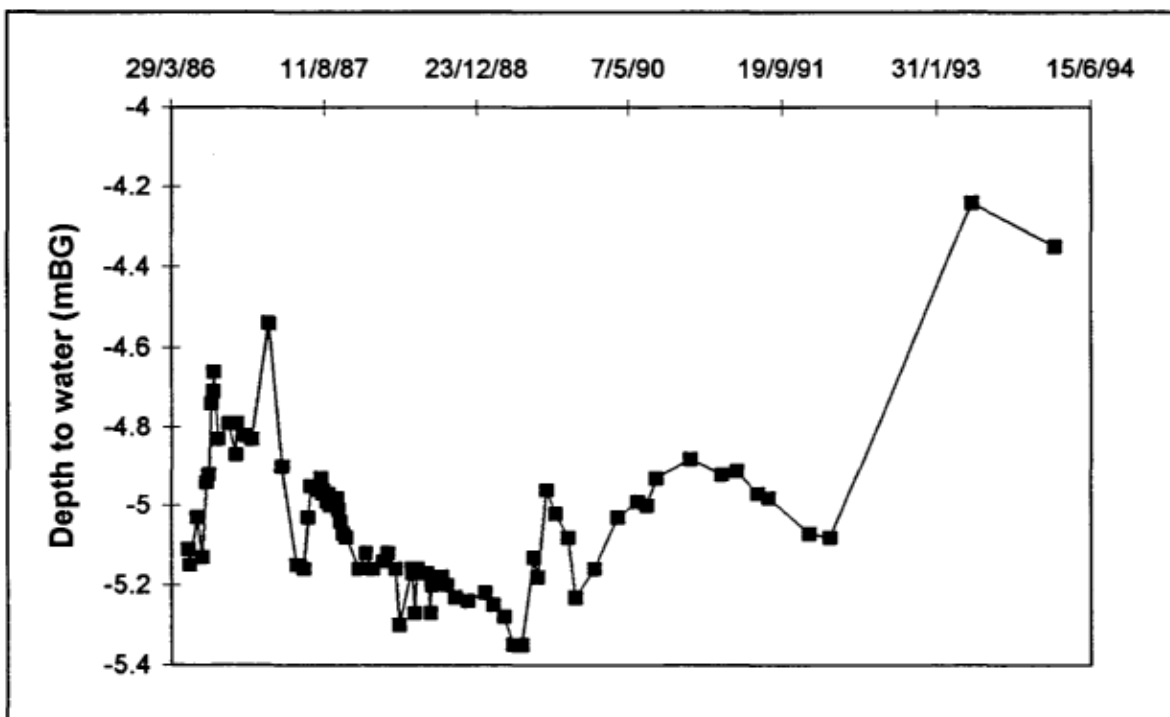
Location: Merredin

Landscape position: Generally catchment divide or as an upland feature. Land unit: Ulva.

Land use: Wheat/pasture, wheat/lupin rotation.

Features: Located in upper regions of catchment. Characterised by shallow sands to sandy loams over massive or indurated gravels. Generally little runoff except during large events. Under the current agricultural systems watertables respond quickly to rainfall but drain seasonally to a base level. Response to a summer episodic event was rapid causing a substantial rise in water levels. These gradually drained away in the following season.

Treatment sites



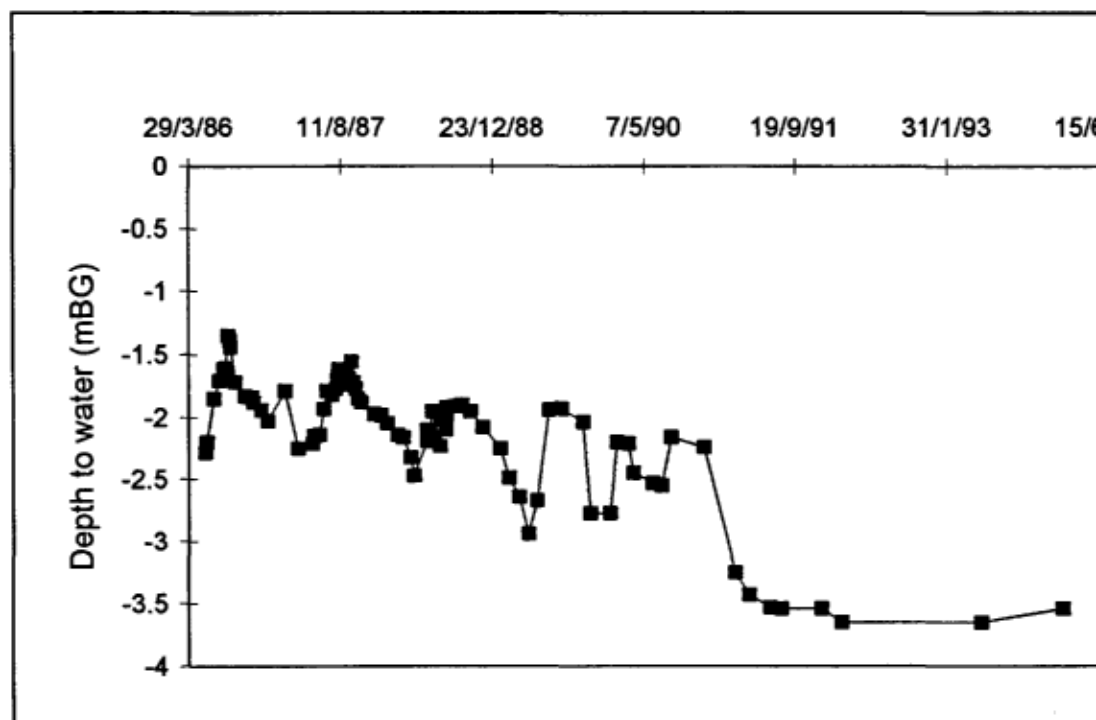
Bore ID: AB12 (619951E, 6484715N)

Location: East Belka

Landscape position: Toward top of catchment on sands. Land unit: Norpa.

Land use: Wheat/lupin, Triticale/serradella (acid).

Features: Located in the midslope this is the recharge zone for an adjacent sandplain seep. Sands are to depths of 7 m above a further 2 m of gravel. Watertables have continued to rise in the deeper aquifer in this zone. This is consistent with high recharge zones occurring in upper catchment areas of other regions. This water is being used by a tree plantation downslope (see ABO1a and ABE 13).



Bore ID: ABO1a (619951E, 6484715N)

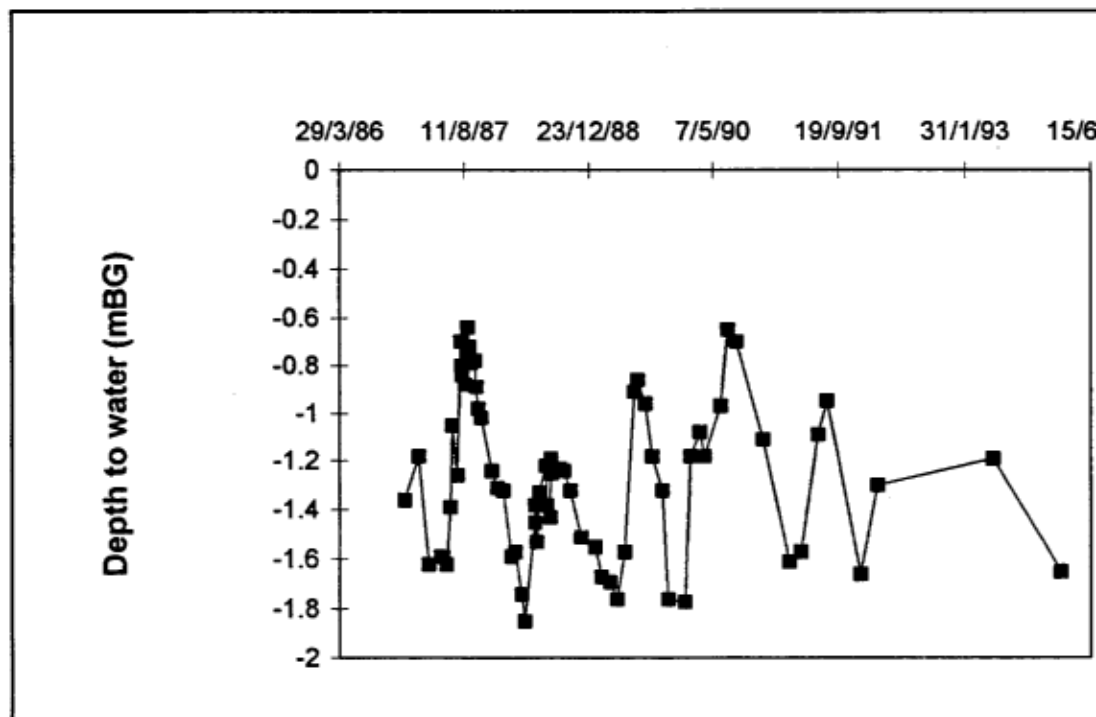
Location: East Belka

Landscape position: Toward top of catchment. Land unit: Norpa.

Land use: Mixed eucalypts planted in 1986.

Features:

Sand depth of 2-3 m above gravel and saprolite. A siliceous hardpan at 5 m is also responsible for a sandplain seep development further downslope. This piezometer is located within a tree plantation, planted to dry up the seep, and the fall in water levels indicates that the trees are being effective.



Bore ID: ABE13 (619951E, 6484715N)

Location: East Belka

Landscape position: Toward top of catchment on sands. Land unit: Norpa.

Land use: Wheat/lupin, Triticale/serradella (acid).

Features:

Located in the seep, i.e. where groundwater is discharging. This was potentially good cropping land prior to groundwater rising and salinity development. Sand depth 1-1.5 m over gravels and clay. This region is now being controlled by the tree plantation. It can be seen that despite an increase in water levels about 150 m upslope of the seep the trees are using sufficient water to control the water levels within the seep.

Sufficient recharge on the seep causes seasonal fluctuations. Cropping has resumed on most of the previously saline area:

References

- Geological Survey of Western Australia (1990). Geology and mineral resources of Western Australia, Memoir 3. State Printing Division, Perth 1990, pp. 10-79.
- George, R.J. (1990). Preliminary groundwater and salinity investigations in the Eastern Wheatbelt. 4. Kitto's hillslope Tammin: 1985-1990. Department of Agriculture, Western Australia, 1990. *Div. Resource Management Tech. Report No. 92.*
- George, R.J. (1992). Groundwater processes, sandplain seeps and interactions with regional aquifer systems in South-Western Australia. *Journal of Hydrology* 134: 247-271.
- George, R.J. and Frantom, P.W.C. (1990a). Preliminary groundwater and salinity investigations in the Eastern Wheatbelt. 1. Brennand's catchment. Department of Agriculture, Western Australia, 1990. *Div. Resource Management Tech. Report No. 88.*
- George, R.J. and Frantom, P.W.C. (1990b). Preliminary groundwater and salinity investigations in the Eastern Wheatbelt. 2. Merredin catchment. Department of Agriculture, Western Australia, 1990. *Div. Resource Management Tech. Report No. 89.*

South West and Upper Great Southern Region

Richard George and Don Bennett

Regional introduction

The South-West and Upper Great Southern hydrological province covers the catchments of the westward and southern flowing rivers. It extends from Rockingham in the north to Walpole in the south and includes the catchments of the Serpentine, Murray, Harvey, Collie, Preston, Blackwood, Donnelly, Warren and Deep Rivers. The area contains about three million hectares of cleared land. The range of agricultural land use within the area is diverse and is governed by annual rainfall and can be divided into four broad areas based on land use, geomorphology and hydrogeology.

These are:

- (i) the Wheatbelt;
- (ii) the Woolbelt;
- (iii) the South-West Hills; and
- (iv) the Coastal Plain.

(i) The Wheatbelt

The Wheatbelt lies in the upper Blackwood River Catchment. The major land use is broad scale cereal cropping together with sheep grazing of annual pastures (300-500 mm per year rainfall). The Wheatbelt sits in the zone of Ancient Drainage (Tille, P.J and Percy, H.M., 1995), where water courses only flow in very wet years. This zone lies to the east of the Meckering Line, which forms the limit of geomorphologic rejuvenation, running through Toolibin, Wagin, Katanning and Broomehill.

The area is characterised by broad valleys of low gradient (1:1,500 or less) containing salt lake chains. The surrounding landscape is gently undulating (mostly 280-400 m above sea level) with hillslopes of low relief covered by sandy duplex soils and gravels. Most of the soils are derived from the lateritic profile overlaying the Archaean Granite basement which contains intrusive dolerite dykes. Salt stores on the deeper (- 20 m) profiles range from 2,000 t/ha on hillcrests to more than 5,000 t/ha in valleys.

Most salinisation is a result of groundwater recharge due to clearing causing either valley floor salinity or hillside and sandplain seep development. Valley salinity is caused by regional watertables rising to ground level beneath the valleys (George, 1992a). Hillside seeps develop where the watertables on the hillslopes intersect the ground surface changes in surface gradient, or are caught behind barriers, such as bedrock highs or dolerite dykes (~Engel *et al.* 1987). Sandplain seeps develop at the

base of sandplain areas, where the sand sheet and clay soils intersect, causing surface discharge and evaporation of the brackish (<1,000 mS/m), perched, groundwater systems (George, 1990).

Rates of groundwater recharge in the Wheatbelt have increased from less than 0.2 mm per year to between 10 and 50 mm per year after clearing (George, 1992b). Watertables are rising between 0.05 and 0.5 m per year. Run off has also increased to about 20 mm (4% of rainfall) and has an average salt concentration of about 850 mS/m (George *et al.* 1994). It is estimated that there is currently 73,600 ha (9.2% of cleared land) of salt affected land in this zone. It is predicted that the area of salt affected land will increase to 20% of cleared land by 2020 (Ferdowsian *et al.* 1996), with large areas within the valleys at most risk.

(ii) The Woolbelt

The Woolbelt (500-800 mm per year rainfall) encompasses the headwaters of the Murray, Collie and Warren catchments. It incorporated the Zone of Rejuvenated Drainage and the Eastern Darling Range Zone (Tille, P.J. and Percy, H.M., 1995). The main land uses are sheep and cattle grazing of annual pastures together with rotational cropping. Timber plantations (mainly Pine and Tasmanian Bluegum) are becoming an important land use in these areas on previously cleared agricultural land. Towns in the south-west Woolbelt include Boddington, Darkan, and Boyup Brook. Narrogin and Kojonup are situated on the eastern margin of the Woolbelt, while Collie and Bridgetown are near its western edge.

Much of the Woolbelt has undulating to rolling terrain, lying between 200 and 400 m above sea level. Dissection of the lateritic profile has resulted in gently inclined low hills (often containing areas of lateritic breakaways) and broad valley floors. Drainage lines, although sometimes sluggish in the eastern areas, flow along clearly defined water courses in winter. Where dissection has been greatest, areas of basement Archaean granite rock are exposed. Most soils have been formed on the mottled or pallid zones of the lateritic profile or on freshly weathered granite.

The granite basement in the Woolbelt is complex and contains more intensive faulting and dolerite dyke activity than the Wheatbelt. These faults and dykes form the major controls on groundwater movement and valley and hillside soil salinity development in the area (George and Bennett, 1993). The area contains large (~50-300 km long, ~20-800 m wide) faults, capable of transmitting saline (2,000-3,000 mS/m) groundwater across and within sub-catchments. The western half of the Woolbelt also contains the remnants of clayey, Tertiary, lacustrine sediments which remain on the edges of some hillslopes and within valleys at about the 240-260 m contour. These sediments affect the distribution of hillside seeps and the groundwater pressure in valleys. Palaeochannels, or ancestral rivers (e.g. the Beaufort-Towerrinning palaeochannel), occur within some valleys and can contain fresh (100 mS/m), artesian, groundwater supplies. Seasonal waterlogging on lower slopes and in valleys is also a widespread problem of the duplex (sand or loam over shallow clay) soils in the area. Salt-stores in the regolith range between 400 and 1,000 t/ha (George, R.J. and Bennett, D.L., unpublished data).

Run off in the Woolbelt is about 60 mm (10% of rainfall) with rivers having an average salt concentration of 450 mS/m. Stream salinities are increasing between 7 and 17 mS/m each year (McFarlane, D.J. and George, R.J., 1994). Recharge rate increases of between 10 and 100 mm have been observed in western Woolbelt catchments following clearing (Peck, A.J. and Williamson, D.R., 1987). Rates of watertable rise in the Woolbelt are generally estimated to be around 0.3 m per year in the mid and lower slopes (George, R.J. and Bennett, D.L., 1993), however rises of between 1 and 2 m per year have been observed on upper slopes and hillcrests (George, R.J. and Bennett, D.L., unpublished data). It is estimated that currently 125,000 ha, or 7.3% of cleared land, is salinised. This area is predicted to increase to 16.7% of cleared land by 2020 (Ferdowsian *et al.* 1996). In addition to cleared farmland, timber plantations situated near discharge areas are also threatened by salinity (Bennett D.L. and George R.J., 1995). Remnant, fresh groundwater supplies within the palaeochannels are also threatened with incursion by the surrounding saline groundwaters, as their pressures continue to rise.

(iii) The South-West Hills

The South-West Hills (> 800 mm per year annual rainfall) contain the more intensive agricultural industries such dairying, beef production, horticulture and viticulture. It has high population density and land values. The South-West Hills also contain most of the state's native forests (Jarrah and Karri) which cover approximately 50% of the area. There are large areas of Pine and Bluegum timber plantations. The area is bounded by the Woolbelt on the east, the Swan Coastal Plain below the Darling Fault on the west and includes the Western Darling Plateau, the Warren-Denmark Southland and the Donnybrook

Sunklands and the Leeuwin Block on the south-west corner. To the south-west and south it is bounded by the ocean. Major towns include Dwellingup, Collie, Donnybrook, Margaret River, Bridgetown, Manjimup and Northcliffe.

The terrain of much of the area is a mix of gently undulating lateritic plateau and deep, steep sided valleys of the major river systems. The rivers have a steeper grade and are faster flowing than in the east. Soils are mainly sandy and loamy gravels on the hills, with loamy earths formed on the fresh rock exposed in the valleys. There are some areas of sedimentary rocks. Basement is mainly Archean granite, with areas of high-grade metamorphic rock and gneiss.

Salinity has typically developed within minor tributary valleys in the east of the zone, although dolerite dyke and bedrock fracture controlled hillside seeps are also common. In the western areas salinity development is occurring in some recently cleared (> 1970) minor valleys, and within fracture and basement controlled hillside seeps (George and Bennett, 1993). The surface expression of salinity is not always easily recognised due to growth of salt tolerant perennial grasses such as Kikuyu and Paspalum. However, discharge of brackish groundwater from hillside seeps and waterlogging under high-value horticultural crops is a major concern. Similarly, concentration of salt in horticulture supply dams from seep discharge and evaporation causes problems to these high value industries.

