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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.

Information for contributors

Scientists who wish to publish the results of their investigations have access to a large number of journals. However, for a variety of reasons the editors of most of these journals are unwilling to accept articles that are lengthy or contain information that is preliminary in nature. Nevertheless, much material of this type is often of interest and value to other scientists and to administrators, and should be published. The Resource Management Technical Report Series provides an avenue for dissemination of such material. It is a series of occasional papers in the general subject area of resource management and is published by Agriculture Western Australia.

Intending contributors should contact the Natural Resource Management Service Unit. All papers will be reviewed by at least two referees and a relevant Group Leader.

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Summary

(a) Background, objectives and methods

The Mills Lake Catchment is located north of the Ongerup-Jerramungup Road, 35 km west of Jerramungup and 10 km north-east of Ongerup. It covers about 23,800 ha of agricultural land that is more than 90% cleared and predominantly cropped. The average annual rainfall of the catchment is about 370 mm.

Many low-lying parts of the study area have become salt-affected during recent years. The extent of soil salinity is growing rapidly and it is feared that, without any treatment, more land will become salt-affected. There are many lakes in the study area that were fresh, prior to and soon after clearing, but are now salty. It is feared that the Mills Lake, the only natural fresh water in the region, may become saline.

The objectives of this study were to investigate processes that lead to salinity in the study area, assess the extent of the problem and suggest management options that can reverse the salinity trend.

The methods of investigation included:

- Using landform pattern maps of the area;
- Interpreting 1:25,000 scale aerial photographs;
- Results of our drilling;
- Results from previous work in similar areas and similar rainfall zones.

(b) Geology, physiography, landform patterns and hydrological systems

The geology of the catchment varies markedly between the Crests and the Ancient drainage valleys. The soil profile is in situ weathered granites in the Crests. However, the Ancient drainage valleys often have a complete sequence of Tertiary sediments.

There are at least five major faults and three hinge lines (uplifts) in the Mills Lake Catchment that affect the hydrology of the area. The three hinge lines have interrupted the southern flowing regime of the region and changed the area into a closed basin with no significant path for groundwater and surface runoff to flow out of the area.

There are 17 landform patterns (LFPs) in the study area which have been grouped into seven hydrological systems (HSs; in bold):

- Undulating rises, Gently undulating plains, Gently undulating plains with shallow basement rock, and Gently undulating plains with sand dunes are found in **Crests**;

- Gently undulating plains with saline depressions, Gently undulating broad depressions and Rises are found in **Plains with Swampy Floors**;
- Very gently undulating plains, Plains, Very gently undulating plains with swamps and Very gently undulating plains with sand dunes are found in **Very Gentle to Level Plains**;
- **Tertiary Gently Undulating Plains** with sand dunes is a hydrological system and a landform pattern;
- Flat-bottomed valleys with lake systems and Lunette Systems are found in **Ancient Drainage Valleys**;
- Flats with well defined drainage and Stagnant alluvial or sedimentary flats are found in **Swampy Terrains** and all have extremely low relief;
- **Lakes** is a hydrological system and a landform pattern

(c) Hydrology

Groundwater level contours show that the study area is a closed basin and there is no water flow out of this catchment. The isopotentials also show that the lowest parts of the study area have become evaporation pans and groundwater flows to these discharge sites.

The Crests and the upper part of the Very Gently to Level Plains have local aquifers that are separated by the granitic highs (near Crests). However, aquifers in the Swampy Terrains, Undulating Dune Fields, Ancient Drainage Valleys, and lower parts of the Very Gently to Level Plains and the Lakes are regional.

In areas with local aquifers, the salinity and rising groundwater is an on-site issue. Therefore the management of land outside the influence of the local aquifer, will have little or no effect on that aquifer. Salinity in areas with a regional groundwater aquifer will be affected by on-site as well as off-site management.

Annual recharge in the study area varies between a few millimetres in dry years and up to 50 mm in wet years (for medium-textured soil). Recharge can be as high as 80 mm in areas with deep sands.

Recharge has caused groundwater levels to rise. In the Crests, groundwater levels are generally low but in the Swampy Terrains the levels are close to the soil surface.

The rate of groundwater level rise was estimated by three methods. They showed that groundwater levels in the Crests, Plains with Swampy Floors and Very Gentle to Level Plains are rising between 0.19 m and 0.23 m per annum. In the lower parts of the catchment, groundwater levels are close to the soil surface and are discharging through root zones and capillary voids. The rate of rise in these areas is probably very low <0.08 m/year. The groundwater levels in these areas only show strong fluctuations between seasons.

(d) Salinity and Waterlogging

The average salt storage (from 22 bores) was >3860 t/ha and varied from one hydrological system to another depending on the regolith depth, soil type and the attributes of the aquifers. The lowest salt storage (338 t/ha) was in a very shallow bore (4 m deep), on Crests. The highest salt storage (15,125 t/ha) was in a 45 m deep bore in the Swampy Terrains, which have extremely low relief.

Groundwater salinities in the study area vary between 3900 mS/m and 7400 mS/m. Half of the bores we drilled have salinities higher than sea water (5500 mS/m). Groundwater from the Werillup Formation was also very saline. This indicates that the aquifer in these coarse sands has been stagnant and very little or no groundwater movement has occurred.

More than 50% of agricultural land in some of the LFPs of the study area, such as Stagnant Flats, may eventually become salt-affected. Other areas such as Undulating rises, will have very little or no potential salinity. The eastern parts of the study area which were cleared in the 1960s have no salinity yet. In these areas, salinity may occur in a few years time and eventually large areas may become salt-affected.

At present, about 7.1% of the whole study area is salt-affected. Under present management practices, this figure may increase to more than 20%.

We estimate that in a year with decile 8 precipitation (480 mm; 2 years out of ten), approximately 60% of the catchment is affected by moderate to severe waterlogging. The extent of waterlogging varies from one LFP to another.