Run off in the South-West Hills is high, approximately 150 mm or 10-15% of rainfall and has an average salinity of 70 mS/m. The forested hills zone contains most of the surface water catchments for the large population centres, as well as many smaller supply dams for horticulture. Salinisation of surface streams is therefore of large economic importance. Partially cleared south-west rivers such as the Collie and Warren Rivers have shown an average rate of salinity increase of about 10 mS/m per year over the last 20-30 years (Anon. 1989). It is estimated that there is currently 4% or 13,400 ha of cleared land that is saline or affected by seeps. This area is predicted to increase to about 10% of cleared farmland by 2020 (Ferdowsian *et al.* 1996).

(iv) The Coastal Plain

The Coastal Plain (800-1,000 mm per year rainfall) lies between the Darling Fault in the east and the coast to the west and extends from Perth to Busselton. Land use is mainly beef production and dairying on flood irrigated and dryland annual pastures. Population density and land values are high.

The plain is of low relief, formed of sediments deposited from rivers flowing from the Darling Ranges and marine processes which have deposited sands and swamp sediments. Heavy clay soils of the Guilford Formation comprise most of the superficial soils. The sandier, brackish Yoganup formation, which outcrops at the base of the Darling Scarp, separates the Guilford from the underlying Leederville Formation. The Leederville Formation contains large supplies of fresh groundwater and is recharged from the Yoganup formation in the east. Groundwater discharge occurs across the plain from the Guilford and Yoganup Formations, and locally around the bases of sandhills, with summer evaporation concentrating shallow soil and watertable salinities (Anon. 1991). Evaporation and recharge from irrigation water adds to surface soil salinities in irrigation areas. Typical salt storages within the clayey surface (10 m) soils are 200-500 t/ha. The area is extensively drained, however because of the low relief waterlogging is a major problem in winter.

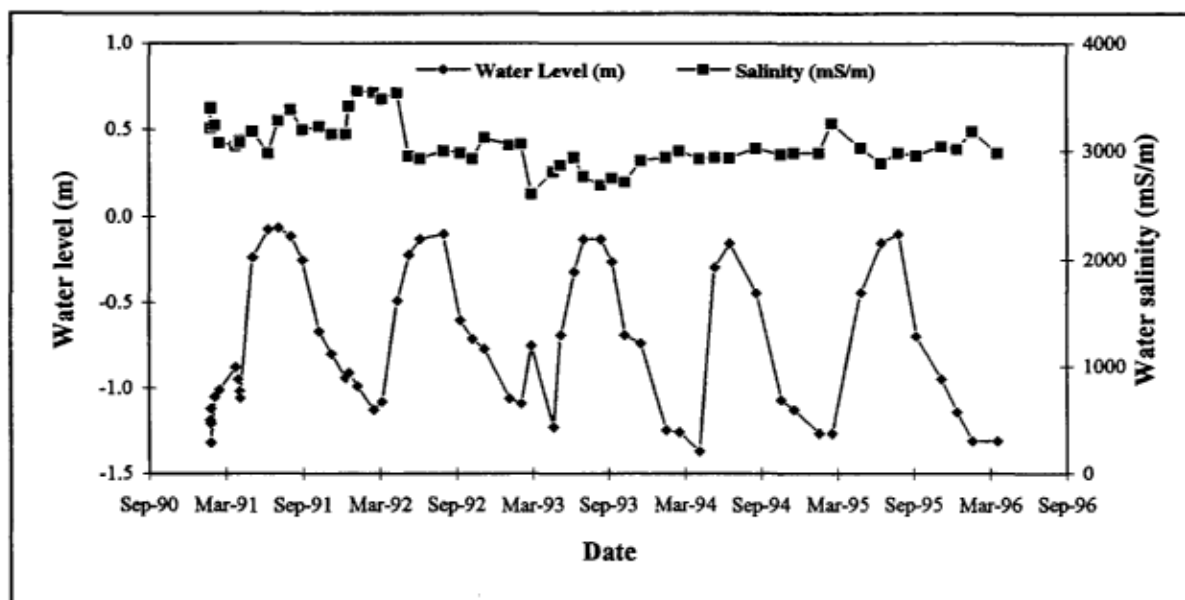
The combination of soil salinity and waterlogging results in pasture yield losses. The effect can be visually less dramatic than in eastern (Wheatbelt and Woolbelt) areas, due to spring pasture growth on surface (0.3 m) salt-leached soils, however production losses are very important. Using electromagnetic induction techniques Hojberg and George (1995) demonstrated 50% yield reduction in clover and ryegrass where EM38 levels exceeded 125 mS/m. Results of EM38 transect surveys show that approximately 20% of areas surveyed had levels in excess of 125 mS/m. Watertables fluctuate between the soil surface in winter and about 1 m below ground in summer. Long term watertable trends are stable because recharge is balanced by discharge into drains and creeks. However, the severity and extent of salinity is increasing due to evaporation and concentration. Currently it is estimated that on the Coastal Plain 10% (5,400 ha) of non irrigated and 22% (7,700 ha) of irrigated agricultural land is salt affected (suffer yield reductions > 25% due to salinity) (Ferdowsian *et al.* 1996). These areas are predicted to increase and may reach a maximum of to 43% and 80% respectively by 2020 if current trends continue.

The estimates for future salinity development (next 20 years) in the South-West and Great Southern areas are based on our current best estimates. They are based on trends from 5-10 years of monitoring and some anecdotal long-term evidence from

older farm wells and bores. More precise predictions will be able to be made when 10-15 years of watertable trend information is available. As well as affecting agricultural land, salinisation is also threatening isolated nature reserves within the Wheatbelt and Woolbelt zones (George *et al.* 1994). Within the South-West Hills and Coastal Plain zones, salinity is more insidious and can cause less-visually dramatic (but equally important) effects than in eastern areas. Pasture yield reductions, salts accumulating in water supplies and brackish water discharges within orchards are important issues of sustainability. In these areas salinity is probably the greatest single environmental factor preventing diversification and intensification of agriculture.

References

- Anon. (1989). Stream salinity and its reclamation in south-west Western Australia. Report of the Steering Committee for Research on Land Use and Water Supply. Water Authority of Western Australia.
- Anon. (1991). Groundwater investigations for the Irrigation Strategy Study, South-West, Western Australia. Water Authority of Western Australia.
- Bennett, D.L. and George, R.J. (1995). Using the EM38 to measure the effect of soil salinity on *Eucalyptus globulus* in south-western Australia. *Agric. Water Management* **27**: 69-86.
- 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 (ed. M.L. Sharma). A.A. Balkema Publish. Co., Rotterdam/Boston. pp. 25-39.
- Ferdowsian, R., George, R.J., Lewis, M.F., McFarlane, D.J., Short, R. and Speed, R. (1996). The extent of dryland salinity in Western Australia. Fourth Australian Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands. Albany, Western Australia.
- George, R.J. (1990). Reclaiming sandplain seeps by intercepting perched groundwater with eucalypts. *Land Degradation Rehab.* **2**: 13-25.
- George, R.J. (1992a). Hydraulic properties of groundwater systems in the saprolite and sediments of the Wheatbelt, Western Australia. *J. Hydrol.* **130**: 251-278.
- George, R.J. (1992b). Estimating and modifying the effects of agricultural development on the groundwater balance of large Wheatbelt catchments. *Applied Hydrogeology* **1**: 41-54.
- George, R.J. (1993). The hydrology of shallow and deep aquifers in relation to secondary soil salinisation in south-western Australia. *Geogr. Fis. Dinam. Quat.* **16**: 47-64.
- George, R.J. and Bennett, D.L. (1993). Hydrology of the Blackwood Catchment. Submission to the Blackwood Catchment Coordinating Committee.
- George, R.J., McFarlane, D.J. and Speed, R.J. (1994). The consequences of a changing hydrologic environment for native vegetation in south-western Australia. Role of Networks in Nature Conservation Conference Proceedings, Geraldton.
- Hoejberg, L.S. and George, R.J. (1995). EM38 correlation with soil salinity and the yield of irrigated pastures in south-western Australia. Report, Agriculture Western Australia, Bunbury.
- McFarlane, D.J. and George, R.J. (1994). How sustainable is grazing sheep on annual pastures in the Woolbelt? *J. Agric. W. Aust.* **35**(4): 16-21.
- Peck, A.J. and Williamson, D.R. (1987). Effects of forest clearing on groundwater. *J. Hydrol.* **94**: 47-65.
- Tille, P.J. and Percy, H.M. (1995). In: Remnant Vegetation and Natural Resources in the Blackwood Catchment - Atlas. *Agriculture Western Australia Bulletin*.

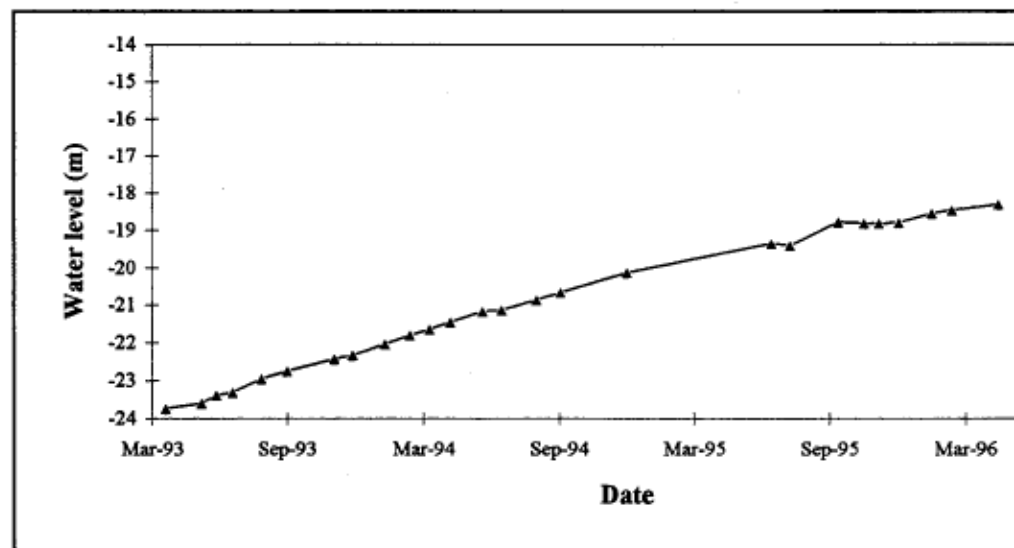


- Location:** Harris Road, Waterloo, Western Australia. (380235 mE, 6308104 mN, 21 m AHD).
- Landscape position:** On the Swan Coastal Plain within the Leschenault catchment.
- Land use:** Dairying on flood-irrigated perennial and annual pastures (850 mm annual rainfall).
- General information:** This bore was drilled to a depth of 2 m in January 1991. The bore is sealed from surface water (irrigation water and direct rainfall) in the top metre, and is screened between 1 and 2 m only. The soil salt storage is 400 t/ha (to 10 m depth).

Interpretation:

This hydrograph is typical of shallow watertables on the Coastal Plain. The watertable rises to the ground surface in winter, waterlogging pastures for 3-4 months each year. In summer, the watertable recedes to about 1 m below the ground surface.

The salinity of the watertable remains fairly constant and is high (3,000 mS/m). Salt is concentrated in the watertable by artesian aquifer discharge and summer evaporation from shallow watertables and irrigation water (in irrigation areas). The pasture species that are commonly grown survive the high salinity only by confining their roots to the soil surface (0.3 m) which is fresher because of leaching during winter. However, pasture growth can be severely reduced because of high soil salinities during summer (irrigated areas) and waterlogging during winter.

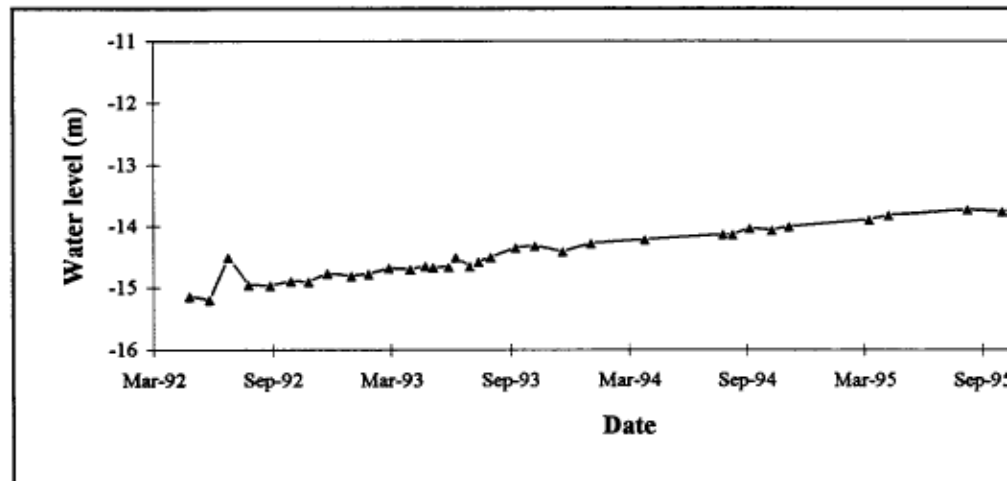


- Location:** Gibbs Road, Dinninup, Western Australia.
(454975 mE, 6270553 mN, 240 m AHD).
- Landscape position:** Upland plateau (sub-catchment divide), Blackwood River catchment.
- Land use:** Sheep grazing of annual pastures and rotational cropping (650 mm annual rainfall).
- General information:** This bore was drilled in March 1993 to granite basement at a depth of 27 m. The soil has a salt storage of 685 t/ha and the groundwater has a salinity of 910 mS/m. The hill has been cleared for 15 years.

Interpretation:

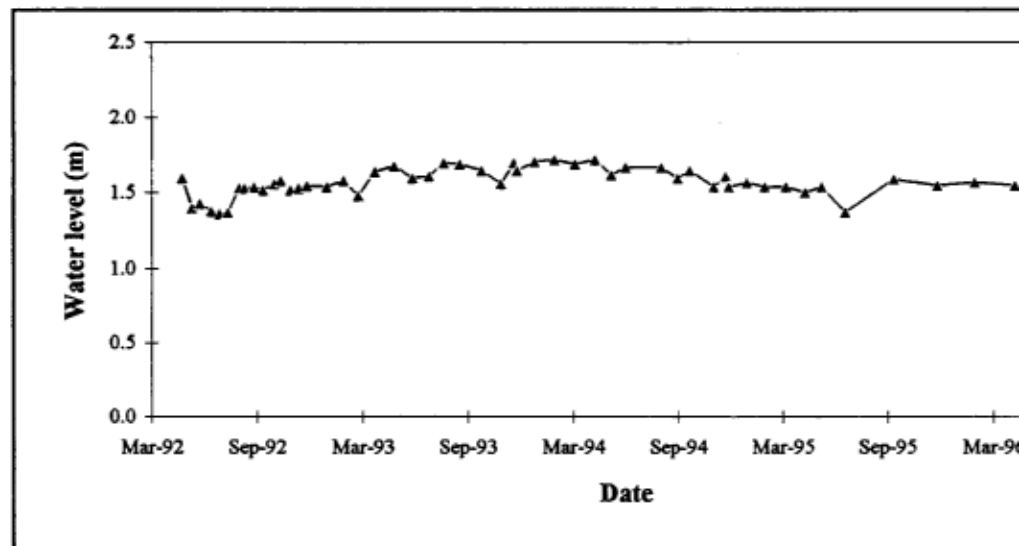
The groundwater is rapidly rising at an average rate of 2 m per year. On the hillslope below this bore, a small, saline hillside seep developed in 1992. Since then, the seep has rapidly grown to 4 ha in size, having extended approximately 200 m uphill from its original outbreak.

Watertable rates of rise of over 1 m per year are common in bores located near the tops of hills and on upland plateaus in the medium rainfall Woolbelt zone. High rates of recharge occur within these areas because the surface soils are often deep, free draining gravelly or sandy barns which allow soil moisture to rapidly infiltrate past the rootzones of annual pasture and crop species. Midslope hillside salt seeps then develop as a result of this rapid recharge.



- Location:** O'Connell Road, Duranillin, Western Australia. (478832 mE, 6293686 mN, 257 m AHD).
- Landscape position:** Midslope in the Date Creek catchment (Arthur-Blackwood river system).
- Land use:** Sheep grazing of annual pastures and rotational cropping (550 mm annual rainfall).
- General information:** This bore was drilled to fractured granite basement (17 m deep) in April 1992. It is located within a bedrock fault which crosses three surface sub-catchments. The water in this bore has a salinity of 1,700 mS/m.
- Interpretation:** The groundwater is steadily rising at an average rate of 0.5 m per year. The groundwater has built up to a level allowing flow along the fault, under the catchment divide and discharge into the neighbouring catchment.

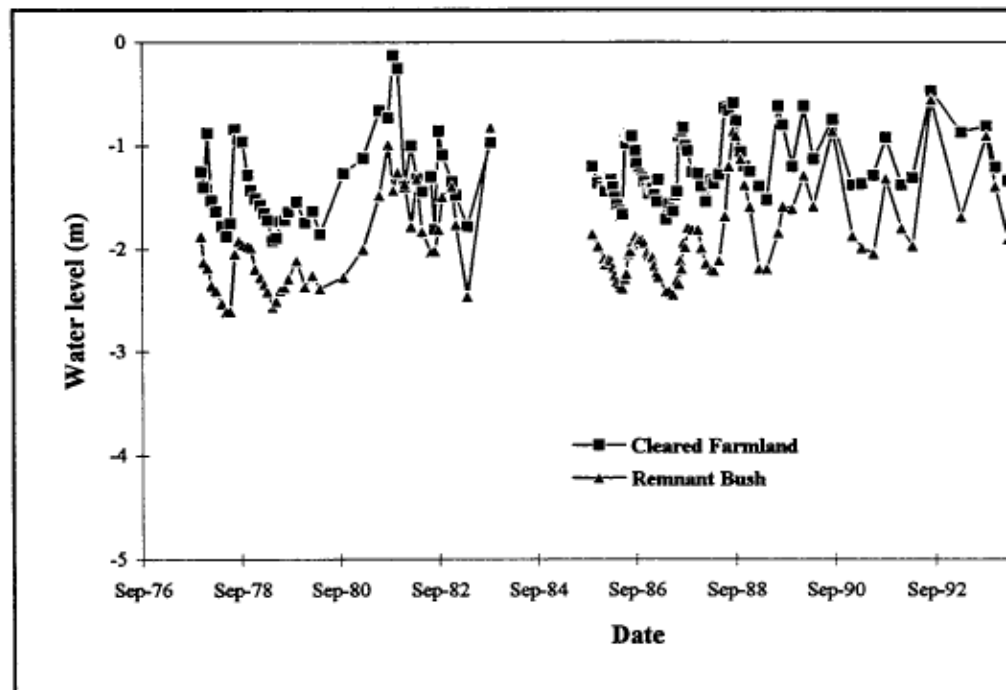
Faults are lineal zones of intensely fractured bedrock. They are usually more deeply weathered than the surrounding bedrock and are zones of faster groundwater movement. Because faults cross surface catchment divides they have the ability to transfer groundwater between catchments.



- Location:** Scott Road, Capercup, Western Australia. (4693006 mE, 6289401 mN, 244 m AHID).
- Landscape position:** Broad valley flats within the Arthur-Blackwood river system.
- Land use:** Sheep grazing of annual pasture with some cropping (580 mm annual rainfall).
- General information:** This bore was drilled (14 m deep) into the edge of a paleochannel (an ancient infilled river channel). The sand and gravel aquifers near the centre of the channel contain large yields of fresh (100 mS/m) water. Towards the edges of the channel the water becomes brackish (1,095 mS/m - this bore) due to groundwater intrusion from the surrounding hillslopes.

Interpretation:

Groundwater pressures under sedimentary valleys remain high (1.5 m above ground) as a result of recharge in the surrounding sub-catchments. Large saline springs which discharge saline water into the creek system have developed near the bore. A combination of this discharge and below average rainfall in 1993/94 have stabilised the aquifer pressure close to the bore. More springs can be expected to develop further up-catchment where pressures continue to rise. Failure to reduce these pressures will cause extensive soil salinity in the valleys and will threaten the fresh water resource of the paleochannel.



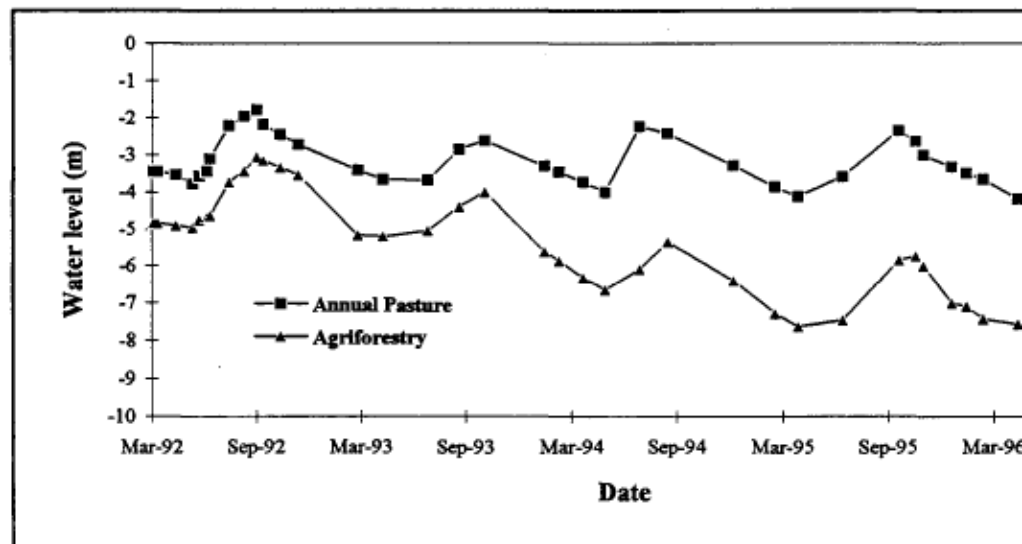
Location: Canal Road, Toolibin, Western Australia.
(557821 mE, 6360357 mN, 305 m AHD).

Landscape position: Broad valley flats, Lake Toolibin sub-catchment within the Arthur-Blackwood river system.

Land use: Cereal cropping and sheep grazing of annual pasture (400 mm annual rainfall).

General information: The bores were installed in 1977. 92% of the Lake Toolibin catchment has been cleared of native vegetation for agriculture. Rising groundwaters and saline run off are threatening the lake and its reserves.

Interpretation: The saline groundwaters beneath both cleared farmland and remnant bush reserves in the valley have risen significantly over the past 17 years (there is a gap in the monitoring records between October 1983 and November 1985). The groundwater beneath the bush reserve has been rising at an average rate of 0.05 m per year to within 1 m of the surface and is now killing the remnant bush species. Salt discharge from shallow saline watertables in the cleared catchment have resulted in an increase in the volume, and a deterioration in the quality, of run off waters reaching the lake. The lake water quality has deteriorated from base levels of less than 200 mS/m to more than 500 mS/m in recent years (George *et al.* 1994).

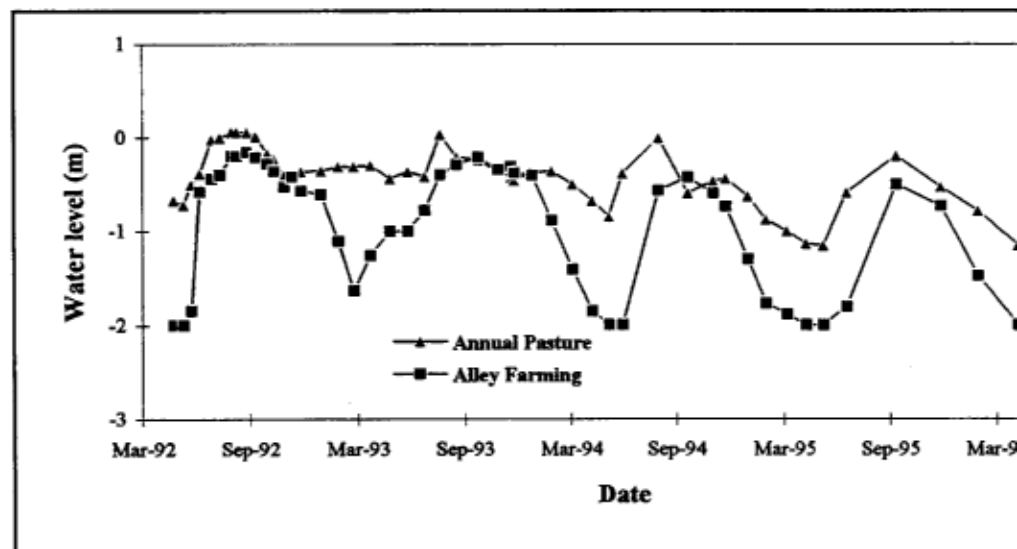


- Location:** Peninsula Road, Bridgetown, Western Australia (414577 mE, 6241669 mN, 234 m AHD).
- Landscape position:** A midslope sub-catchment in the lower Blackwood River Catchment.
- Land use:** Sheep and cattle grazing of annual pasture and hay cropping with some areas of intensive horticulture (900 mm annual rainfall).
- General information:** The agroforestry area was planted with Tasmanian Bluegum (*E. globulus*) and Sydney Bluegum (*E. saligna*) in 1987 at overall density of 450 trees/ha. The design incorporates 3-row tree belts separated by 25 m wide pasture bays allowing inter-belt cropping and grazing. Approximately half of the

sub-catchment (25 ha) has been planted, with the other half remaining annual pasture. The bores were drilled in March 1992. The sub-catchment has a salt storage of 164 t/ha, with the watertable salinity ranging from 100 to 530 mS/m.

Interpretation:

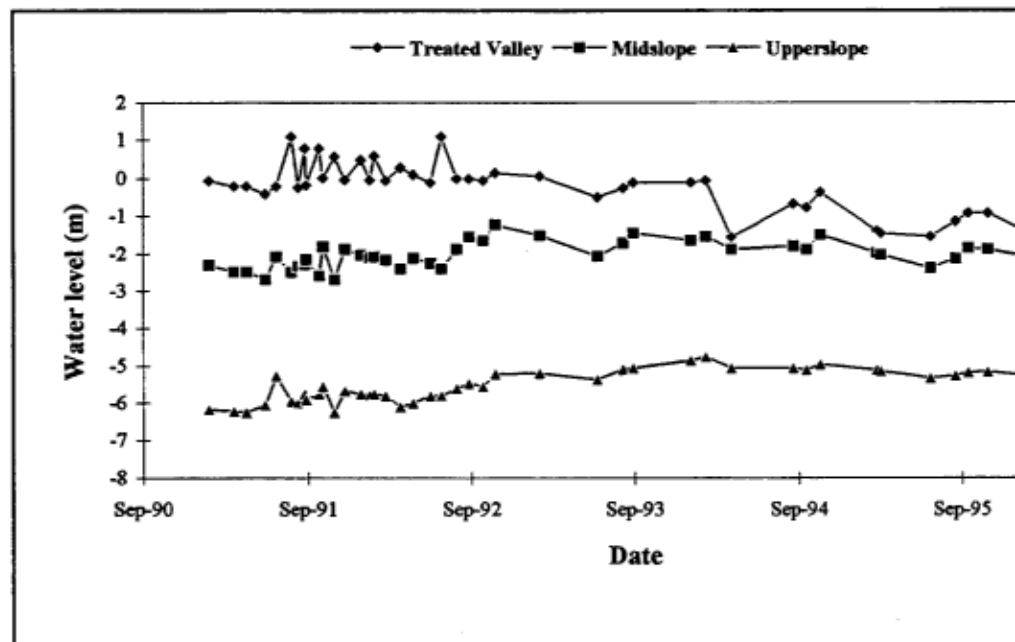
The watertable beneath the agroforestry has been falling at an average rate of 0.8 m per year since the bores were installed. The water level in the bore on the adjacent, untreated half of the sub-catchment shows no falling trend and has remained 2-3 m below ground. A saline seep below the agroforestry has become drier and ceased discharging water during the summers of 1994 and 1995. Both bores show seasonal watertable fluctuations.



- Location:** Scott Road, Capercup, Western Australia (471193 mE, 6288795 mN, 238 m AHD).
- Landscape position:** Broad valley flats in the Arthur-Blackwood river system.
- Land use:** Sheep grazing of annual pasture with rotational cropping (580 mm annual rainfall).
- General information:** The bores (2 m deep) were drilled in March 1992 and have salinities of 2,600 mS/m and 2,100 mS/m (alley farming and annual pasture respectively). The trees were planted in 1985 in a single-row alley layout (pasture alleys 15 m wide) to give an overall density of 250 trees/ha. The species planted are salt tolerant Flat Topped Yate (*E. occidentalis*).

Interpretation:

The trees within the alley farming area have been able to lower the watertable in the late summer, autumn and early winter periods. This reduces the evaporation and salt concentration in the surface soils during the summer and autumn. Winter recharge takes longer to affect the alleys, allowing pastures to germinate and establish in less saline and less waterlogged soil. Winter recharge may also be diluting the surface of the groundwater, allowing the trees to access and use the groundwater.



Location: Gunwarrie Road, Frankland Western Australia (521502 mE, 6202044 mN, 250-280 m AHD).

Landscape position: A sub-catchment hillslope within the Frankland river catchment.

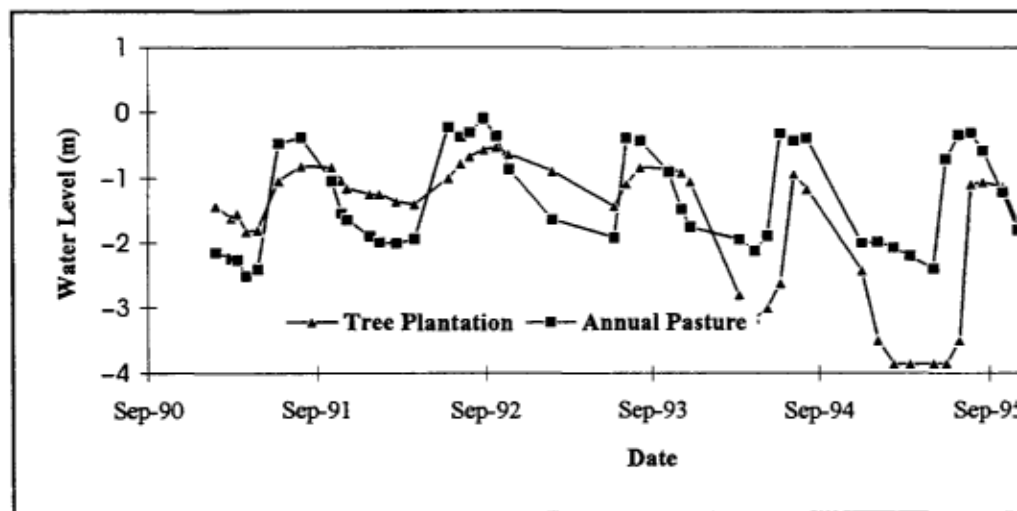
Land use: Sheep grazing of annual pasture with cropping (650 mm annual rainfall).

General information: The valley was planted to salt tolerant trees (density 625 trees/ha) and perennial pastures in 1990, and the transect of bores was drilled in February 1991. The trees planted are River Red Gum (*E. camaldulensis*) and Flat Topped Yate (*E. occidentalis*), with perennial pastures Phalaris, Tall Wheatgrass and Puccinellia sown between the rows. The upperslope, midslope and valley bores have salinities of 1,385, 3,090 and 3,370 mS/m respectively, and the soils of the sub-catchment have a salt storage of 695 t/ha.

Interpretation: The tree/perennial pasture combination is beginning to lower the watertable under the plantation. This effect is greatest in late summer (March 1994 and 1995).

However, watertables are continuing to rise upslope of the plantation in the untreated midslope and upperslope areas. The midslope watertables are continuing to rise at an average rate of 0.1 m per year and are within 1 m of the surface. Concentration of salts at the soil surface by evaporation can be expected to begin to adversely affect crop and pasture growth near the midslope bore over the next few years. The upperslope watertables are rising at an average rate of 0.2 m per year.

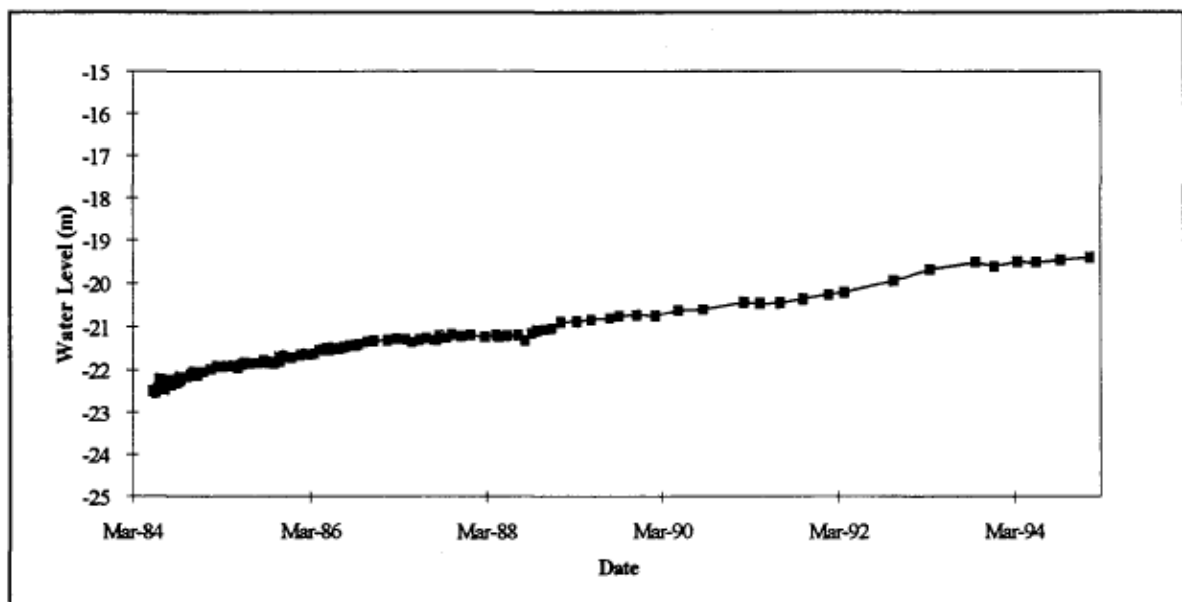
These hydrographs demonstrate that dense plantations of salt tolerant trees and pastures on groundwater discharge areas can lower the watertable under the plantations. However, watertables will continue to rise (and the salt affected area expand) unless more efficient water use (with deep rooted pastures and trees) occurs on the adjacent hillslopes.



- Location:** Bailye Road, Kojonup Western Australia (511591 mE, 6268735 mN, 292 m AHD).
- Landscape position:** Midslope in the Kojonup Brook catchment, upper Blackwood River system.
- Land use:** Sheep grazing of annual pastures in rotation with cereal cropping (525 mm annual rainfall).
- General information:** The bores were drilled in February 1991 to a depth of approximately 4 m. The watertable is fresh (250 mS/m), with the soils having a salt store of 350 t/ha. In response to a developing salinity problem in the valley below, trees were planted in 1991 in the lowerslopes (alley farming layout) and midslopes (70 m wide, dense contour belts). High water-use species with potential for timber production were planted where the watertable was fresh (<1,000 mS/m).

Interpretation:

The hydrographs compare watertables under the contour tree belt to the adjacent, untreated annual pasture paddock. The tree plantation is beginning to lower the watertable, particularly in late summer and early winter (the bore dried out during autumn 1996). The watertables under annual pasture remain within 2 m of the surface. Both bores show seasonal fluctuations.



- Location:** Clayton Road, Narrogin, Western Australia (495406 mE, 630016 mN, 300 m AHD).
- Landscape position:** Upperslope in a sub-catchment of Minning Brook, upper Murray/Williams River system.
- Land use:** Sheep grazing of annual pastures in rotation with cereal cropping (520 mm annual rainfall).
- General information:** The bore was drilled in May 1994 to granite bedrock at a depth of approximately 26 m. The watertable is brackish (690 mS/m).

Interpretation: The watertable is rising at a steady, average rate of 0.30 m per year. There is a saline seep at the base of the sub-catchment and the lower slopes are saline and waterlogged (approx. 10% of the sub-catchment).

Western South Coast Region

Ruhi Ferdowsian, Don McFarlane and Arjen Ryder

1. Climate

The western South Coast of Western Australia has a Mediterranean climate with warm, mostly dry summers and cool, wet winters. The mean annual rainfall of the region varies between 1,200 mm in the south-west and 400 mm per year in the north-east. Annual rainfall drops about 7 mm/km travelling north-east away from the coastline. Approximately 75% of the annual rain falls between May and October. Average number of wet days varies between 180 days per year in high rainfall areas to 110 days per year in low rainfall areas. Average annual evaporation increases from 1,200 mm in the south-west of the region to 1,900 mm in the north-east.

2. Geology

2.1 Precambrian

Archaean

The northern part of this region lies within the Archaean, Yilgarn Craton. This Craton is a major tectonic unit consisting of a large stable mass of rock, generally igneous and metamorphic, with a thin veneer of sediment in depressions. This zone has numerous dolerite dykes that have a west-north-west direction.