(e) Mills Lake

The Mills Lake (Figure 1) is the freshest water resource in the area. The surface area of the Lake was 18.5 ha in June 1996, and its maximum depth about 1.50 m. Its volume was approximately >90,000 m^3 and the salinity 283 mS/m. There is a pump station on the north-western bank of this Lake and a pipe line is used to pump water to Ongerup (12 km south-west), in dry years.

- There had been no permanent water in the Lake before or soon after clearing (as indicated by the remnants of natural vegetation).
- The present water level in the Mills Lake is controlled by runoff as well as the regional groundwater levels. As these levels rise, the depth of water in the Mills Lake will increase.
- The regional groundwater is flowing west, towards Windmill Lake (Figure 1), which has become an evaporation pan in recent years (Figure 11).
- There is a *fresh groundwater mound* to the east of the Mills Lake that is perched on a saline regional aquifer.
- The *fresh groundwater mound* is discharging into the eastern side of the Lake. Small volumes of the regional, saline groundwater may also enter the Lake.

- While the eastern part of the Lake is discharging groundwater, the western portion is recharging the regional aquifer.

We think that the Mills Lake is in danger of becoming saline but it is possible to prevent this. Four factors may contribute to increasing the salinity of this Lake:

1. Soil salinity in its catchment;
2. Rising levels of the regional aquifer;
3. Removing the perched fresh groundwater and;
4. Excessive pumping of water out of the Mills Lake.

(f) Management options to reduce recharge and the extent of salinity

Degradation problems in the study area are catchment issues. This means that the best results will be achieved if management options are applied throughout the area. Isolated treatments may have a localised effect but will not address the problem at the catchment level.

To reverse the increasing salinity, the present rates of recharge need to be reduced. This reduction can be made by:

- Reducing recharge and increasing surface and sub-surface runoff (surface drains);
- Increasing the area under perennial pastures;
- Introducing phase cropping;
- Applying management options that improve the productivity of crops and pastures;
- Increasing water use by revegetating selected areas;
- Regenerating existing native vegetation;
- Pumping saline groundwater and lowering groundwater levels.

There are also specific management options that reduce recharge and the extent of salinity. They include:

- Specific management options in relation to the landform patterns and hydrological systems of the study area
- Managing surface runoff
- Management and use of fresh and saline groundwater
- Specific management options for the Lakes and small depressions
- Specific management options for the Mills Lake

(g) Application of these findings to other areas

In absence of detailed studies, the findings in this report may be applicable to other areas which have similar rainfall and similar hydrological systems. These include the Upper Warperup Catchment and the *Ancient Drainage Valleys* that are north of the study area.

1. Introduction and background

1.1. The study area

The study area, which is known as the Mills Lake Catchment, is named after a fresh water lake. It covers about 23,800 ha of agricultural land and more than 90% is cleared. The area is located north of the Ongerup-Jerramungup Road, 35 km west of Jerramungup and 10 km north-east of Ongerup (Figure 1). The study area has internal drainage with numerous lakes and swamps that receive runoff from the catchment (mostly from eastern and western slopes). Some farmers remember an exceptionally wet year, about 50 years ago, when the lake system was full of water and excessive runoff spilled into the headwaters of the Pallinup River. Thus the area is considered part of, and forms the north-eastern corner of, the Upper Pallinup Catchment.

1.2. The salinity problem

Precipitation transports a small amount of airborne salt (cyclic salt; 20-50 kg/year on every hectare of land) to the soil. In the low rainfall (< 1000 mm per annum) areas, much of the cyclic salt is stored in the soil profile. Clearing the native vegetation for agriculture has reduced evaporation, increased recharge and resulted in rising groundwater levels, mobilising the stored salt. This salt-laden groundwater then surfaces as valley floor and hillside springs and seeps, causing soil salinity and contaminating previously potable water resources.

Many low-lying parts of the study area have become salt-affected recently. The extent of soil salinity is growing rapidly and it is feared that, without treatment, more land will become salt-affected.

There are a few lakes in the study area that were fresh prior and soon after clearing but are now salty. The Mills Lake is the only remaining fresh water lake in the region. This lake is pumped to supplement the water supply in Jerramungup and Ongerup Towns during dry years. It is feared that the Mills Lake may also become saline.

The farmers of the study area have formed an active group and want to reverse the salinity trend. Conservation and Land Management (CALM) and Water and Rivers Commission (WRC) have special interest in this area because there is a freshwater lake that is in danger of salinity.

The Mills Lake Catchment was nominated as a Focus Catchment in the Salinity Action Plan (Government of Western Australia,1996). This choice was confirmed by the North Stirling and Pallinup Forum (25 March 1997) which was attended by representatives from Agriculture WA and from subcatchments of that region.

The Catchment Hydrology Group has been asked to study the Mills Lake Catchment and suggests management options that may reverse the salinity trend in that area. This report is in response to that request.

1. 3. Objectives of this study

The main objectives of this study were to:

1. investigate processes that have led and are leading to salinity in the Mills Lake Catchment, in relation to the geology and hydrological systems of the study area;
2. assess the extent of the present salinity problem;
3. predict the potential salinity in the study area, if present management practices are continued;
4. predict the future salinity of the Mills Lake itself, if current practices are continued, and suggest ways to maintain its water quality;
5. suggest ways to reverse the present salinity trend;
6. define the areas that the findings of this study may be applicable to;
7. recommend measures for monitoring soil salinity and water resources in the study area.

1.4. Approach

The objectives were addressed systematically:

Objective 1

- investigate the geology and physiography of the area and the role they play in processes leading to salinity. Are there any sediments and palaeochannels in the area? (Section 4);
- describe the attributes of hydrological systems in the study area and their role in the extent of salinity (Sections 5 and 6);
- find out if the aquifer is regional or local. This may affect the treatments for preventing salinity (Section 7.1);
- investigate if the aquifer forms a closed basin or does it flow out of the area (Section 7.1);
- estimate the rate of annual recharge in relation to annual rainfall and soil type (Section 7.2).

Objective 2

- document the present groundwater salinities in the study area (Section 6.2);
- document the present groundwater levels in the study area and their rising trend (Sections 7.3);
- estimate the present extent of soil salinity (Section 8.1);

Objective 3

- identify the areas that would be in danger of salinity, under present management practices (Section 8.1);
- document other environmental hazards such as waterlogging and deterioration of the natural vegetation in the study area (Sections 8.2 and 8.3).