Proterozoic

The highest mountains in the South West are the Stirling Ranges and Mount Barrens. These ranges are composed of metamorphosed sediments that have been pushed up along the southern margin of the Yilgarn Craton.

The southern part of the area lies within the Albany-Fraser Orogen which is Proterozoic material welded to the southern margin of the Yilgarn Craton. Contact between the Craton and the Orogen is not a clear boundary but is a broad zone with attributes which change gradually from that of the Craton to that of the Orogen. The Albany-Fraser Orogen consists of two main tectonic belts; the Biranup Complex and Nornalup Complex.

Biranup Complex

The Biranup Complex is to the south of the Yilgarn Craton and was probably formed from remnants of Yilgarn Craton (e.g. some dykes continue from the Craton into the Complex where they become increasingly metamorphosed). There are hardly any granitic plutons within the Complex and its rocks are highly metamorphosed.

Nornalup Complex

Further south is the less metamorphosed Nornalup Complex that forms the southern margins of the Albany-Fraser Orogen. This belt is characterised by abundant plutonic intrusions the biggest of which is the Porongurup Range.

2.2 Cainozoic

The Cainozoic period covers the last 65 million years. Geological units that were developed during this period may be divided into the Tertiary (between 2 and 65 million years old) and the Quaternary (<2 million years old).

Tertiary

Low lying Precambrian rocks north and north-east of Albany, and even some areas north of the Stirling Ranges, are mostly covered by Eocene sediments. These areas are commonly known as sand plain and the sediments consist of the Werillup Formation and the overlying Pallinup Siltstone. Together these sediments form the Plantagenet Beds.

The Werillup Formation was first deposited over bedrock in a swampy environment. These sediments consist of dark-coloured clay, dark-coloured siltstone and sand (sandstone). A dark-coloured silt usually overlies the sand. The sand has coarse grains and a higher hydraulic conductivity than the siltstone and clay. The lowest layer of the Werillup Formation may contain very coarse material, including rounded pebbles, which were deposited in river beds.

The Pallinup Siltstone was deposited over the Werillup Formation in a marine environment. The maximum known depth of the Siltstone in the study area is about 60 m. Colluvial, alluvial, and fluvial sediments may cover the Siltstone. The Siltstone contains pink and white spongolite (a siltstone full of sponge spicules). Mount Barker Stone and Woodgenellup Stone are examples of these sediments. Closed depressions occur in areas underlain by the Siltstone. Occasional sinkholes may appear in areas that have thick spongolite sediments because lime which was in the spongolite has been dissolved.

Occasional granitic highs indicate that the bedrock has an irregular surface. There are also outcrops of Precambrian bedrocks in the Tertiary sediments that form the hills of this zone.

A period of lateritisation occurred in the Oligocene and/or Miocene (15 to 30 million years ago). Over a large part of the study area the weathering profile was capped by a massive pisolitic laterite, 2-4 m thick. This period was marked by wet and dry seasons. During the wet season leaching of the underlying material occurred. During the dry season an iron oxide rich solution was drawn to the surface by capillarity. Oxidising conditions caused the iron oxides to precipitate in the near surface profile and form laterite. Relics of the lateritic cap and overlying sands are common throughout the region.

Quaternary

The Quaternary is the last two million years. During this period, alluvial and colluvial sediments were deposited in depressions and footslopes of the study area. These sediments consist mainly of clay, silt, sand and occasionally well-rounded pebbles and cobbles. These rounded rocks can be seen on high grounds, on top of the Pallinup material, on footslopes of the Stirling Ranges (the latter being quartzite and sandstone from the Stirling Range Beds). Rounded pebbles along the Pallinup River are Archaean in origin and form the lowest part of the Werillup Formation that is exposed in the river bed.

There were very dry periods in the Quaternary which denuded the natural vegetation of the area and allowed winds to erode the landscape (particularly the lakes and stream beds) to form north-west/south-east oriented sand dunes. Most of the present lakes of the study area were also formed during the Quaternary.

3. Physiography

The hypothesis that the Darling Plateau was uplifted during the Tertiary was proposed 80 years ago (Jutson, 1914). There is a tilted landscape from the Plateau to the continental shelf known as the Ravensthorpe Ramp (Cope, 1975). Tilting of the Ravensthorpe Ramp occurred in the Oligocene (Cope, 1975). An east-west drainage divide separates the Darling Plateau from the Ravensthorpe Ramp. This divide, which is about 120 km from the coast (about 50 km north of the southern margin of the Yilgarn Craton), forms a hinge line named the Jarrahwood Axis (Cope, 1975). This divide forms the northern boundary of the South Coast of Western Australia.

The Ravensthorpe Ramp has other east-west axes such as the Perillup Hingeline (Ferdowsian and Greenham, 1992). The formation of these axes and later erosional processes have resulted in the formation of distinct Hydrological Provinces on the western South Coast of Western Australia.

4. Hydrological Provinces of the western South Coast of Western Australia

A Hydrological Province (HP) can cover a large area (>10,000 ha) and it has a stream frequency, dissection and channel development pattern which is similar across its area. Its unique geology, physiography and erosive processes has affected its landform patterns and aquifers. The area may be in more than one rainfall zone.

The following seven provinces have been defined for the western South Coast of Western Australia.

4.1 Dissected rejuvenated drainage areas near northern catchment divides

This province has an elevation of between 240 and 360 m AHD (Australian Height Datum) and is an erosional zone with well-defined creeks and moderately deep to shallow (<20 m) bedrock that surfaces on some ridges. Salt storage varies with the weathering depth and can exceed 2,000 t/ha on hillslopes and twice that in valley floors. Aquifers are mostly local and their boundaries are the same as the catchment divides. Groundwater salinities vary with rainfall, being >2,500 mS/m in the <500 mm per year rainfall zone to about 1,300 mS/m in the 700 mm per year rainfall zone. Groundwater level rises are abrupt with strong seasonal trends and significant jumps in wet years. There has been a net rise in their groundwater levels which will continue until a discharge zone is formed. Soil salinity is in form of hillside seeps and valley floor salinity and may be affected by dolerite dykes and shear zones.

4.2 *Very gently to gently undulating areas near the catchment divides*

This province has an elevation of between 180 and 280 m AHD and forms the divides between the catchments on the South Coast. These areas have both erosional (hilly areas) and aggradational zones (depressions). Their depressions are well-defined but have no defined creeks. Bedrock is moderately deep (>30 m) and few rock outcrops appear on ridges. Salt storage varies with the weathering depth but generally is high (1,000-3,000 t/ha). This region has mostly a regional aquifer and the groundwater flow continues under the undulating areas. Groundwater salinity decreases with increasing rainfall being >2,500 mS/m in <500 mm per year rainfall zones to 800 mS/m in the 800 mm per year rainfall zone. Soil salinity is in the form of broad valley and depression floors. Groundwater levels are rising and will continue until a discharge zone is formed. The rises are less erratic (Hydrographs 1-4) than the dissected areas except near discharge zones that have strong seasonal fluctuations (Hydrographs 5 and 6). Water levels in a bore that was drilled in 1980 in a parkland cleared area (20 large trees per hectare) has had very little rise (Hydrograph 7). This area is a very gently undulating land that is moderately waterlogged. Without those trees water levels would have been much higher than present.

4.3 Stagnant broad valley floors and lake systems in broad flats

There are three main areas that form this province; the middle of the Frankland and Upper Kent Catchments (220 m AHD); the North Stirlings (240 in AHD) and sumps and ancient drainage flats that are north-west to north-east of Jerramungup (300 in AHD). This province has broad flats that have either Tertiary sediments or Quaternary material in broad valley floors. Surface or internal drainage is almost non-existent. Run off from the areas of this province, as well as some run off from the very gently to gently undulating areas, flows into flats, lakes and swamps. Salt storage is very high. Some profiles have >10,000 t/ha of salt stored in them. Even prior to clearing the groundwater levels were close to soil surface (Hydrograph 8). These levels drop to a few meters below soil surface after dry years. Groundwaters are very saline (2,500-6,500 mS/m) and in cleared areas are close to the soil surface

and widespread soil salinity has occurred. Flats with groundwater levels near the soil surface are recharge zone in winter and discharge zones in summer. This situation creates strong seasonal changes in groundwater levels. In this province, a moderately deep (>0.3 m) sandy A horizon will prevent soil salinity while the areas that have a shallow A horizon (<0.1 m) have already been or will be affected by soil salinity. Geological features such as shear zones and dykes will not affect the occurrence of salt patches as much as in the dissected areas. Coarse material that may exist in the regolith of some in-filled valleys may assist groundwater movement and cause seeps in low-lying areas.

4.4 Dissected Precambrian areas that are close to the coast

These areas have younger soils that are mostly derived from *in situ* weathering of crystalline rocks. Occasionally thin layers of Tertiary sediments may cover the midslopes of this area. Salt storage is moderately low (<2,000 t/ha). The salinity of the groundwater depends on the amount of rainfall, landscape position and the soil profile and varies from <160 mS/m in the >1,100 mm per year rainfall zone to 800 mS/m in the 800 mm per year rainfall zone. Shear zones affect and facilitate the movement of groundwater in this province. Groundwater levels under annual pastures are rising abruptly in some years (Hydrograph 9). Bluegum plantations in these areas have reduced groundwater levels (Hydrograph 10).

The depth to bedrock is usually less than 20 m with mainly local aquifers. Salt expresses itself in the form of hillside seeps, spring lines and salt-affected swampy depressions and creeks. Shear zones carry groundwater to particular parts of the landscape.

4.5 Elevated Tertiary Coastal Belt

This is a belt of Tertiary sediments that extend from the Lower Hay River (west of Redmond) to Albany, the Pallinup River, Bremer Bay and further east to the Fitzgerald River National Park. The western part of this belt is about 30 km wide, extending to Narrikup, north of Albany. The width of this belt decreases to 10-15 km near the Pallinup River and further east. The elevation is mainly between 50 and 90 m AHD.

Many deep (>20 m) streams with swampy floors dissect this belt providing natural drainage to the Southern Ocean. The location of creeks and open depressions in this province is probably caused by shallow bedrock. The deep (>30 m) Tertiary sediments have many internally drained swamps while the shallow Tertiary sediments (<15 m deep) have open depressions and creeks.

In addition to the surface drainage, there is a significant groundwater flow to the sea for those areas close to the coast. Shallow bedrock often blocks the movement of this groundwater. The flow of groundwater to the rivers and coast lines is mainly through ancient valleys that are filled with sediments from the Werillup Formation.

Salt storage varies from 300 t/ha in moderately shallow areas (15-30 m) to 3,000 t/ha in very deep holes (80-90 m). Despite some very high salt storages, the groundwater in this belt is fresh to brackish (<250 mS/m) and the streams that flow in the western

part of this area have perennial, fresh to brackish water. Groundwater levels, except in swampy valley floors, are generally very deep. Despite this, there are abrupt changes in groundwater levels (Hydrograph 11). This is because the groundwater of this province can relatively easily discharge into dissected creeks or into the ocean. No, or very little, soil salinity exists in this hydrological unit and little is expected.

4.6 Coastal flats with shallow Tertiary sediments

Youngs Siding and Sleeman Flats to the west of Albany and west of the Coastal Belt are typical of this province. These stagnant, shallow (<20 m), Tertiary flats have an elevation of 15-40 m AHD and few defined streams. There are occasional granitic hills among the flats.

The depth of the Tertiary sediments is less than 25 m. Soil profiles consists of Pallinup silt that in some places may be buried under Quaternary sands. Where the depth of sediments exceeds 20 m, Werillup Formation material may occur on top of the bedrock. Salt storages vary between 400 and 2,000 t/ha.

Although this area has a high rainfall (>900 mm), groundwater salinities are high (350-2,500 mS/m). The lower range of groundwater salinities are in areas that have Quaternary sands or are near the Elevated Coastal Belt. The high groundwater salinity is because of poor dissection and very, low hydraulic gradients which has historically prevented the flushing of salt by surface or groundwater flow.

Saline groundwater levels are above or near the soil surface (Hydrograph 12). Groundwater levels have strong seasonal fluctuation (between 1-2 m). This is typical of the flats where groundwater levels are close to soil surface. In this hydrological province, soil salinity, waterlogging and inundation are very common.

4.7 Inland sand plains

This province is a belt of deep Tertiary sandplains, with many sand dunes, swamps and lakes. The area is north of and parallel to the Coastal Belt, and continues from south of Mount Barker to South Stirlings, Wellstead, north of Swamp Road in the Jerramungup District and eventually to the Fitzgerald River National Park. This belt is about 25 km wide and about 60 km long and has an elevation of between 70 -150 m AHD. Its annual rainfall varies from 700 mm in the west to 400 mm in the east.

There is no external drainage in this area. Numerous lakes and closed depressions form the internal drainage. Creeks and open depressions have only developed along the river margins of this province wherever shallow bedrock exists. Discharge of groundwater out of the area is small and restricted to the river margins and to the areas bordering the Elevated Coastal Belt. Historically, little groundwater flowed out of the area through ancient valleys and underground depressions that were filled by sediments of the Werillup Formation.

Salt storages are very high (mostly >10,000 t/ha) and may exceed 20,000 t/ha in the north-east of the area. In higher rainfall western areas which are close to dissected creeks, salt has been leached out of the soil profile and low levels of salt storage are found (<1,000 t/ha). Recharge occurs under crops and pastures, especially under

sand dunes. Other major recharge zones include alluvial fans on the footslopes of the Stirling Ranges that receive run off from the rocky hills and mountains of the Ranges and fresh perched swamps and lakes.

In a wet year more than 30% of some of the landform patterns of this province become inundated. The lakes and swamps now receive much more run off than prior to clearing. In future as soil structures decline more water may run off the landscape.

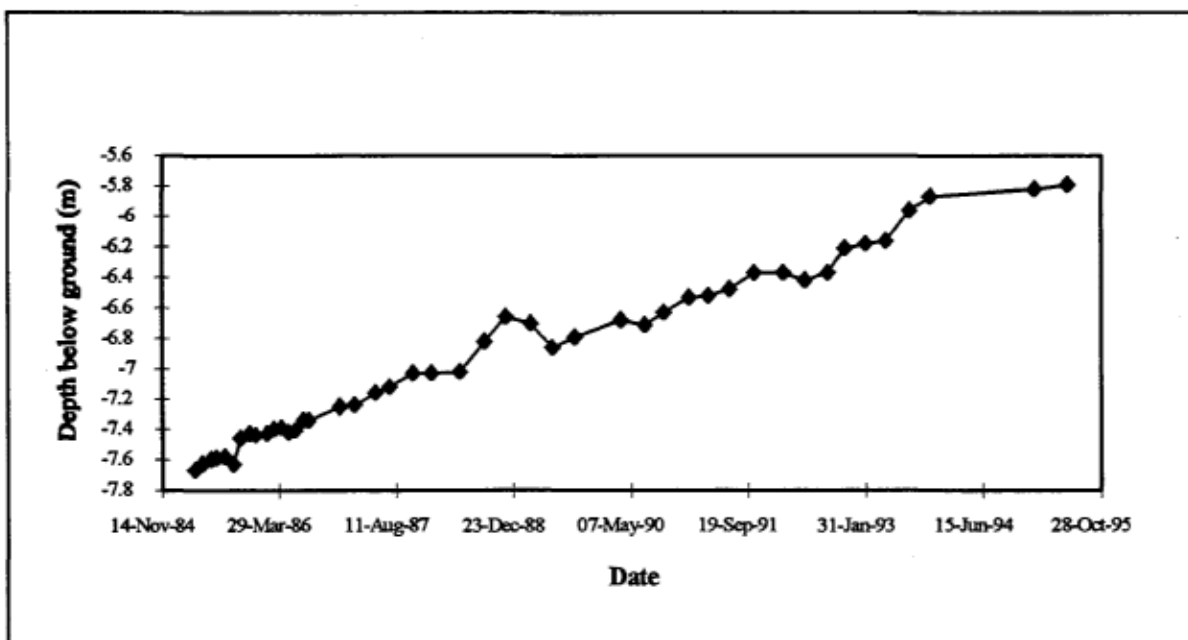
Prior to clearing groundwater levels were very deep (between 20-40 m). During the last 20 years groundwater levels have risen at about 0.1 m/year.

High hydraulic conductivities of material from the Werillup Formation have prevented significant groundwater rises along the coastline and certain areas along the Pallinup and the Kalgan Rivers. Areas that are far from the coastline or dissected rivers (e.g. South Stirlings) have shown a continuous rise of about 0.2 m per year. There are areas that have ground water rises up to 0.5 m per year. In most cases the rises have been very uniform and regular with little seasonal fluctuations. This continuous rise is an indication of the groundwater being contained in a basin with little or no outlet. On the southern margins of this province and close to the Coastal Belt, the water levels have a strong seasonal trend as well as annual rises. This is due to some groundwater flow to the south.

Groundwater levels under some seasonally dry lakes have risen to well above their floors. These lakes are thought to be recharge areas in winter and discharge areas in summer. Little groundwater flows from this province to the rivers or to the ocean.

There is no defined natural surface drainage in the main area. The groundwater flow is affected by bedrock highs. The zone of shallow bedrock with defined open depressions and some creeks has a local saline (1,300-3,300 mS/m) aquifer while the deep Tertiary area has a regional aquifer. There are isolated fresh to brackish (80-800 mS/m) groundwater mounds that have developed under alluvial fans and under large sand dunes. Other areas of the northern part of this province have high salinity levels (2,500-3,500 mS/m). Groundwater salinity under the southern part of this province reduces to the south until it becomes brackish along the southern margins.

Rising groundwater and its evaporation over summer has caused salt to concentrate in lakes to levels which kills the natural vegetation. Soil salinity is a problem in flats to the north of this area. Salt seeps have also developed in tributaries of the rivers as a result of rising groundwater levels and increases in the gradient of groundwater between the sandplain and the river. If the present rate of groundwater rise continues soil salinity will be a major problem in this zone.



Location: Sidcup Road, Perillup, Upper Kent River Catchment, Western Australia.
526190 mE, 6180361 mN (*Id. 60418024*).

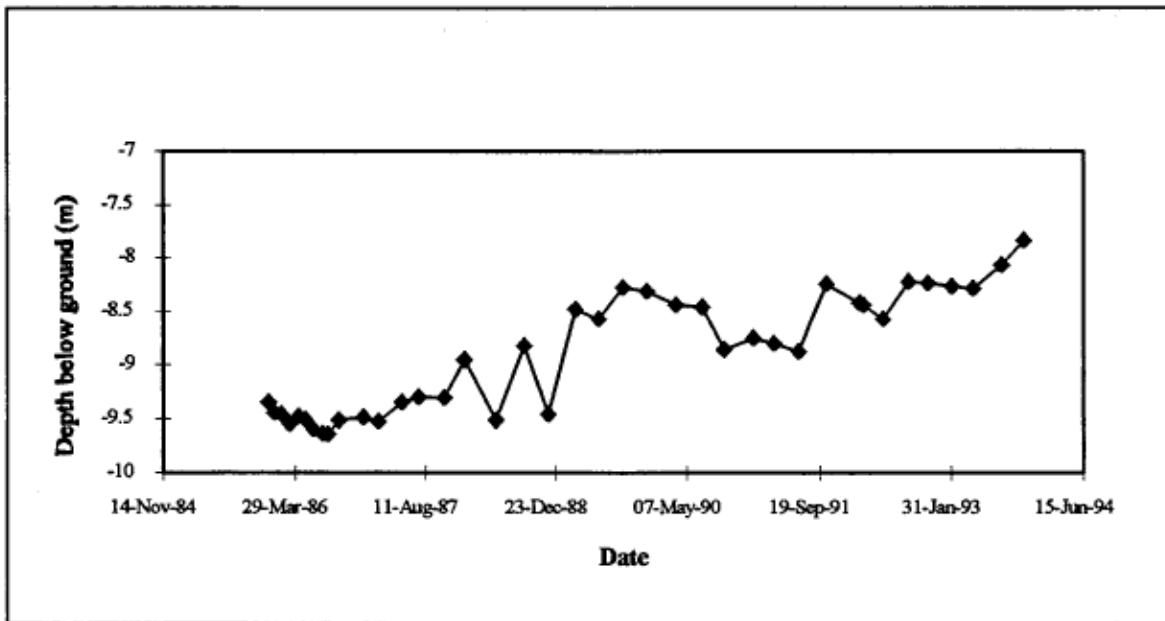
Landscape position: Hilltop.

Land use: Annual pasture and occasional cereal crops.

General information: The bore was drilled in April 1985. The groundwater salinity is 850 mS/m.

Interpretation:

Groundwater is rising steadily at 0.3 m per year. There is very little seasonal fluctuation, apart from the wet year in 1988. A drain has been in place for some 8 years to reduce waterlogging. A broad saline tributary to the Kent River is approximately 2 km downslope which has been fenced and planted. The groundwaters from this hilltop are probably still contributing to the pressures in the valley.



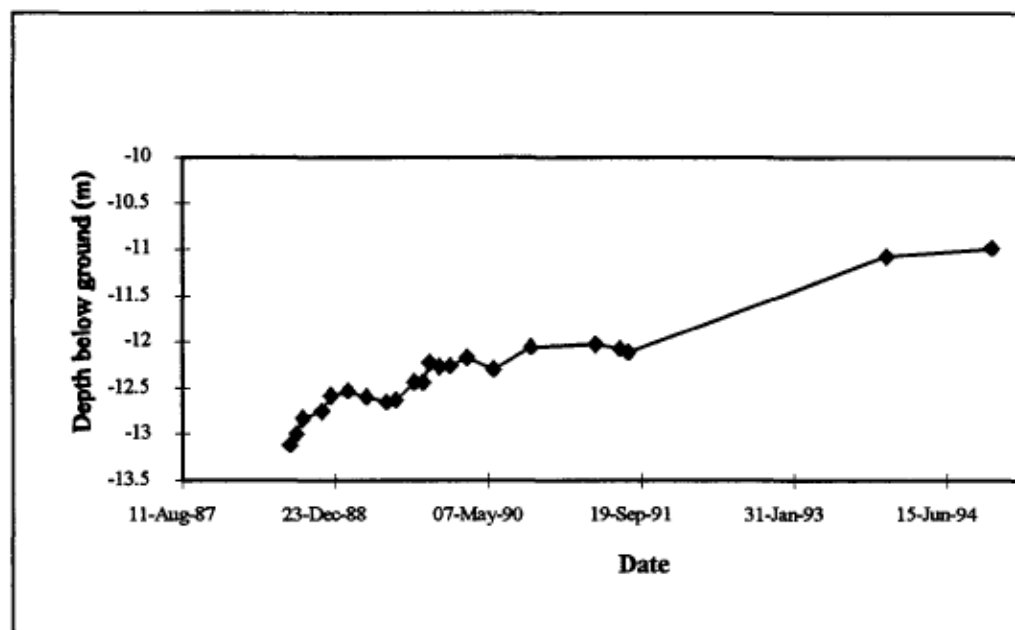
Location: Perilup Road, Perilup, Upper Kent River Catchment, Western Australia.
698400 mE, 6267300 mN (*Id. 60418043*).

Landscape position: Midslope.

Land use: Annual pasture and occasional crops.

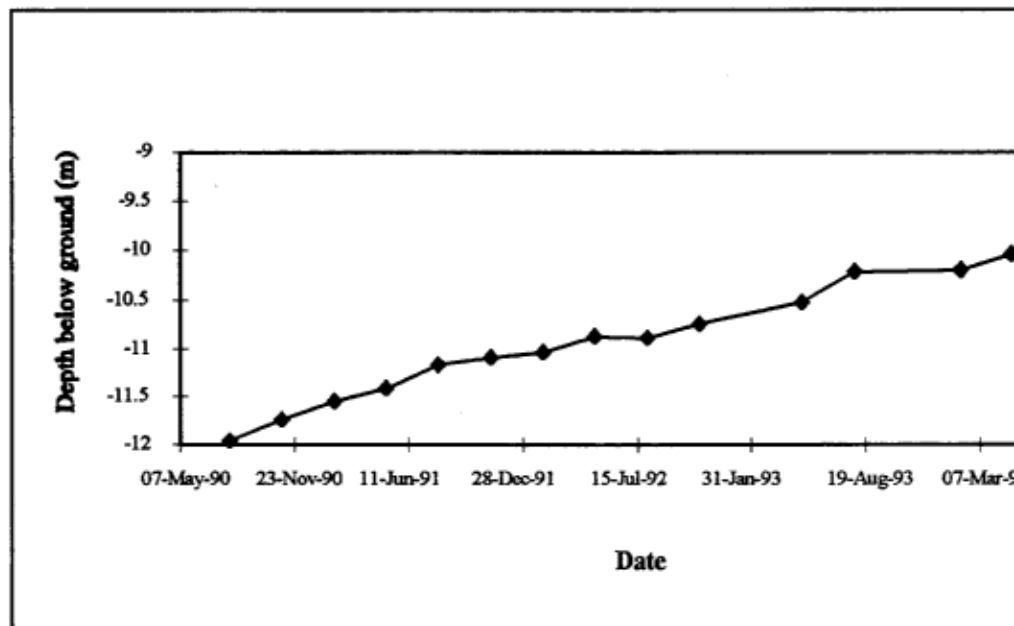
General information: The bore was drilled in December 1985. The groundwater has a salinity of 780 mS/m.

Interpretation The wet winter of 1989 is a major feature and gives a large jump in the hydrograph. Seasonal rainfall dictates the shape of the graph with the average rise being 0.2 m per year.



- Location:** Amarillup Road, Denbarker, Upper Denmark Catchment, Western Australia.
529200 mE, 6162500 mN (*Id. Hand I*).
- Landscape position:** Top of a very undulating area on a shear zone.
- Land use:** Annual pasture, 50 in away from native vegetation.
- General information:** The bore was drilled in May 1988. The groundwater has a salinity of 800 mS/m.

Interpretation: On average a rising trend of 0.4 m per year. Water levels would be affected by the native vegetation. Frequent readings were taken till September 1991, since then only two measurements have been recorded. It seems from this hydrograph that monthly readings for the first two years and then quarterly, are sufficient to determine trends.



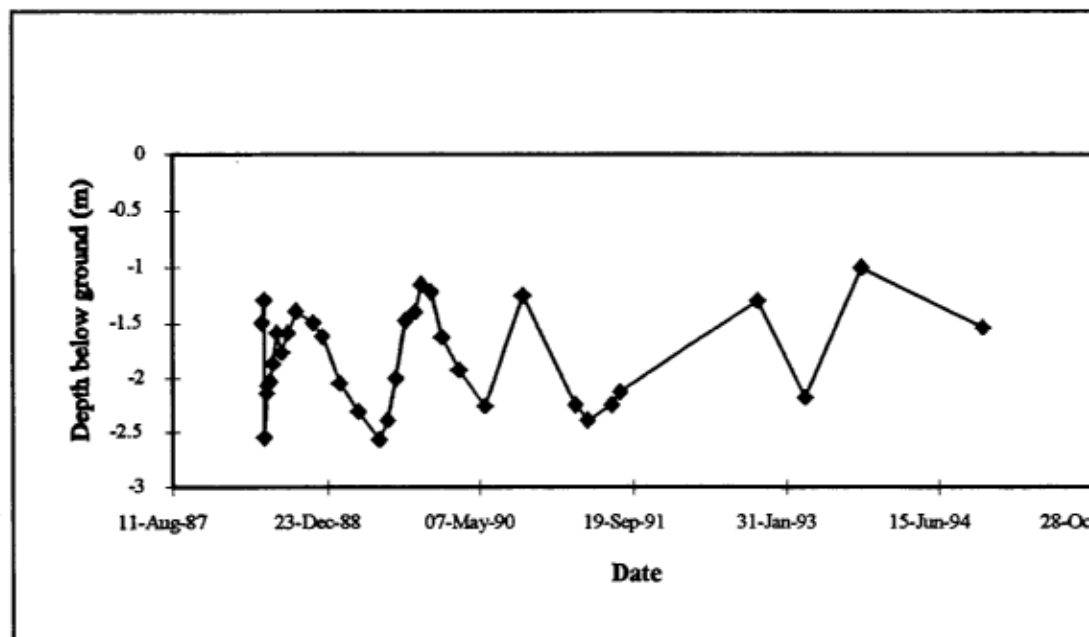
Location: Jacup, Jerramungup, Western Australia.
698400 mE, 6267300 mN (*Id. J88*).

Landscape position: Midslope.

Land use: Annual pasture and crops.

General information: The bore was drilled in June 1990. The groundwater salinity is 4,900 mS/m.

Interpretation: A steady rise of 0.6 m per year.



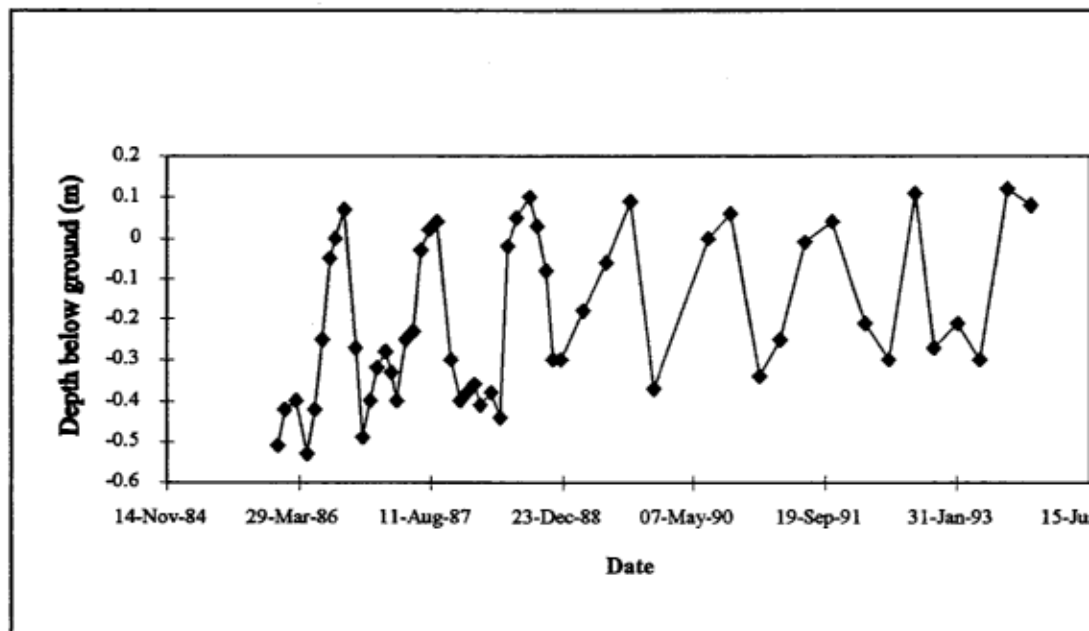
Location: Seymour Road, Denbarker, Western Australia.
531300 mE, 6161100 mN (*Id. AJ1C*).

Landscape position: Flat upperslope.

Land use: Annual pasture (Bluegums planted 1995).

General information: Treatment sites was drilled in May 1988. The groundwater salinity is 1,230 mS/m.

Interpretation: The watertable is reasonably stable fluctuating between 2.5 m and 1.5 m below ground. The bore is close to a discharge area which has turned saline since 1985.



Location: Poorrarecup Road, Upper Kent River Catchment, Western Australia. 520992 mE, 6184291 mN (*Id. 60418082*).

Landscape position: Valley.

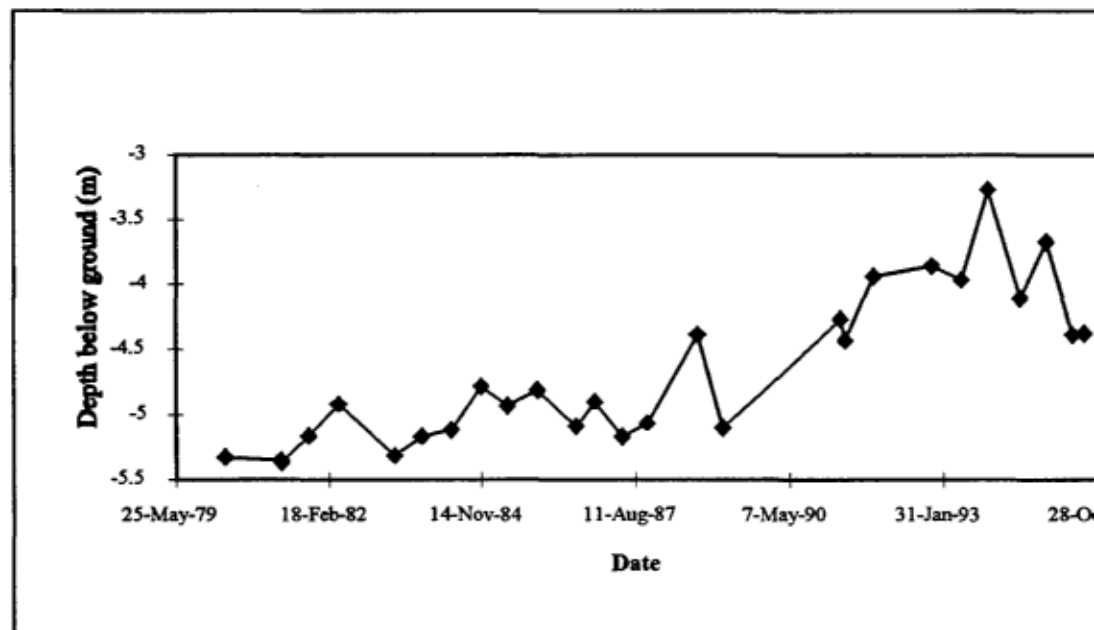
Land use: Grazing, bare soil with some barley grass.

General information: The bore was drilled in January 1986. The groundwater salinity is 2,200 mS/m.

Interpretation:

This is a common hydrograph from bores drilled in discharge areas. There is a direct response to rainfall. There is very little trend as the groundwater fluctuates between 0-1 m of the soil surface. The site is mostly bare and produces run off due to the high watertable.

This hydrograph illustrates that bores in discharge areas generally cannot be used to determine trends in groundwater levels.



Location: Muir Highway, Perillup, Western Australia.
52400 mE, 6174544 mN (*Id.* 60419002).

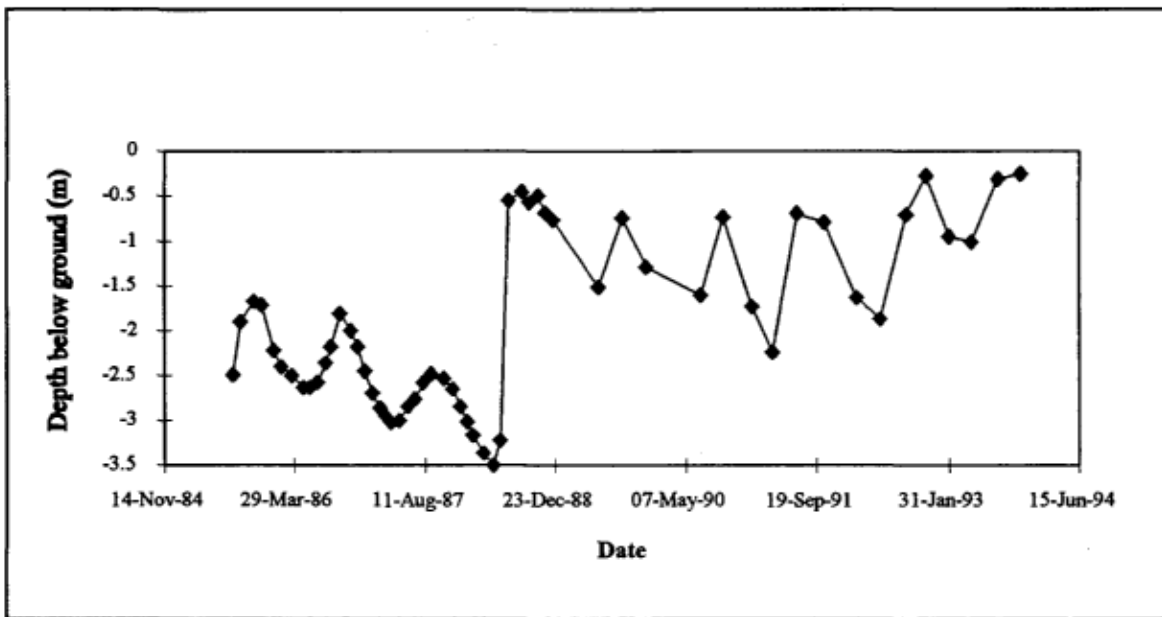
Landscape position: Midslope.

Land use: Parkland cleared (20 stems/ha remain) with annual pasture (grazing).

General information: The bore was drilled in April 1980. The groundwater salinity is 1,100 mS/m. The bore was drilled and monitored by the Water Authority of Western Australia.

Interpretation:

Bores were installed to see whether parkland clearing is viable in the long term. The hydrograph shows that the watertable fluctuates with seasonal rainfall. The water level trend is 0.06 m per year rise.



Location: Poorrarecup Road, Upper Kent River Catchment, Western Australia.
521435 mE, 6191337 mN (*Id. 60418077*).