Objective 4

- predict the future salinity of the Mills Lake if current practices are continued and suggest ways to maintain its water quality (Sections 7.4, 8.4 and 9.6);

Objective 5

- recommend management options that will help reverse the salinity trend in the area (Section 9);

Objective 6

- define the areas that the findings of this study may be applicable to (Section 10);

Objective 7

- recommend the future monitoring of groundwater levels, salinities and the effect that treatments may have on them (Section 11).

1.5. Previous studies

McAvan (1984) studied the Mills and the nearby Windmill Lakes as water supply sources for Ongerup and Jerramungup. He concluded that:

- at the time of his study both lakes were fresh;
- runoff filled the Mills Lake first and then flowed into the Windmill Lake;
- runoff was generated if their catchment was wet and rainfall exceeded 100 mm in a month or 50 mm in a day;
- no significant inflow would have occurred in 53 years out of a total 68 years of recorded rainfall.

The Geological Survey of Western Australia (Thom and Chin, 1984; Thom *et al*., 1984), produced 1:250,000 geological maps and Explanatory Notes for Bremer Bay and Newdegate which cover the southern and the northern parts of the study area respectively. Based on these reports, the study area is on the southern margin of the Yilgarn Craton. The basement rocks in hilly areas are Archaean in origin while the plains and flats are reworked sandplain and ancient drainage flats.

Martin (1992), drilled a network of 110 bores in the Jerramungup Shire for monitoring groundwater levels and the extent of salinity. He concluded that “with water-tables rising an average of 0.3 m per year and average depth of 9 m,” management needed to be changed to prevent large areas becoming saline.

Ferdowsian (1997) mapped 38 landform patterns (LFPs) in the North Stirling and the Upper Pallinup Catchments between 1995 and 1997. Eighteen of these LFPs are also found in the Mills Lake Catchment. Ferdowsian and Ryder (in preparation) then grouped the LFPs of the North Stirling and the Upper Pallinup Catchments into 14 hydrological systems (HSs); seven are found in the Mills Lake Catchment (Figure 5).

Ferdowsian, Ryder and McFarlane (1994, 1995 and 1996) defined the Hydrological Zones of the Fitzgerald Biosphere which includes the eastern part of the study area. They described attributes of these zones and predicted their potential salinity and waterlogging. Based on their predictions, more than 30% of the study area may eventually become salt-affected.

Robinson (1997) investigated the impact of land degradation (resulting from clearing for agriculture), on the sustainability of farming and biodiversity in the Fitzgerald Biosphere. His study area extends to the eastern margins of the Mills Lake Catchment. He recommended revegetation within each catchment and the creation of effective wildlife corridors to link larger remnants within and outside the biosphere reserve. He suggested that direct seeding a diverse range of native species was the best method of controlling land degradation and preserving biodiversity within the agricultural areas.

2. Catchment

2.1. Climate

The study area has a "Mediterranean" climate with hot, mostly dry summers and cold, wet winters. The mean maximum temperature in January, which is the hottest month, is 30.4°C. There are occasional heat waves (mostly in February), during which the maximum temperature exceeds 45°C. The mean monthly temperature in July (the coldest month) is 9.8°C. During 12 days per year, the minimum temperature drops below 2.0°C.

The mean annual rainfall is about 370 mm. Seventy percent of this falls in the growing season (between May and October; Figure 2). The mean annual rainfall gradually decreases from the south-west (Ongerup; 375 mm) to the north-east (350 mm). The annual precipitation in 30% of years, (decile 3) is less than 320 mm and in 20% of years (decile 8) exceeds 460 mm.

The mean annual evaporation for the area is about 1830 mm. The monthly evaporation (from Class A evaporation pans) varies between 47 mm in June and 310 mm in January (Figure 2).

2.2. Clearing history

Clearing started early this century and became large scale in the 1940s. By 1950, most of the western and central parts of the study area had been cleared. These areas were flat, with mallees and shrubs which were easy to clear. Clearing the eastern parts, which had undulating areas and larger trees, started in the 1960s. At present, approximately 97% of the study area is cleared. The uncleared parts of the area vary with the landform patterns. In the flats and swampy landforms uncleared areas are associated with swamps and lakes. The uncleared areas of the undulating landforms are on deep sands, sand dunes and rocky areas.

2.3. Land use

The main land use of the area is cereal production, about 50 to 70% of the cleared farming land is under rotational cropping. The other areas are under annual pastures. The pastures and the crop residues are used for grazing merino sheep to produce wool.

3. Methods and materials

Drilling methods

Bores (Figures 1 and 3) were sited using aerial photographs (1:25,000 scale,1993 and 1:50,000,1985) and landform pattern maps (Figure 3). A total of 22 deep (to basement rock or into Werillup Formation) and 15 shallow (<9 m deep) holes were drilled using a Gemco HM12 Rotary Air Blast drill rig, between 6 and 17 May 1996. Soil samples were collected from every meter depth interval.

All the holes were cased with 40 mm PVC pipe for future monitoring. Drill logs and information on these holes (ML1/96 to ML 22/96) are presented in Appendix 1. These logs show groundwater levels and salinities, salt storages, depth to basement rock and lithology.

A further 18 sets of shallow (3 m) and medium depth (6 m) bores had been drilled by landholders in the area (Appendix 2). Stephen Newbey, a local Land Care Technician, had sited the position of those holes. Groundwater levels and salinities in these bores were also used to assess the salinity status of the study area.

Soil and water analysis

Standard techniques were used to analyse soil and water samples. Here is a brief description of these methods:

- Soil samples were air dried at 60°C for more than 5 days, crushed and sieved (<2 mm). Distilled water was added to make a 1:5 soil:water suspension (by weight) for measuring the electrical conductivities ($EC_{1:5}$).
- The $EC_{1:5}$ figures were multiplied by 0.0032 to estimate the percentage (by weight) of total soluble salt concentration (TSS) in soil samples.
- Electrical conductivity (EC) of water samples have been measured as an indication of their salinity. Water salinities therefore are quoted in milliSiemens per metre (mS/m). The electrical conductivity figures of the water samples were multiplied by 5.5 to estimate their total soluble salt (TSS in mg/L).