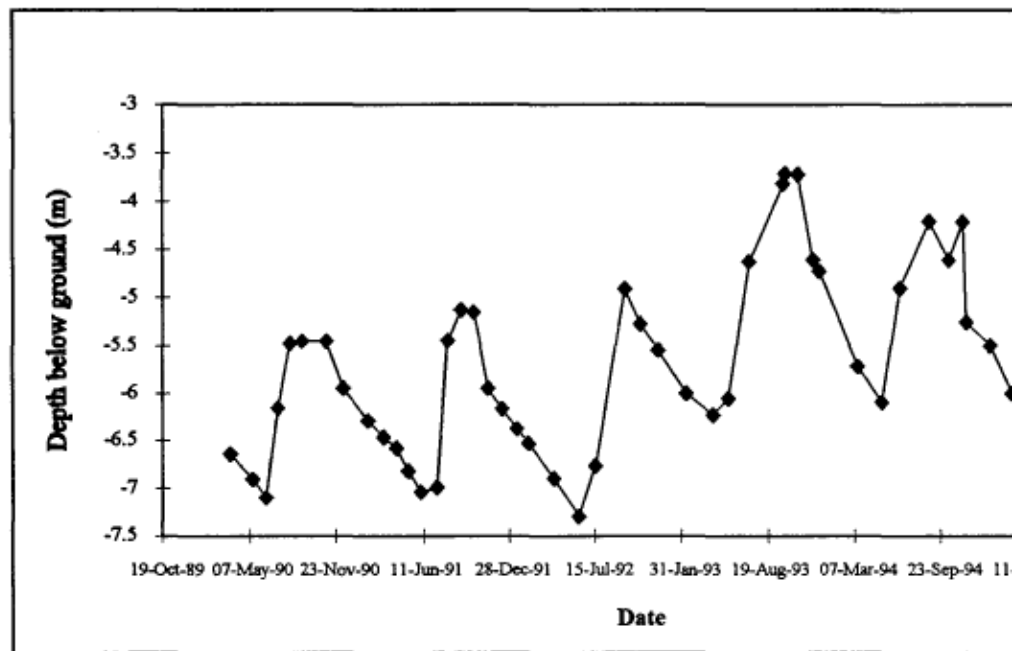
Landscape position: Next to Lake Poorrarecup.

Land use: Native vegetation.

General information: The bore was drilled in August 1985. The groundwater salinity is 1,120 mS/m.

Interpretation: For the first two years the hydrograph shows a downward trend due to low rainfall. The above average rainfall in 1988 produced a 3 m rise. Since then the watertable has not varied greatly apart from the seasonal inputs. The 1988 rainfall can be called an episodic event which has lifted the watertable from around 3.5 m-0.5 m below ground.

Present fluctuation is due to recharge in winter and discharge through evaporation in summer. This hydrograph shows that the groundwater levels in this landform, even with native vegetation, are close to the soil surface.



Location: Spencer Road, Narrikup Hay River Catchment, Western Australia.
554748 mE, 6153511 mN (*Id. 60318011*).

Landscape position: Midslope.

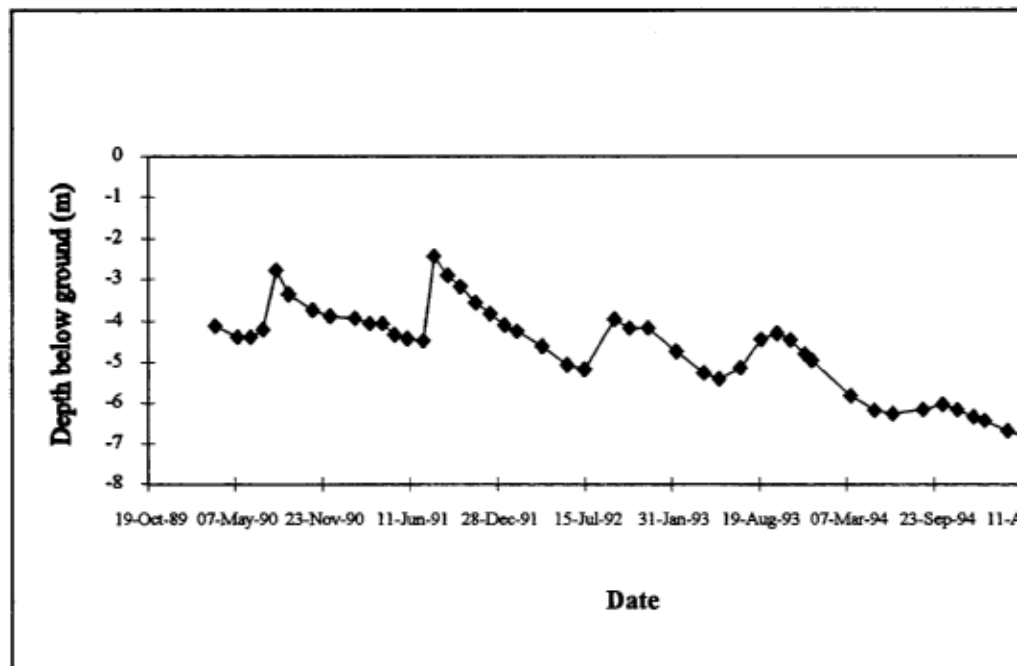
Land use: Annual pasture.

General information: The bore was drilled in March 1990. The groundwater salinity is 220 mS/m.

Interpretation:

Responds to seasonal rainfall. The rise in 1993 was due to an above average winter rainfall. Overall the trend is 0.22 m per year rise in the watertable.

This hydrograph can be compared with the following one (60318008) which is under Bluegums.



Location: Spencer Road, Narrikup Hay River Catchment, Western Australia.
553801 mE, 6153469 mN (*Id.* 60318008).

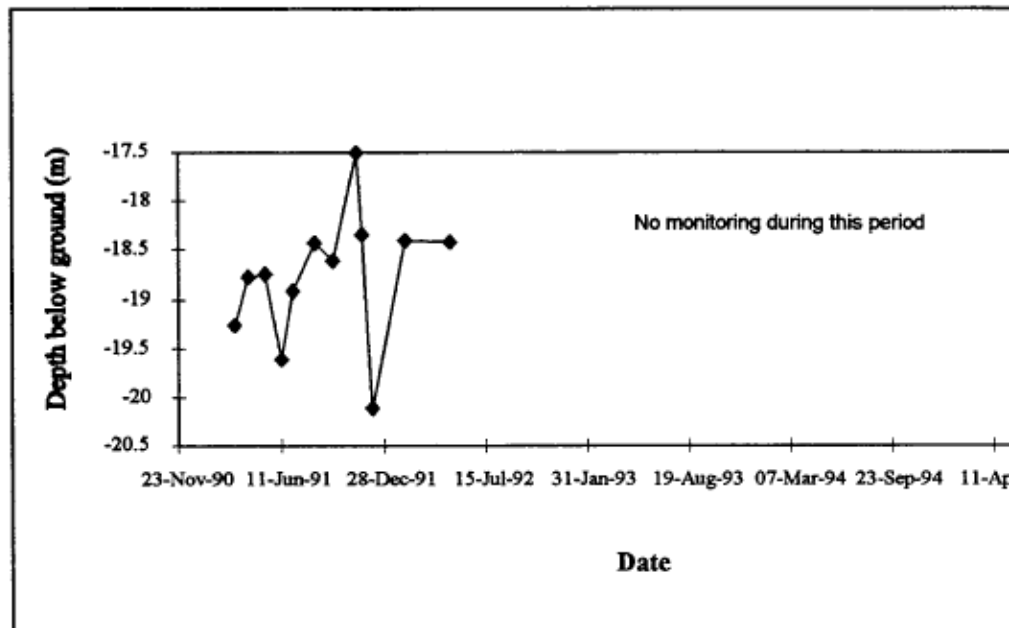
Landscape position: Mid to top of slope.

Land use: Bluegum (*Eucalyptus globulus*) plantation.

General information: The bore was drilled in March 1990. The groundwater salinity is 55 mS/m. Salt storage to bedrock (8 m) is 36.3 t/ha. The trees were planted in July 1990.

Interpretation: The seasonal rainfall is having a effect on the behaviour of groundwater as well as the trees. For the first two years after planting there was no response, however since then the groundwater has been lowered by an average of 0.4 m per year. The depth to bedrock is 8 in, at this rate the bore should be dry within two years. The 1994/95 seasonal fluctuation is not as great as previous years. This is because groundwater levels are dropping close to bedrock. If supply dries up some trees may die due lack of water. The plantation has also affected groundwater levels in the valley floor. A bore 80 m downslope with its groundwater pressure 0.4 m above ground has been lowered to ground level five years after planting. This lowering should continue even if the groundwater upslope dries up.

This hydrograph can be compared to the previous one (60318011) which is under annual pasture.



Location: Hassell Highway, Mount Manypeaks, Western Australia. 606719 mE, 6143739 mN (*Id.* 60218402).

Landscape position: Midslope, slightly undulating.

Land use: Annual pasture.

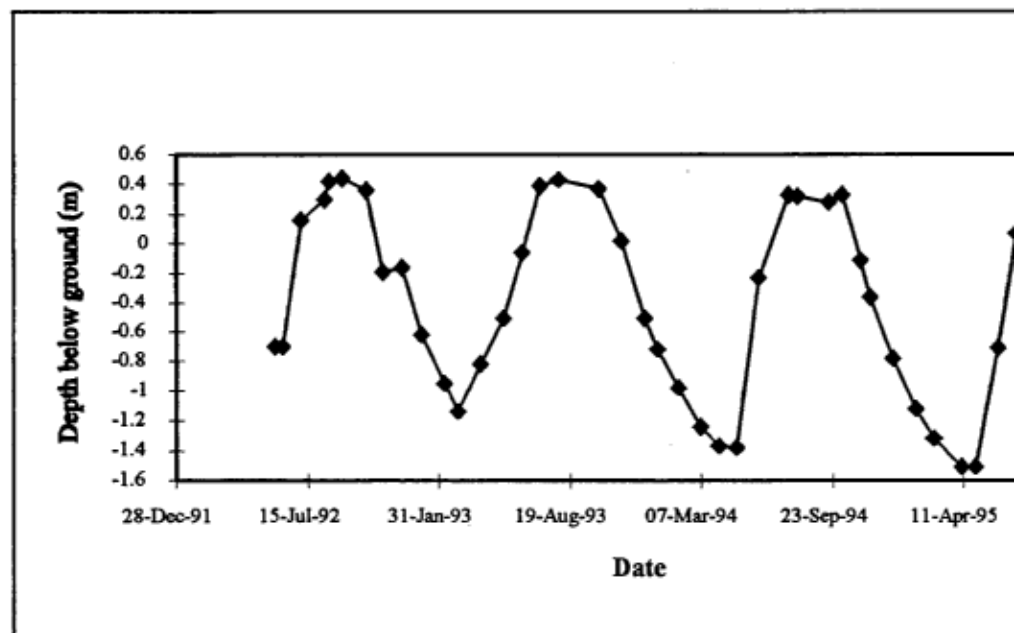
General information: The bore was drilled in March 1991. The groundwater salinity 450 mS/m.

Interpretation:

A rising trend of around 0.1 m per year. The site has no salinity however it has significant areas of waterlogging. Groundwater is reasonably deep and future salinity is low. One of the waterlogged depressions at this site has been revegetated with trees.

Bore monitoring started off with monthly readings for the first year, then it was left till 1995 to continue. It is necessary to have quarterly readings to give some quality to the data.

Water levels are read by the Mount Manypeaks school students as part of a Landcare project.



Location: Meanwood Road, Youngs Siding Torbay Catchment, Western Australia.
556263 mE, 6124593 mN (*Id. 60318084*).

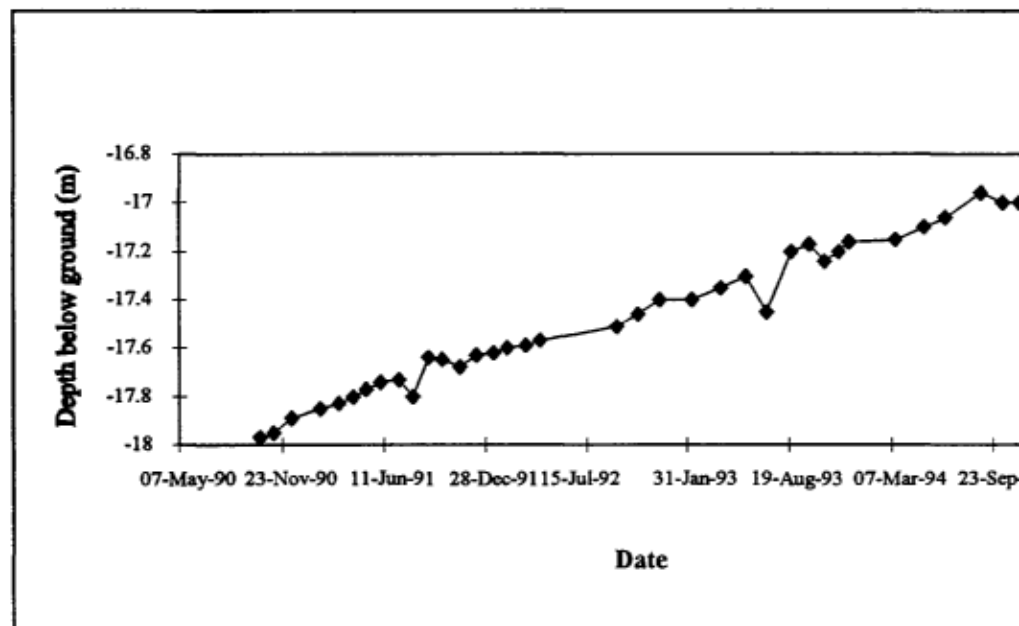
Landscape position: Flats, margins of stagnant flats.

Land use: Cleared with annual pasture (grazing).

General information: The bore was drilled in May 1992. The groundwater salinity is 830 mS/m.

Interpretation:

The hydrograph has definite seasonal fluctuations. These fluctuations are due to groundwater discharging during the summer months by evaporation. As the soil fills up in winter groundwater levels are pushed above ground level by hydraulic pressure from upperslopes. This site has already reached its limit in terms of waterlevel rises and can only drop over the long term if changes are made to increase plant water use within the catchment.



Location: Armstrong Road, Porongurup, Western Australia.
591675 mE, 6158375 mN (*Id.* 60218309).

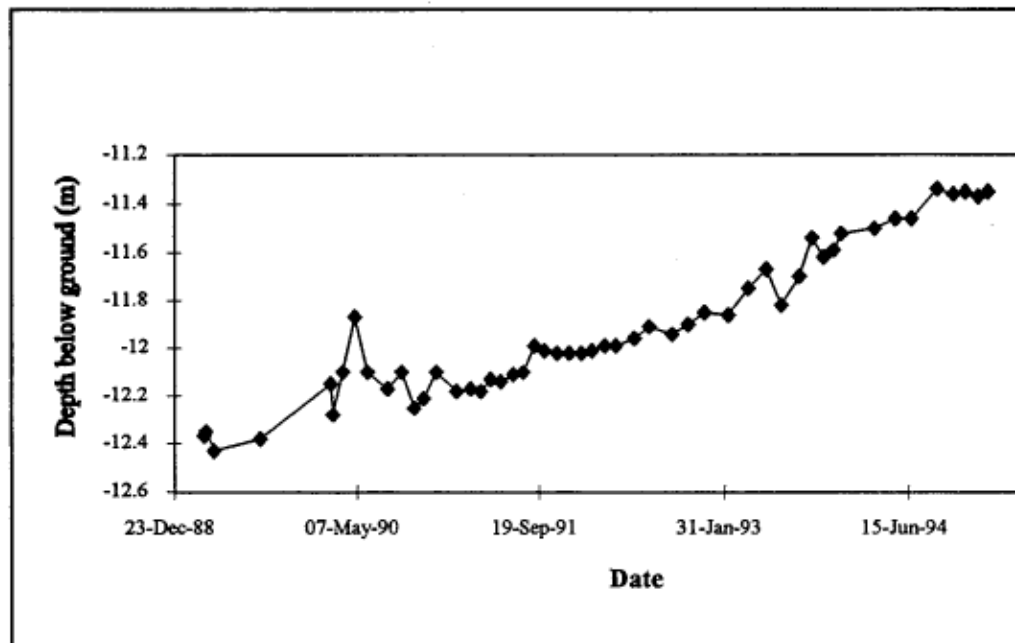
Landscape position: Midslope on deep Tertiary sediments.

Land use: Annual pasture, grazing only.

General information: The bore was drilled in September 1990. The groundwater salinity is 155 mS/m. Salt storage to 30 m is 479 t/ha (the bore was not drilled to bedrock).

Interpretation:

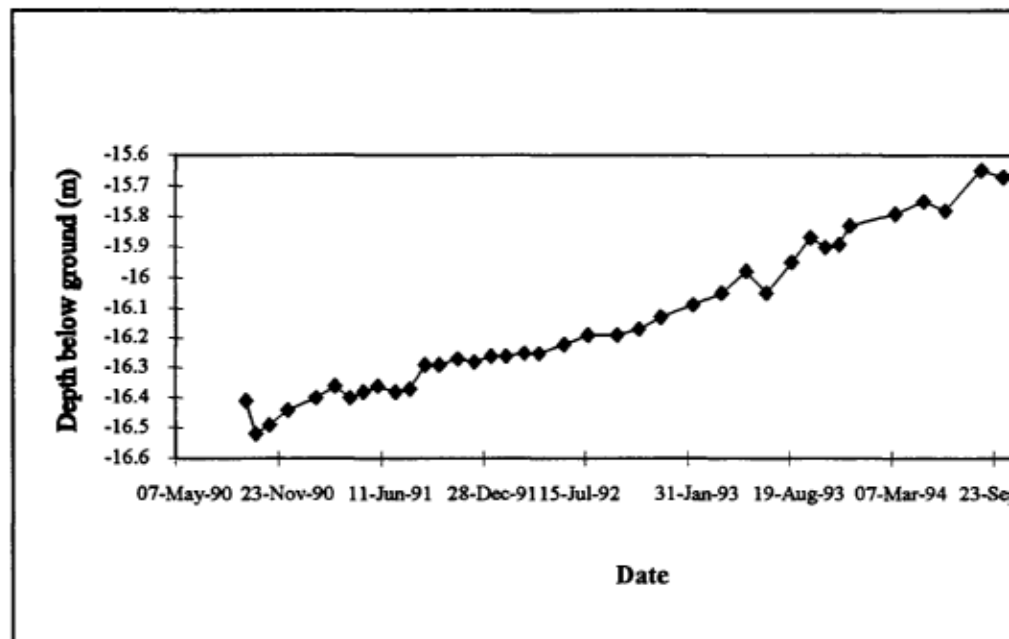
A steady rise of 0.25 m per year. The groundwater is reasonably deep and as yet there are no ill effects on site or in the drainage line below. However, it is showing that the current agricultural practices are not using enough water and a future problem is likely.



- Location:** Chillinup Road, South Stirling, Western Australia. 622079 mE, 6180941 mN (*Id.* 60218393).
- Landscape position:** Sandplain on deep Tertiary sediments.
- Land use:** Annual pasture and crops.
- General information:** The bore was drilled in January 1989. The groundwater salinity is 2,000 mS/m.

Interpretation:

The average groundwater rise is 0.2 m per year. This hydrograph represents the trend for a large percentage of internally drained land. Salinity has not affected agricultural production on this property, however a number of sumps (depressions) have become saline since clearing.



Location: Pfeiffer Road, South Stirlings, Western Australia.
610681 mE, 6168551 mN (*Id.* 60218380).

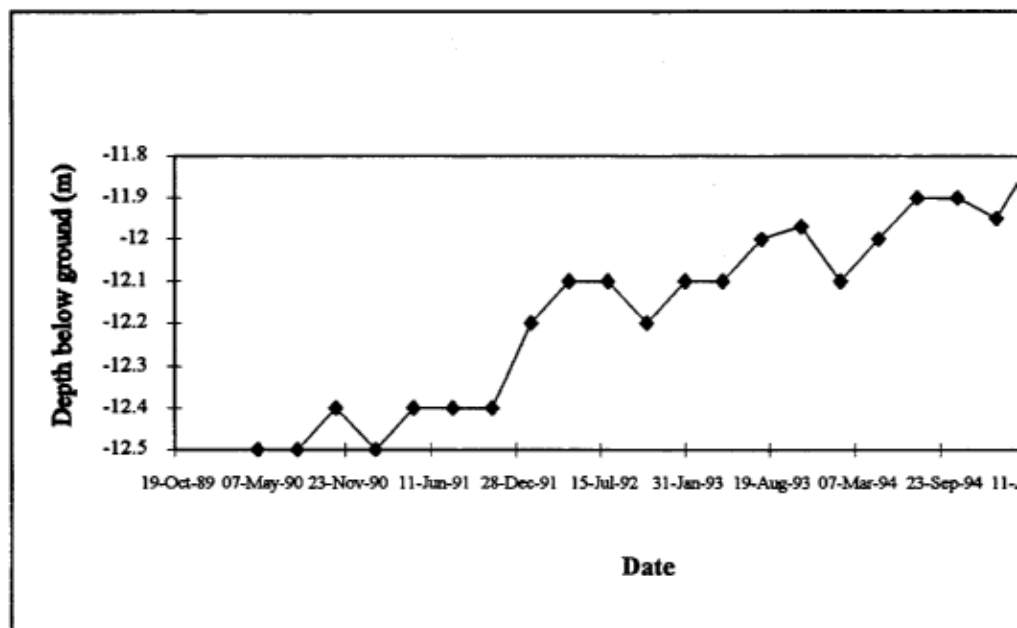
Landscape position: Sandplain on deep Tertiary sediments.

Land use: Annual pasture and occasional cereal crop.

General information: The bore was drilled in September 1990. The groundwater salinity is 1,400 mS/m and the salt storage is 731 t/ha.

Interpretation:

A steady rising trend of 0.2 m per year. The depth to water is significant, as most holes with a watertable deeper than 10 m show steady rises. When the watertable is closer to the surface there is a tendency for the watertable to fluctuate more due to seasonal recharge from rainfall and discharge into streams and/or seeps.



Location: Swamp Road, Bremer Bay, Western Australia.
688750 mE, 6198950 mN (*Id. 1106*).

Landscape position: Sandplain, deep Tertiary sediments.

Land use: Annual pasture and crops.

General information: The bore was drilled in May 1990. The groundwater salinity is 2,800 mS/m.

Interpretation: Seasonal fluctuations and an episodic recharge event in 1991/92. Generally rising at 0.1 m per year.

Eastern South Coast Region

Rod Short, Gerry Skinner and Steven Gee

The Esperance district covers approximately two million hectares of cleared agricultural land. Importantly, Esperance has an environmental uniqueness - diverse vegetation, national parks and wetlands of international significance. Development of the southern part of the Esperance district began in the 1950s after trace element deficiencies were identified on the Esperance Downs Research Station (EDRS). The district can be broadly divided at the 450 mm annual rainfall isohyet into a Mallee area in the north and a coastal sandplain (Esperance Sandplain) in the south. Rainfall isohyets represent broad changes in agricultural practices with agriculture focused mainly on both cropping and livestock production.

Rainfall (mm)	Agricultural practice
>550	80% Pasture (50:50 cattle/sheep), 20% Crop (80% oats/barley)
450-550	60-70% Sheep, 30-40% Crop
350-450	60% Crop, <40% Sheep
<350	Mainly crop

Climate

The district has a Mediterranean climate with cool, wet winters and dry, temperate summers. Average annual rainfall ranges from 670 mm at Esperance, decreases rapidly away from the coast to 350 mm in the northern Mallee. Annual Class A pan evaporation (with birdguard) ranges from approximately 1,840 mm at Esperance to around 2,200 mm at Salmon Gums (Luke *et al.* 1987). The increase in evaporation parallels the decrease in rainfall, resulting in a decrease in the agricultural growing season from seven months at Esperance to approximately five months at Salmon Gums. Approximately two-thirds of the annual rain falls between May and October (66% at Jerramungup and 67% at Esperance Downs Research Station). Rain bearing depressions from ex-tropical cyclones and local thunder storms occur during October to March. Wind directions are generally from the north-east and south-west in summer. The passage of eastward low pressure fronts in winter can result in gale force winds from the north and west.

Geology

The Esperance district is underlain by crystalline basement rocks; either the Archaean Yilgarn Block or the Proterozoic Albany-Fraser Orogen. The Archaean basement rocks occur mainly to the west of Esperance and are similar to those in much of the Western Australian Wheatbelt. These basement rocks are made up of granites and gneisses with some older greenstone belts occurring near Ravensthorpe. The Archaean rocks are divided from the basement rocks of the

Albany-Fraser Orogen along a line which runs approximately north-east from the Dalyup River. Basement rocks are overlain by Tertiary sediments of the Plantagenet Group. Basement rocks form coastal headlands, offshore islands or can be seen inland as high points in the landscape such as Wittenoom Hills or Mount Howick. Quaternary sand and limestone extends along the coastline.

Antarctica began to break away from Australia in the Cretaceous. This resulted in the continental margin sagging to form the Bremer Basin (Cockbain and Hocking, 1990). A marine transgression in the Middle to Late Eocene deposited the Werillup Formation and the Pallinup Siltstone units of the Plantagenet Group in paleodrainages and in depressions in basement rocks. The Werillup Formation consists of a dark grey siltstone, sandstone, claystone and lignite (brown coal) and limestone deposited in fluvial or backswamp environments. The Pallinup Siltstone consists of siltstone and spongolite deposited in a marine environment.

The Darling Plateau began to be uplifted in the Oligocene (about 30 million years ago) and this resulted in the southern coast tilting towards the south forming the Ravensthorpe Ramp; the hinge line is known as the Jarrahwood Axis (Cope, 1974). Drainage lines were rejuvenated and sand deposits were redistributed by the wind. Carbonate leaching and lateritisation took place to form the present topography and soil profiles.

Soils

Sandplain soils are dominantly deep duplex soil with of 30-80 cm of fine sand and ferruginous gravels topsoils overlying a dense sodic (Exchangeable Sodium Percentage (ESP) > 6) clay subsoil. Approximately two-thirds of these soils are prone to annual waterlogging. Deep, loose gradational sands are the major associated soil consisting of greater than 80 cm of fine sand.

In the Mallee the dominant soil type is shallow, sandy surfaced, alkaline duplex soils. The depth of the sandy topsoil is typically less than 30 cm with some areas less than 5 cm.

Water repellent topsoils can increase water logging and salinity problems by increasing runoff and inhibiting water entry into the soil. Light rains on water repellent soils at the start of the season affect germination and crop establishment. All 800,000 hectares of the sandplain contains soils susceptible to water repellency. All Sandplain and Mallee soils are susceptible to wind erosion.

Salt storage in the top 6 in of the regolith ranges up to 1,300 t/ha in the Mallee and 900 t/ha on the sandplain.

Surface drainage

The present surface drainage patterns are a result of the geological history of the South Coast. Prior to the Eocene (about 50 million years ago), drainage was to the west towards the Perth Basin and to the east towards the Eucla Basin. Uplifting of the Darling Plateau and tilting of the continental margin during the Tertiary diverted drainages to the south. On plateaus formed by Eocene sediments, drainage is

usually internal and terminates in paperbark (*Melaleuca* spp.) and yate (*Eucalyptus occidentalis*) swamps. To the east of Esperance, catchment boundaries are very poorly defined. Drainage lines filled with Eocene sediments are now being reactivated because clearing has increased runoff and raised the watertables.

The salinity of rivers to the west of Esperance ranged from 1,200 to 7,240 mS/m (6,600-40,000 mg/L) in September 1993. Both salt loads and runoff have increased dramatically since clearing. For example, at the Munglinup Gauging Station, on a tributary of the Lort River, salinities increased from 350 mg/L in 1975 to a maximum of 97,140 mg/L in 1993. Water flows across the weir have increased in both frequency and volume.

Along the South Coast, the rivers discharge into estuaries and coastal lagoons. Many have a high conservation value which is reflected in their status as National Parks or A Class Reserves. The drainage system around Esperance is protected under the International RAMSAR Convention for the Protection of Migratory Birds. Protection of these areas may set limits for available solutions to water management in agricultural areas.

Hydrogeology

The hydrology of the district is influenced by both its geological history and surface erosive processes that have shaped the present landscape.

Tertiary sediments overlie Precambrian basement rocks over much of the region. Sandplain cover often masks the underlying geology.

Basal sands of the Werillup Formation are confined to lows in the basement topography and are relatively more permeable than the Pallinup Siltstone. Groundwaters in the Plantagenet Group and Werrillup Formation sediments are usually saline.

Studies in the Esperance district have shown that three aquifers may be present; a deep semi-confined/confined regional aquifer in weathered basement rocks; semi-confined/unconfined aquifers in overlying Tertiary sediments, and a perched aquifer in duplex soils (responsible for waterlogging). These aquifers may be connected and, with the exception of the perched aquifer, are usually saline.

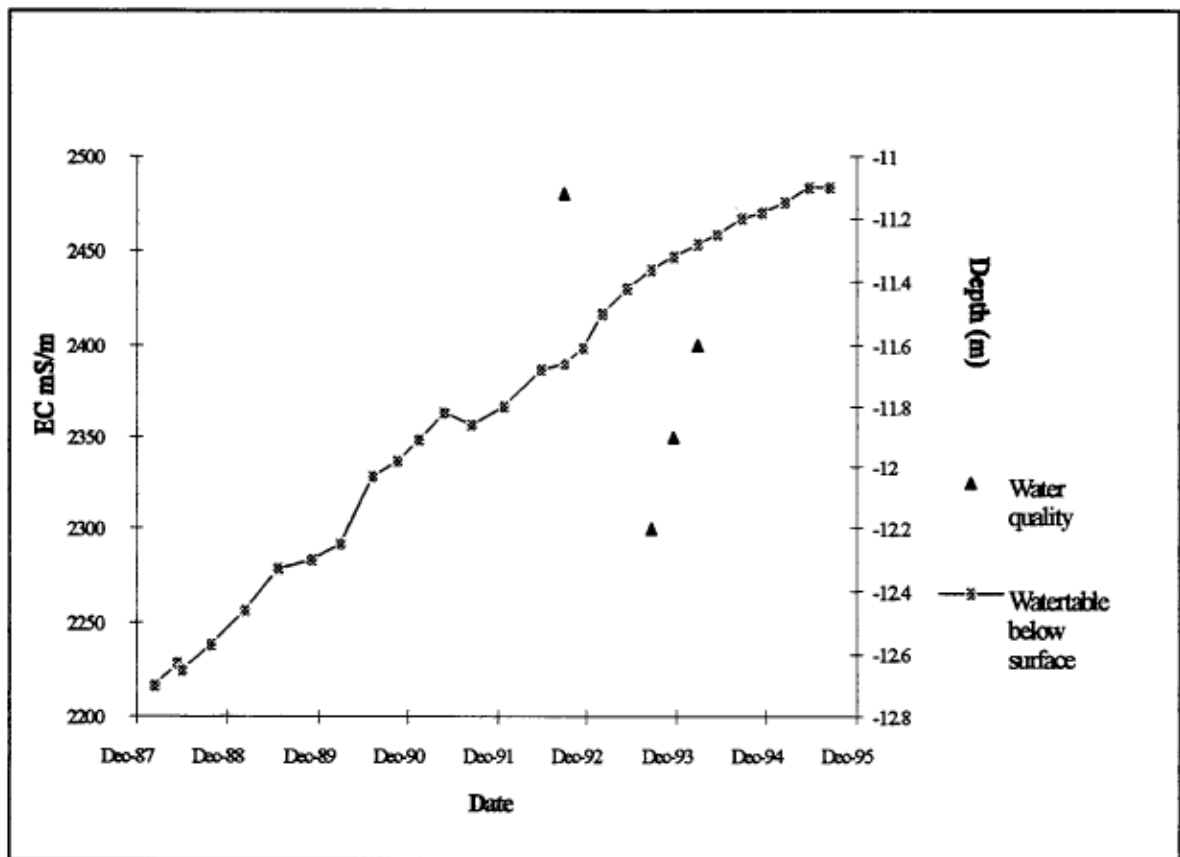
The finely grained nature of the Pallinup Siltstone and the upper part of the Werillup Formation result in low groundwater yields and a low hydraulic conductivity. Spongolite sections of the Pallinup Siltstone are more permeable. Recharge to groundwater is probably through preferred pathways such as solution cavities and root channels. These have been observed at 8 m below the surface. Hydraulic gradients appear to be less than 0.1% and pre-clearing, many aquifers were probably separated by Precambrian bedrock barriers.

Perched aquifers in deeper sands and sand sheets can contain water of stock quality (<2,000 mS/m). Lateral movement of water through these sands towards topographic lows causes seasonal waterlogging. Other end points, such as paperbark and yate swamps, may be recharge sites for deeper regional aquifers. Hearne (1991) showed

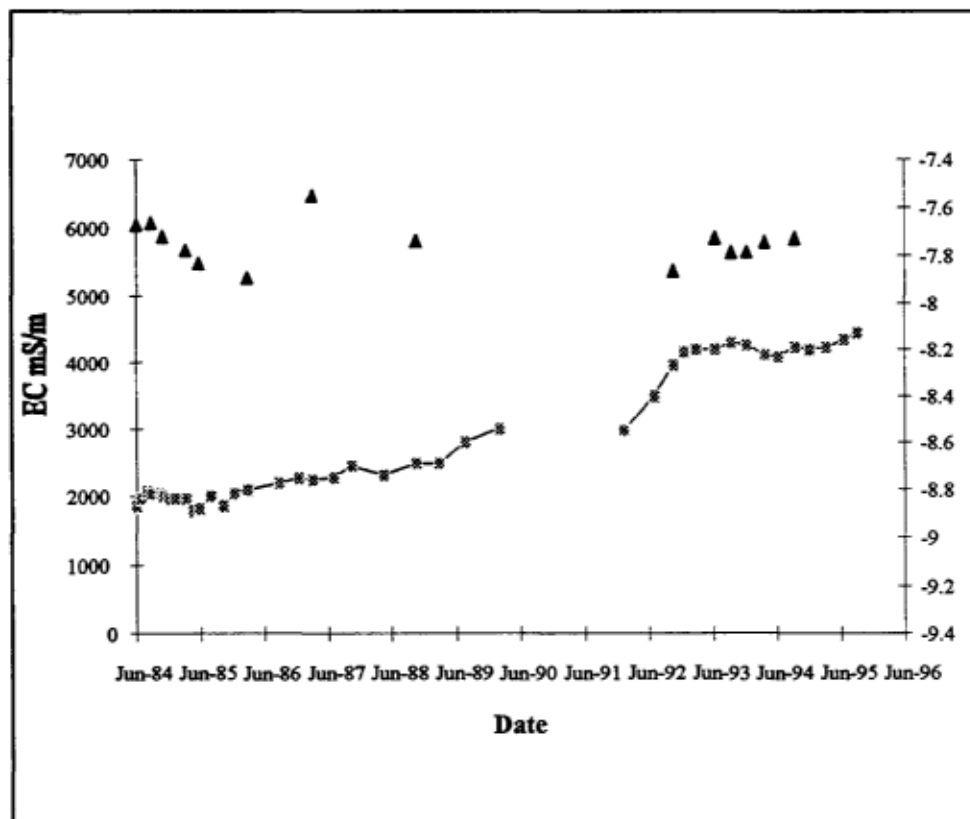
that a saline area in the Cascades area was due to a perched aquifer and that the regional aquifer was more than 13 m deep. In the Esperance district, drilling to the east of Esperance has located the Werillup Formation along paleodrainage lines in the Mallee. The extent of the Werillup Formation under the Sandplain is still unclear.

Groundwater salinity increases away from the coast with fresh to brackish water occurring south of Fisheries Road and along the South Coast Highway. Groundwater under the Sandplain ranges from 45 to 5,065 mS/in while saline groundwater under Mallee areas is up to 13,300 mS/m. Although reliable, long-term records are scarce, groundwaters are rising at between 0.1-0.3 m per year and in some cases, at up to 0.5 in per year. Waterlogging on shallow duplex soils on the Sandplain and Mallee reduces crop and pasture production annually. The present agricultural systems have changed the natural water balance and are adding water to groundwater storage.

Dolerite dykes do not intrude into the sediments, therefore bedrock highs are probably the major barrier that water accumulates behind to form seeps. In many areas where there is shallow bedrock, such as the central part of the Esperance District, watertables are often within 2 m of the surface and are the cause of secondary salinity. As watertables rise in Mallee areas, areas of high salt storage in the regolith are being remobilised along drainage lines or in low points in the landscape and this is causing salt scalds. Fault zones in basement rock have a high salt storages. However their influence on secondary salinity is unknown.



Bore number:	EM 27.
Average annual rainfall:	525 mm.
Location:	Mount Howick, Esperance Sandplain. 70 km east of Esperance. Esperance Hydrogeological Zone 1. AMG (approximately). 6268040 mN, 468190 mE.
Elevation:	99 m AHD (approximately).
Landscape position:	Gently inclined plain.
Land use:	Cropping/pasture.
Soil:	Shallow duplex soils (waterlogged).
Features:	Long term regional groundwater rise. Episodic response to the high rainfall events in 1989 and 1992. Long term rate of rise (23 cm per year). Cleared 1966-1967.