Bore data collection and analysis

Agriculture WA drilled six bores in or near the study area (bores J12, J13, J14, J15, J56 and J58) in 1989 (Martin, 1992) and the farmers have been monitoring the groundwater levels in these bores since 1989.

These levels were used to assess groundwater trends in the study area.

We interpreted the salt storage profile of the deep bores to predict the groundwater levels prior to clearing (Section 7.3).

All bores were surveyed and their water levels measured in June 1996. The relative groundwater levels in the bores were used to draw groundwater isopotentials and find the direction of groundwater flow.

Extent of soil salinity

Three tools were used to determine the extent of present and potential soil salinity in the study area:

- Salt-affected areas and areas that are in danger of soil salinity were marked onto the 1993 aerial photographs;
- A Geonic EM38 instrument was used to confirm the present extent and severity of salt-affected areas. The severity of salt-affected land in relation to EM38 readings was based on limits recommended by Ferdowsian and Greenham (1992).
- Groundwater levels and groundwater level contours (Figure 6) were used to confirm the areas which are in danger of salinity.

Physiography and geology

Four tools were used to gain an understanding of the geology and physiography of the study area:

descriptions of the geology and regolith from drilling profiles;

interpretation of aerial photographs;

interpretation of Total Magnetic Intensity maps (1:250,000; Bureau of Mineral Resources; BMR); and

- interpretation of 1:50,000 sheets.

Landform pattern and hydrological systems

Landform pattern maps of the area (Figure 3) were used to differentiate between and describe the attributes of various landforms of the study area. LFPs that have similar hydrological properties were grouped together as one hydrological system (HS).

4. Physiography and geology of the study area

4.1. General description of geology and physiography

Quaternary sediments were deposited during the last two million years. These sediments consist of aeolian (wind blown), fluvial (water deposited) and colluvial (gravity deposited) sand, clay and silt.

Tertiary sediments were deposited in the period between two and 65 million years ago. A complete Tertiary profile consists of the Werillup Formation and overlying Pallinup Siltstone. The Werillup Formation was first deposited over basement rock in a swampy environment. These sediments consist of dark-coloured clay and silt (lignite) overlying medium to coarse sand. The sand has a higher hydraulic conductivity than the silts and clay because it is coarser. The lowest layer of the Werillup Formation may contain very coarse materials including rounded pebbles deposited in river beds.

The Pallinup Siltstone was deposited over the Werillup Formation in a marine environment. The Siltstone may contain pink and white spongolite (a siltstone full of sponge spicules). Closed depressions and lakes occur in areas where the siltstone lies over the Werillup Formation.

Landforms of the study area are a product of tectonic movements, geology and erosive processes. It seems that erosive forces were very active during first half of the Tertiary period when the sands and silts were deposited and it was probably during this time that the sedimentary profiles, in this area, were formed. During recent geological periods (the last 10 million years or so) the surface of the catchment has been fairly stable; only aeolian and colluvial sediments have been deposited. Salt in the soil profile has probably been accumulating for the past 500,000 years.

4.2. Physiography

In this section, we describe the evolution of the present geomorphology of the study area and its effect on the present landforms. Geomorphology reflects tectonic movements, erosive processes and underlying geology.

The hypothesis that the Darling Plateau was uplifted during the Tertiary Period was made 83 years ago (Jutson 1914). To the south of this Plateau, there is a gradual transition from the Plateau to the continental shelf which is called the Ravensthorpe Ramp (Cope 1975). The Ravensthorpe Ramp has a gradual southerly slope from about 300 m elevation near the southern edge of the Darling Plateau to sea level. The rivers draining to the south coast are relatively short, and are incised into the tilted surface of this Ramp. The dissected and rejuvenated areas that are north of Gnowangerup, Ongerup and west of the study area form the northern margins of the Ravensthorpe Ramp.

An east-west drainage divide separates the Darling Plateau from the Ravensthorpe Ramp. This divide, which is between 100 and 120 km from the south coast of WA, forms a hinge line (an uplifted ridge) named the Jarrahwood Axis (JWA; Cope 1975; Figure 4). Traces of the JWA may be found as far as Esperance, running parallel to the south coast.

The study area is located within two tectonic units: the southern margins of the Darling Plateau and the northern precincts of the Ravensthorpe Ramp. The JWA, which is one of these hinge lines, extends eastwards and stops (or deforms) at the western boundary of the Mills Lake Catchment and south of Cassincarry Lake (Figure 1). Tectonic movements in the Tertiary Period caused major faults and hinge lines which have produced unique landforms in the study area.

Most of the lakes in the Mills Lake Catchment are formed in two fault zones. The first zone has at least two active faults (No 1 and 2; Figure 4) lying north-west-north. This fault zone starts about 30 km south-east-south of the study area and continues for approximately 150 km. Myers (1989) mapped (1:1,000,000 Geological Map) the north-western part of this fault (unnamed fault). Three other faults exist in the study area (No 3, 4 and 5; Figure 4) that have a north-east direction. In addition to these faults, we have also mapped four hinge lines (uplifts) in the region that affect the hydrology of the area. Three of these hinge lines are parallel to faults 1 and 2. The first hinge line forms the south-western boundary of the study area (hinge line A; Figure 4). The second hinge line (B; Figure 4) forms the north-eastern boundary of the area and the third one (C; Figure 4) is further north and out of the study area. The fourth hinge line (D; Figure 4) has a east-north-east direction and forms the southern boundary of the study area.

In bores that are near or on the hinge lines (bores ML4/96 and ML20/96), the top of the Tertiary sediments lies between 4 and 22 m above those in the major fault zones and the valley floors. This variation indicates that the faults and hinge lines probably formed after the Tertiary sediments were deposited.

The three hinge lines that are to the west, north and south of the Mills Lake Catchment have probably interrupted the southern flowing regime of the region. This has changed the area to a closed basin, with no significant path for its groundwater and surface runoff to flow out of the area.

ridges that have caused formation of the present landform patterns and hydrological systems of the study area

4.3. Geology

The study area lies within the Yilgarn Craton. This Craton is a major tectonic unit consisting of a large stable mass of rock. Basement rocks are Archaean in age (>1500 million years old), generally igneous and metamorphic. This zone has numerous dolerite dykes that have an east-west direction. In hilly areas, the regolith (weathered or sedimentary material that is over basement rock) is shallow to moderately shallow (<10m) and occasional rock outcrops may be seen. The regolith in this area includes a thin veneer of Quaternary sediment above *in situ* weathered material.

In broad depressions and the lower part of the landscape, the regolith depth could be more than 40 m. The regolith in these areas consists of mainly Tertiary sediments that in most areas lays over a veneer of *in situ* weathered material. Both the Pallinup Siltstone and the underlying Werillup Formation were found in drill holes near lake systems. In other low-lying areas, away from the lake systems, only the Pallinup sediments may be found. The Tertiary sediments and the *in situ* weathered material could be covered by few meters of alluvial and colluvial sediments of Quaternary origin (<2 million years old). Dune fields that cover west-south-west areas of the large lakes are fine sand and silt deposited by wind. The origin of these material is from lakes and depressions west of the dune fields. The flat floors in some lakes are covered by a few meters of lacustrine sediments that have probably been transported from the undulating areas surrounding the study area.

We have found conglomerates that contain water-rounded pebbles and cobbles on the hilly areas south-east of the study area. This material indicates that remnants of palaeodrainage patterns can be found on high ground.

5. Landform patterns and hydrological systems of the study area

A *landform pattern* (LFP) is a topo-sequence (valley floor, hillside and ridge) described by its relief, slope, landform elements and degradation problems associated with its use. Landform patterns are products of tectonic movements, erosive and depositional processes.

Hydrological systems (HS) are groups of LFPs with similar hydrological properties. There are 17 LFPs in the study area (Figure 3). We have grouped these LFPs into seven hydrological systems (Figure 5):

5.1. Crests (CR)

This hydrological system covers 28.5% of the study area. It is developed on *in situ* weathered granitic and gneissic material. The weathering profiles in these areas are shallow to moderately deep (10 to 20 m). The drilling profile changes from sand or loamy sand near the soil surface to sandy clay (or heavy sandy clay), to moderately weathered basement rock with coarse grit, to basement rock. Bores ML7/96, ML15/96, ML18/96 and ML19/96 (Figure 3 and Appendix 1) are in this hydrological system. The gritty layer has high hydraulic conductivity that facilitates the flow of groundwater to the lower hydrological systems.

Bore ML20\96 is also in the **Crests** but unlike other areas of this HS has about 12 m of Tertiary sediments (Pallinup Formation). The existence of Tertiary sediments in this bore and its elevation (22 m above valley floor) are indications that this ridge has been uplifted since the Tertiary sediments were deposited.

This HS has very low relief (5 m-30 m within a circle of about 300 m radius), eroded crests and slopes and aggraded open depressions that become gradually swampy on their downstream parts. This HS will have some waterlogging in wet years. Waterlogging is limited to the floors of the open depressions and flat crests. Soil salinity is rare but contributes to salinity in the lower HSs. Almost all of the areas are recharge areas, particularly the waterlogged sandy depressions. Thus, this HS has a higher recharge than the other hydrological systems.

5.2. Plains with Swampy Floors (PSF)

This hydrological system is found in mid-catchment positions and covers 5.9% of the study area. It includes landform patterns that have well-defined drainage or swampy floors and very gentle to gentle side slopes. The high ground of this HS resembles the Crests. Thus, it also has layers of sandy clay over a thin layer of gritty material that in turn is over basement rock. Most of the weathering profiles are moderately shallow (5 to 10 m) but in some areas the profile is moderately deep (10 to 20 m). The coarse sandy material which is over basement rock (saprolite) has a high hydraulic conductivity that facilitates movement of groundwater to the depressions and lower parts of this HS where saline seeps occur.

The basement rock in the lower areas of this HS is moderately deep (10 to 20 m). These areas have a few metres of Pallinup silty clay near the soil surface. These sediments are often buried by about 1 m to 4 m of sandy clay or sandy loam (alluvium). Alluvium that is derived from the higher grounds, including the granitic hills, has covered the Pallinup sediments during recent geological periods. ML16/96 is a good example of a weathering profile in this HS.

The Plains with Swampy Floors have continuous and active erosion and aggradation. Waterlogging and soil salinity are confined to the floors of the open depressions. Saline groundwater seeps up through root channels to the soil surface in the depressions and then spreads over the land causing soil salinity.

5.3. Very Gentle to Level Plains (VGP)

This hydrological system occurs in mid-catchment positions of the study area and occupies 31.6% of the catchment. The upper reaches are usually a transitional zone that changes gradually to the **Crests**. The upper reaches of VGPs may have some coarse material over basement rock. In these areas, the near surface layers may consist of 1 m to 4 m of sandy clay or sandy loam (Quaternary). These sediments are derived from the higher grounds, including the granitic hills. The depth of the Pallinup material in the higher areas of this HS is between 5 to10 m. ML4/96, ML5/96, ML17/96 and ML8/96 are in the VGP system. Bore ML4\96, which is about 7 m above the valley floor and 26 m deep, is near the uplifted ridge that forms the western boundary of the study area. Bore ML8/96 is on a sand dune but has a profile that is similar to the profiles in the Very Gentle Plains.

The lower parts of this HS could have moderately deep to deep (>20 m) Tertiary sediments (Pallinup Formation only) over in situ weathered basement rock. Bores ML13/96 and ML14/96 (Figure 1 and Appendix 1) are typical of these areas. There is neither saprolite nor any other coarse material in these profiles and this absence, plus the low hydraulic gradient, has consequences that are discussed later (Section 8). This HS has depressions which are broad and poorly defined.