Bore number: Mount Beau 3D.

Average annual rainfall: 425 mm.

Location: Mount Beaumont, Esperance Mallee. 70 km north-east of Esperance. Esperance Hydrogeological Zone 3. AMG (approximately).
6299538 mN, 450473 mE.

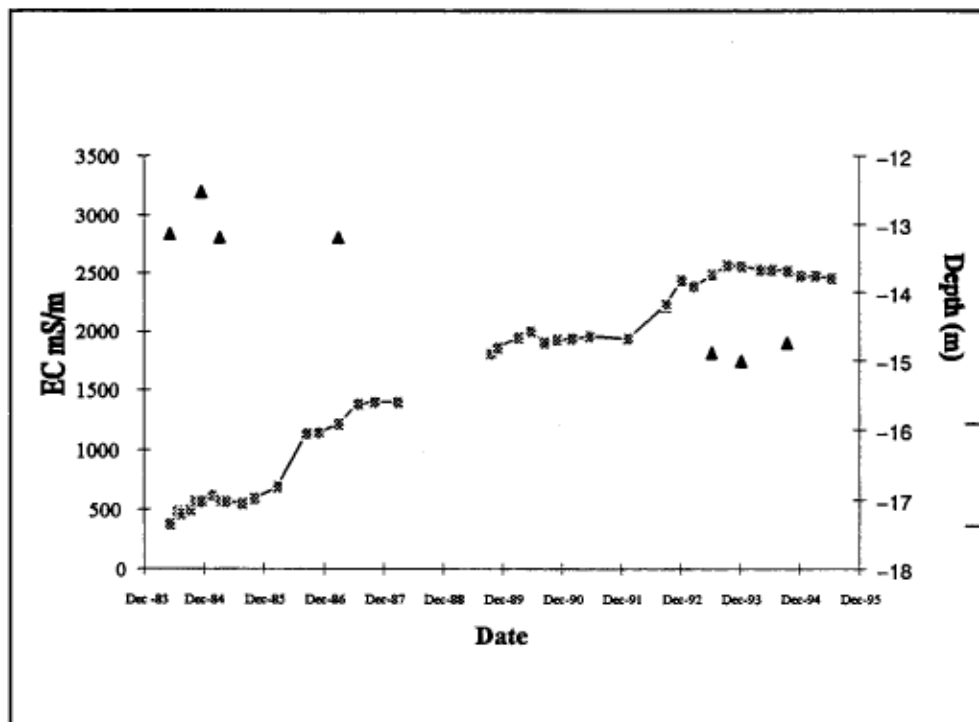
Elevation: 180 m HD (approximately).

Landscape position: Level plain.

Soil: Shallow duplex soils (waterlogged).

Land use: Cropping/pasture.

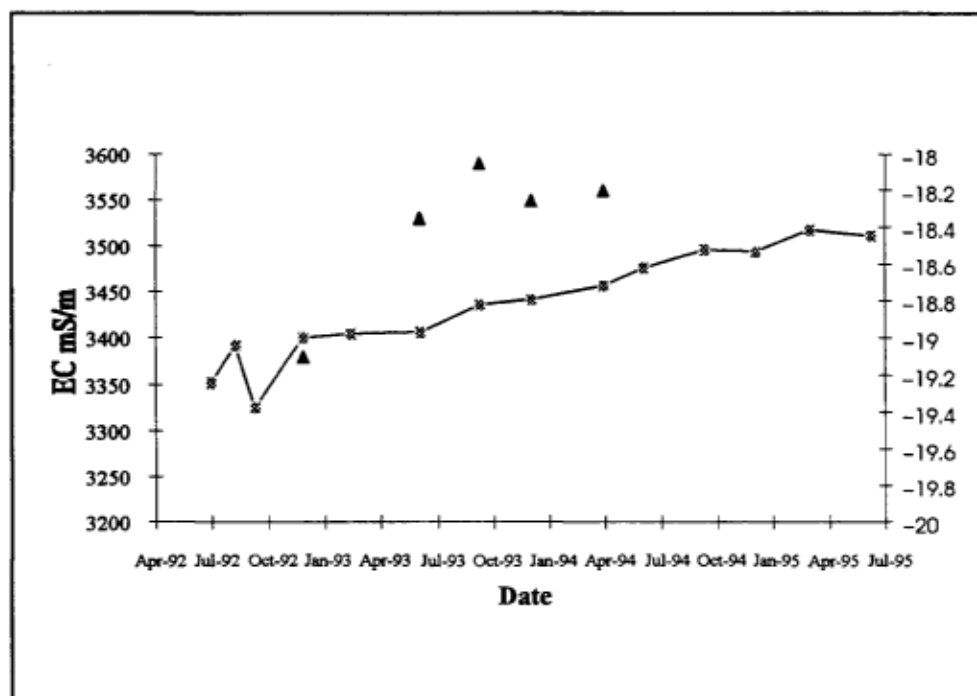
Features: Long term regional groundwater rise. Response to the high rainfall events in 1992 (1989 event not monitored). Long term rate of rise (7 cm per year). Water quality 5,300-6,500 mS/m. Seasonal perched watertable in wet years (shallow observation bore).



Bore number: Cas1D.

Average annual rainfall: 350 mm.

Location:	Cascade, Esperance Mallee. 110 km north-west of Esperance. 23 km north-west of Cascade. Esperance Hydrogeological Zone6. AMG. 6307895 mN, 302352 mE.
Elevation:	260 m MID (approximately).
Landscape position:	Level to gently inclined plain.
Soil:	Shallow duplex soils (waterlogged).
Land use:	Cropping/pasture.
Features:	Long term regional groundwater rise. Episodic response to the high rainfall events in 1986 and 1992 (1989 event not monitored). Long term rate of rise (37 cm per year). Change in water quality over time. Seasonal perched watertable (shallow observation bore).



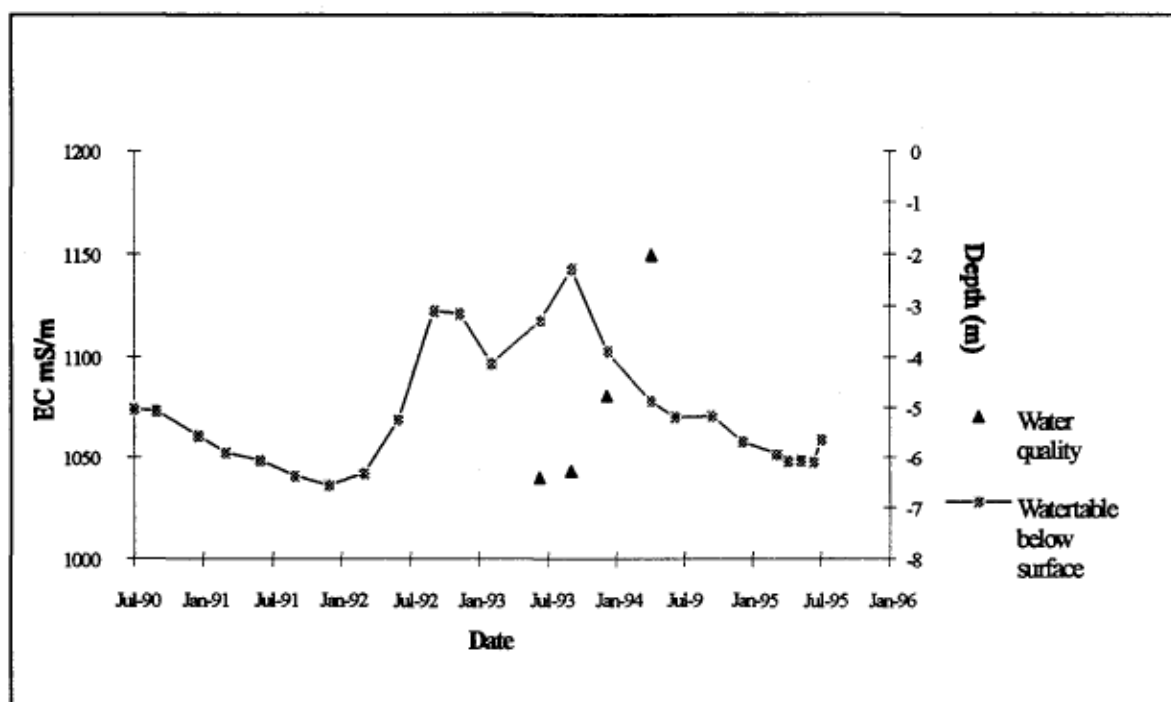
Bore number: MF1d.

Average annual rainfall: 450 mm.

Location: Cascade Road, Esperance Sandplain/Mallee transition. 75 km north-west of Esperance. Esperance Hydrogeological

Zone 6. AMG.
6289011 mN, 332810 mE.

- Elevation:** 170 m AHD (approximately).
- Landscape position:** Gently inclined plain.
- Soil:** Shallow duplex soils (waterlogged).
- Land use:** Cropping/pasture.
- Features:** Long term regional groundwater rise. Comparatively deep watertable. Long term rate of rise > 30 cm per year (below average annual rainfall during monitoring period).
Seasonal perched watertable (shallow observation bore).



Bore number: CC 9.

Average annual rainfall: 520 mm.

Location: Ashdale Road, Esperance Mallee. 50 km west of Esperance. Esperance Hydrogeological Zone 4. AMG. 6274161 mN, 350084 mE.

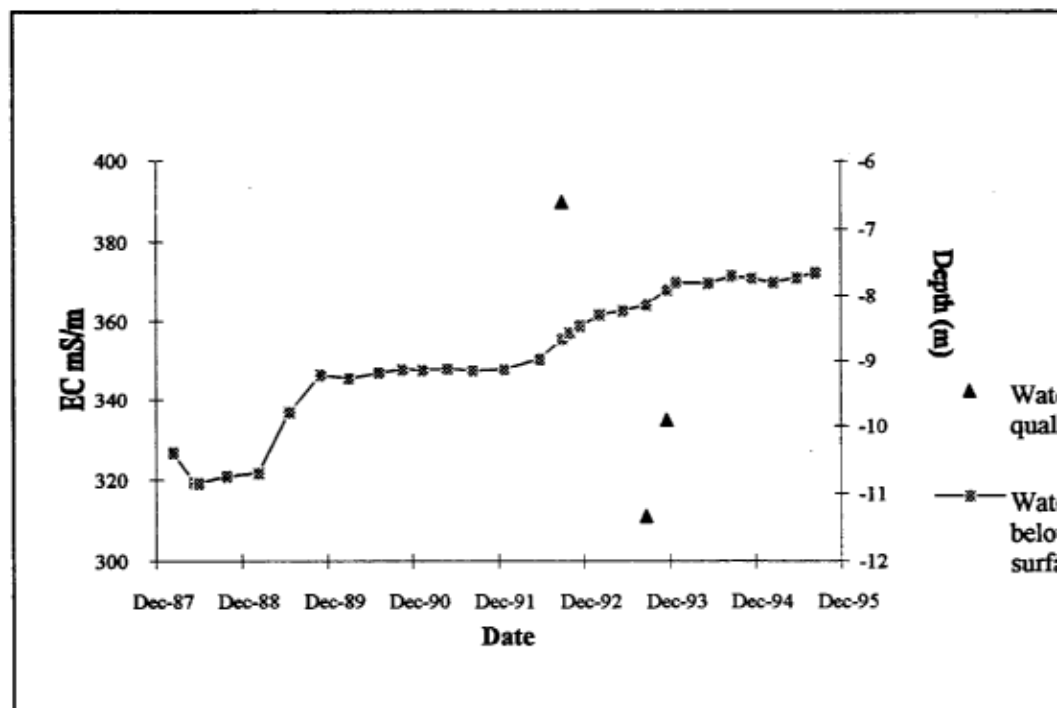
Elevation: 111 in AHD.

Landscape position: Gently inclined.

Soil: Shallow duplex soils (waterlogged).

Land use: Pasture.

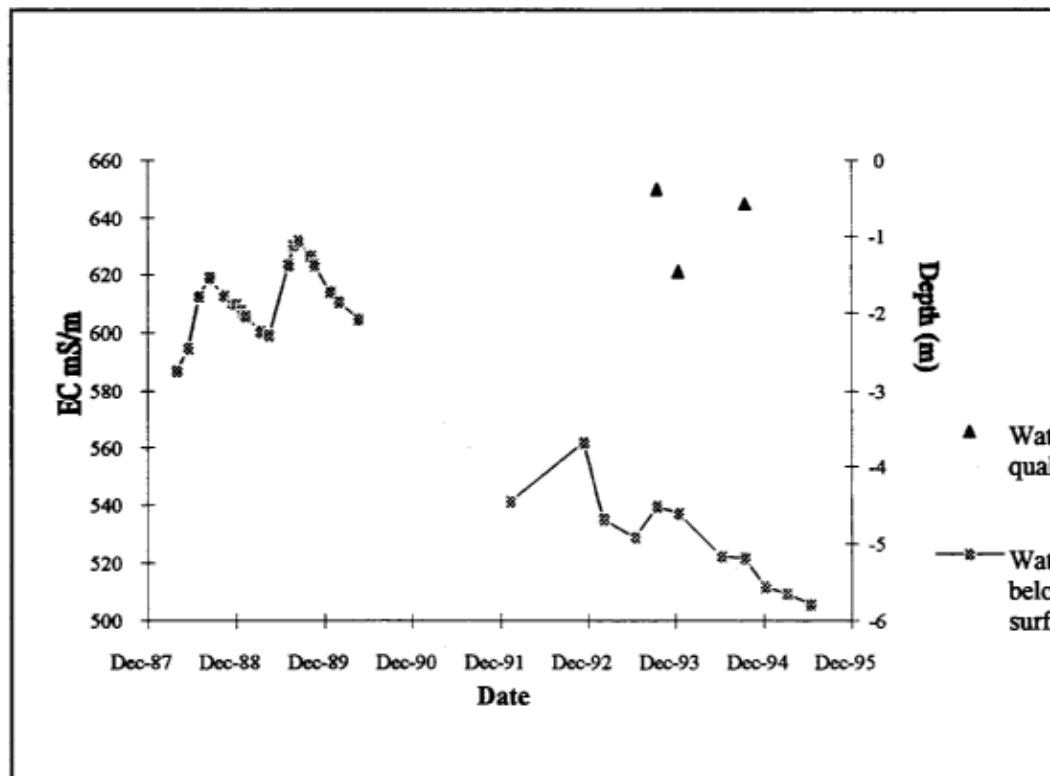
Features: Episodic response to the high rainfall event in 1992 resulting in the watertable rising to approximately 2 m beneath the surface -near salt scald.



Bore number: EM 11.

Average annual rainfall: 525 mm.

Location:	Savages Road, Esperance Sandplain. 40 km north-east of Esperance. Esperance Hydrogeological Zone 1. AMG. 6273636 mN, 430836 mE.
Elevation:	115 m AHD.
Landscape position:	Midslope in sand sheet.
Land use:	Cropping/pasture. Alley farming (<i>E. globulus</i> established 1993).
Soil:	Deep gradational sand.
Features:	Perched system in deep sand. Long term groundwater rise. Episodic response to the high rainfall events in 1989 and 1992. Response to dry period from 1993. Long term rate of rise (33 cm per year). Groundwater quality <400 mS/m.



Bore number:

K 2A.

Average annual rainfall: 550 mm.

Location: Dalyup, Esperance Sandplain. 70 km east of Esperance. Esperance Hydrogeological Zone 4. AMG (approximately). 6270200 mN, 362000 mE.

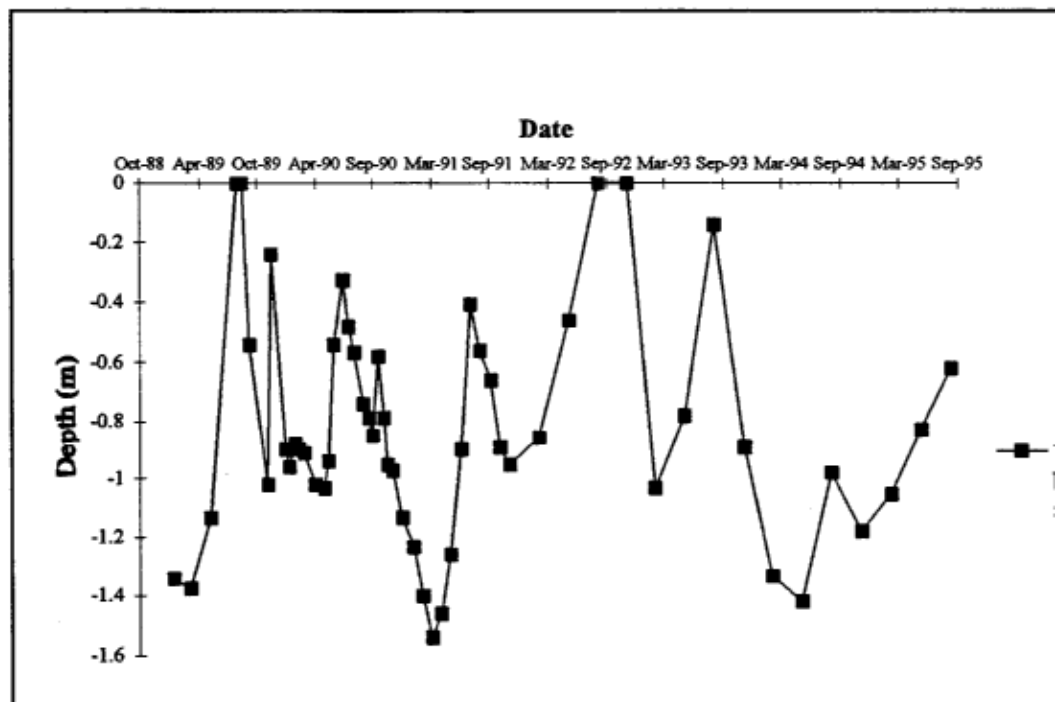
Elevation: 95 m ARD (approximately).

Landscape position: Depression in sand sheet.

Land use: Tagasaste grazing, established June 1987.

Soil: Deep gradational sand.

Features: Response to treatment. Long term fall in watertable of 50 cm per year (not monitored 1990 to 1991). Response to 1992 high rainfall event.



Bore number: E 1.

Average annual rainfall: 500 mm.

Location:	Gibson, Esperance Sandplain. 33 km north of Esperance. Esperance Hydrogeological Zone 4. AMG (approximately). 6285900 mN, 395900 mE.
Elevation:	160 m AHD (approximately).
Landscape position:	Midslope.
Land use:	Alley farming (<i>P. pinaster</i> windbreaks and pasture).
Soils:	Shallow duplex, waterlogged.
Features:	Effect of high rainfall events in 1989 and 1992 causing waterlogging. 1992 waterlogging event resulted in some tree deaths in windbreaks.