5.4. Undulating Dune Fields in Tertiary areas (UDF)

This hydrological system is located to the east and south-east of the Mills Lake (Figure 3) and covers 115 ha of land (0.5% of the study area). Areas of this HS have a full Tertiary profile (for example bore ML10/96). Drilling showed that this bore had about 23 m of Pallinup Siltstone on top of Werillup Formation. The bore collapsed just after 23 m and drilling was abandoned. We estimate that the regolith (depth to basement rock) is very deep (>40m). The Pallinup Formation consisted of fine sand and not the silt that is commonly found in the area. The fine sand gives the UDF system a unique hydrological role that is discussed later (Sections 6.2 and 7.4). We usually class this HS as part of Ancient

Drainage Valleys. In the Mills Lake Catchment, we have given this HS a class of its own because of its unique hydrological role.

5.5. Ancient Drainage Valleys (ADV)

This hydrological system covers 12.5% of the study area (2990 ha).There are two landform patterns in this HS: *Flat bottomed valleys with lake systems* and *Lunette fields* to the (east of the lakes). This HS is formed on full Tertiary profiles which consist of Pallinup Siltstone (between 20 and 30 m thick) over Werillup lignite (< 1 m thick) over Werillup coarse sand which is very loose. These sediments have filled the *Ancient Drainage Valleys* that existed prior to the Tertiary period. It was not possible to drill more than 8 m into the loose Werillup sandy layer because the holes collapsed. The sandy layer has very high hydraulic conductivity and bore holes yielded more than 1 L of water per second. The regolith in this zone is probably deep to very deep (>40 m). The higher grounds of this HS have deep, aeolian sand that has been blown in from the lakes. The low lying areas contain salty flats and salty closed depressions. Bore numbers ML11/96, ML12/96, ML21/96 and ML22/96 are typical of this zone.

5.6. Swampy Terrains that have extremely low relief (ST)

This HS occupies 4170 ha of land (17.5%) and is located mainly in the broad flats of the study area. The regolith is deep (20 to 40 m) and consists of < 4 m of alluvium over 10 to 25 m of Pallinup silt, over sandy clay (in situ weathered material), over basement rock. Rock outcrops are very rare and are only found where the granitic highs come near the soil surface. The Pallinup silt and clay in most of these areas have weathered to very heavy silty clay that prevents the movement of water. This characteristic will be referred to later in relation to drainage. Bores ML1/96, ML2/96, ML3/96 and ML6/96 are typical of these profiles.

The most common soil type in this HS is gilgai or ‘crabhole’ soil. Bore ML2/96 shows that the top few meters (3 to 4 m) of the soil profile typically consists of a heavy clay that may swell when wet and shrink when dry. The successive swelling and shrinking results in crabhole formation.

This HS has extremely low relief (<5 m). Stream channels are sparse or non-existent. Open depressions are broad, widely spaced and not defined enough to drain their areas. Erosion and aggradation vary from continuously active to barely active. The groundwater is more saline than that in other hydrological systems and is often at or near the soil surface (Section 7.1 ; Figure 7a and 7b). Saline groundwater reaches the soil surface through root channels and capillary pores, causing soil and water salinity. Salt storages are high in this HS.

5.7. Lakes (L)

Lakes cover 3.5% of the total area (828 ha) and include all closed water bodies and swamps that are more than 500 m in diameter. Lakes are formed on two different geological units:

- Most of the lakes are in the **Ancient Drainage Valleys** and within areas which have full Tertiary profiles. They are not usually formed in areas that have only Pallinup Siltstone, unless the next condition applies.
- Some of the lakes are formed where major faults cross or in the hollows left between blocks of land that have been shifted due to tectonic movements. A good example of this is Cassincarry Lake (Figure 1) which is the largest lake in the study area. This lake straddles the Ongerup/Pingrup road. Bore ML9/96, which is in the middle of the lake, had little or no Tertiary material.

Some of the lake floors in the study area are covered by alluvial and colluvial sediments that have been transported from the nearby granitic areas. Bore ML9/96 (in the Cassincarry Lake) had about 6 m of alluvial and colluvial sediments on top of *in situ* weathered material.

Runoff passes through a swamp with gilgai soils before flowing to the Mills Lake. This swamp is the remnant of a deeper lake that has been filled by sediment. It is likely that the original floors of most of the lakes in the study area were much lower than the present levels. The original floors were formed a long time ago when the weather was very dry. The dry period was probably followed by a very wet period that generated large runoff and flooding events, infilling part of the lakes.

6. Salt storage and groundwater salinity in hydrological systems of the study area

6.1 Salt storage

Annual rainfall deposits about 25 kg of airborne salt (cyclic salt) over every hectare of land in the study area. Some of this salt is stored in the soil profile while the rest is redistributed through groundwater movement. The present salt storage of the soil profile depends on: depth of the profile, soil type, historical recharge and flushing by groundwater movement. Thousands of tonnes of salt have accumulated in the soil profiles of the study area (Table 1). The lowest salt storage was 338 t/ha in a very shallow bore (4 m deep; ML19/96) on the **Crests** systems. The highest salt storage (15,125 t/ha) was in Swampy Terrains that have extremely low relief (Stagnant flats; Bore ML3/96). Salt storage varies from site to site and from one HS to another (Table 1) depending on the regolith depth, soil type and attributes of the aquifers:

In the Crests that have moderately shallow profiles, salt storages are moderately low (average 2000 t/ha; ranges 300 to4000 t/ha).

The only bore in the Plains with Swampy Floors had 3300 t/ha of salt stored. We expect that this figure would be typical for this HS.

Average salt storage in 6 bores drilled in the Very Gentle to Level Plains was 6570 t/ha (range1850 to 12,000 t/ha).

Bores drilled in the Undulating Dune Fields and in the Ancient Drainage Valleys had between 1600 and 4700 t/ha (average 2000 t/ha) of salt. The lower salt storages in this HS belong to bores not drilled to basement rock. The highest salt storage (4700 t/ha) was in a bore which was drilled to basement rock (ML21/96; 34 m deep). This amount of salt would probably be common in these two HSs.

Swampy Terrains that have extremely low relief had the highest salt storage (8850 t/ha; average of 4 bores) recorded in the study area.

Lakes probably have similar salt storages to the Ancient drainage valleys.

6.2. Groundwater salinities in the Mills Lake Catchment are very high

Groundwater salinity in 35 out of 36 bores varied between 3900 mS/m (bore ML15/96) and 7400 mS/m (bore ML3/96; Table 1).

Half of the bores had salinities that were higher than sea water (6200 mS/m). The HSs in order of increasing groundwater salinities (mS/m) are: Lakes (5250); VGP (5350); ADV (5650); CR (5900); ST (6650) and PSF (7100). Groundwater salinity is very high (5100 to 5600 mS/m; Table 1) in bores that have Werillup coarse sands (the deepest Tertiary sediments; Section 4).

Table 1: Groundwater levels and groundwater salinities in relation to the hydrological systems of the study area

Bore No	Hydrological system	Depth of groundwater levels (m)	Groundwater salinity (mS/m)	Salt storage (t/ha)
ML7/96	Crests	6.92	7090	3660
ML15/96	Crests	12.38	3910	3359
ML18/96	Crests	6.40	6380	369
ML19/96	Crests	Dry	Dry	338
ML20/96	Crests	17.53	6100	2783
K363	Crests	Dry	Dry	NA*
Average (Crests)		**10.80**	**5870**	**2100**
ML16/96	Plains with Swampy Floors	1.97	5750	3325
K283	Plains with Swampy Floors	0.60	7590	NA
K280	Plains with Swampy Floors	0.60	8000	NA
Average (Plains with Swampy Floors**)**		**1.08**	**7110**	**3325**
ML4/96	Very Gentle to Level Plains	2.25	6850	6588
ML5/96	Very Gentle to Level Plains	1.04	7290	8001
ML13/96	Very Gentle to Level Plains	2.95	4770	11866
ML14/96	Very Gentle to Level Plains	2.09	4120	4558
ML17/96	Very Gentle to Level Plains	2.28	5100	1842
K356	Very Gentle to Level Plains	1.18	5470	NA
K743	Very Gentle to Level Plains	0.93	3890	NA
K1350	Very Gentle to Level Plains	1.32	6200	NA
K1350	Very Gentle to Level Plains	1.03	3170	NA
K361	Very Gentle to Level Plains	2.85	5230	NA
K1211	Very Gentle to Level Plains	1.30	6800	NA
Average (Very Gentle to Level Plains**)**		**1.75**	**5350**	**6571**

Bore No	**Hydrological system**	**Depth of groundwater levels (m)**	**Groundwater salinity (mS/m)**	**Salt storage (t/ha)**
ML11/96	Ancient Drainage Valleys	2.55 (mid-lunette)	5335	>2238
ML12/96	Ancient Drainage Valleys	6.26 (on lunettes)	5060	>1578
ML21/96	Ancient Drainage Valleys	3.50 (on lunettes)	5610	4710
ML22/96	Ancient Drainage Valleys	4.04 (on lunettes)	4580	>1108
ML8/96	Ancient Drainage Valleys	8.84 (on lunettes)	7780	7836
K349	Ancient Drainage Valleys	1.88 (on flats)	6600	NA
K301	Ancient Drainage Valleys	2.22 (on flats)	4620	NA
Average (Ancient Drainage Valleys**)**		**5.4 (lunettes) 2.05 (flats)**	**5650**	**>3495**
ML1/96	Swampy Terrains	1.64	6090	4236
ML2/96	Swampy Terrains	1.53	7000	6859
ML3/96	Swampy Terrains	1.56	7360	15125
ML6/96	Swampy Terrains	2.36	6810	9144
K1456	Swampy Terrains	1.14	6400	NA
K302/1	Swampy Terrains	1.57	5100	NA
K302/3	Swampy Terrains	1.40	8000	NA
Average (Swampy Terrains**)**		**1.60**	**6670**	**8840**
ML10/96	Undulating Dune Fields	**4.00**	**2710****	**>1611**
ML9/96	Lake	**2.20**	**5260**	**>1235**
Average (all bores)		**3.22**	**5770**	**>3860**

*   NA = not available.

** Salinity of bore 10/96 is diluted by a shallow, freshwater mound.

This shows that the aquifer has always been stagnant and very little or no groundwater movement has occurred.

The shallow groundwater (4 to 5 m deep) in bore ML10/96, which is east of the Mills Lake and in the Undulating Dune Fields, was very fresh (148 mS/m). As we drilled deeper, groundwater salinity increased (Table 5; Section 7.4), so that in the deep bore (23 m) which was drilled at the same site, the groundwater was saline (2710 mS/m). The sample was probably diluted by the fresher water that was on top of the aquifer. We expect that the salinity of the deep aquifer at this site is similar to bore ML11/96 (5300 mS/m) which is south-west of the Mills Lake. A thin lens of brackish groundwater may be found under some sand dunes and sandy areas (for example bore K301/2S) or in coarse sand on the footslopes of granitic hills (for example K283/2C). The shallow (<2 m) groundwater near bore ML5/96, which is in a flat area, was very saline (4,800mS/m) and became saltier with depth (Table 2).

Table 2: Groundwater salinity in bore ML5/96 increases rapidly within the first few meters.

Depth intervals (m)	1 - 1.5	1.5 - 2.0	2.0 - 2.5	2.5 - 3.0	24.0 - 26.0
Groundwater salinity (mS/m)	4,830	5,430	5,810	6,070	7,310

7. Hydrology of the study area

7.1. Type and attributes of aquifers in the study area

Groundwater level contours (Figure 6) and groundwater salinities (Section 6.2) show that there is no flow out of this catchment and the study area is a closed basin. Both surface runoff and groundwater flow towards the lowest parts of the catchment. The isopotentials (Figure 6) also show that the lowest parts have become evaporation pans and therefore groundwater flows to these discharge sites. The Windmills Lake, for example, has become a major evaporation pan in recent years. Groundwater from surrounding areas flows into this lake and evaporates. The Cassincarry Lake that is east of the Ongerup-Pingrup Road (Figure 1) is another discharge site. The lakes that become discharge sites will gradually lose their vegetation and eventually become salt pans.

The **Crests** and upper part of the **Very Gently to Level Plains** have local aquifers (Figure 7a and 7b) that are separated by the granitic highs (near **Crests**). Aquifers in the **Swampy Terrains, Undulating Dune Fields, Ancient Drainage Valleys,** and lower parts of the **Very Gently to Level Plains** and the **Lakes** are regional (Figure 7a and 7b). The **Plains with Swampy Floors** are a transitional zone between the two types of aquifers. As groundwater levels rise, a larger proportion of the aquifer that is in **Plains with Swampy Floors** and upper parts of the **Very Gently to Level Plains** will become regional.

In areas with a local aquifer, salinity and rising groundwater are on-site issues. Therefore, management practices outside the influence of the aquifer will have little or no effect on that aquifer. However, the management of land with a local aquifer will affect others downstream. Salinity in areas with regional groundwater is affected by on-site as well as off-site management practices. Farming practices in the higher parts of the catchment will affect all the catchment. Figures 7a and 7b show an east-west cross section of the study area and indicate that:

- the local aquifer which is near the Crests has a higher gradient than the regional aquifer;
- the gradient of the regional aquifer is very low;
- in Swampy Terrains, the regional groundwater levels come close to the soil surface in October. These water levels drop gradually to 1.5 m below the soil surface late in the dry season (April and May);
- in most areas of the *Plains,* the groundwater levels are about 2.50 m below the soil surface. These levels are still below capillary ranges. As groundwater levels in these Plains rise the saline groundwater may be drawn to the soil surface by capillary action and salinity may affect substantial areas.

7.2. Recharge in the study area

Recharge is that component of annual rainfall that by passes the root zone of plants and joins the groundwater. Recharge is difficult to measure directly but soil water balance methods can be used to estimate it indirectly. The soil water balance can be written as:

$$\mathbf{P = R + ET_a + PAWC + dS + dD + U}$$

where:

P is precipitation;

R is runoff and includes surface runoff as well as shallow subsurface seepage;

ET_a is actual evaporation (including transpiration);

PAWC is plant available water capacity; it is stored in the root zoneand is used by plants later in the season when monthly **ET_a** exceeds the monthly rainfall. Therefore **PAWC** will eventually change to **ET_a**.

dS is change in water stored in the unsaturated zone;

dD is change in water stored above the soil surface;

U is recharge to the groundwater.

When annual estimates are made, the changes in dS and dD components can be ignored and the equation becomes:

$$\mathbf{= P - R - ET_a - PAWC}$$

Plant available water capacity depends on the depth of root zone and the water holding capacity of the soil. Table 3 shows the estimated PAWC of the main soil types in the study area. There are two assumptions in formulating this Table:

1̃ It is assumed that the PAWC in sand and gravelly sand is 50 mm/m; in clayey loam 100 mm/m and in clay 120 mm/m (Ferdowsian and Greenham, 1992).

2̃ It is assumed that depth of root zone (m) for annual pastures, crops, perennials, lucerne and trees are 0.40, 0.70, 0.90, 2.00 and 3.00 m correspondingly.

We calculated the rate of annual recharge in the study area for 3 annual rainfall conditions and for the main soil types (Table 4). The calculations are described by Ferdowsian and Greenham (1992). Our results show that:

- In a year with decile 8 precipitation (460 mm; 2 wettest years out of every 10), during May to August the rainfall will exceed the sum of plant water use and runoff. Recharge under annual pastures in sandy areas will approach 80 mm/year. Crops will also cause high rate of recharge (between 21 and 65 mm/year).
- In a year with a mean rainfall (375 mm), precipitation will exceed the sum of plant water use and runoff between May and July. Annual pastures in these years will not be able to use all the precipitation. As a result, between 9 and 33 mm of annual rainfall will recharge the aquifers. Annual recharge under crops will be much less (between zero and 18 mm/year).
- Very little or no recharge will occur in exceptionally dry years (<320 mm annual rainfall; 2 driest years out of ten).

Confirmation of Table 4 figures can be seen in behaviour of some bores in the study area (Bore J14; Section 7.3).

Table 3: Estimated Plant Available Water Capacity (mm) of the main soil types in the study area (based on Ferdowsian and Greenham, 1992)

Main soil types	Depth of the root zone (m)				
	Annuals 0.40	**Crops** 0.70	**Perennials** 0.90	**Lucerne** 2.00	**Trees** 3.00
Sand dunes [1]	20	35	45	100	150
>0.5 m gravelly sand over clay [2]	20	49	73	205	325
0.3 m gravelly sand over clay [3]	27	63	87	219	339
<0.2 m loamy sand over clay [4]	44	80	104	236	356

1. Found in two HSs: Ancient Drainage Flats and Undulating Dune Fields.

2. Common in the Very Gentle to Level Plains.

3. Found in the Crests and Plains with Swampy Floors.

4. Found in the Swampy Terrains.

Table 4: Estimated rate of recharge (mm) in the study area in various soil types and under different land use options.

		Annual rainfall scenario		
Soil types	Land use	2 wettest years out of every 10 (460 mm)	a year with a mean rainfall (375 mm)	2 driest years out of every 10 (<320 mm)
Sand dunes	Annual pastures	80	33	12
	Crops	65	18	00
	Perennials	55	8	00
	Lucerne	1	00	00
	Trees, shrubs	00	00	00
>0.5 m gravelly sand over clay	Annual pastures	80	33	12
	Crops	51	2	00
	Perennials	28	00	00
	Lucerne	00	00	00
	Trees, shrubs	00	00	00
0.3 m gravelly sand over clay	Annual pastures	73	26	5
	Crops	38	00	00
	Perennials	14	00	00
	Lucerne	00	00	00
	Trees, shrubs	00	00	00
<0.2 m loamy sand over clay	Annual pastures	57	9	00
	Crops	21	00	00
	Perennials	00	00	00
	Lucerne	00	00	00
	Trees, shrubs	00	00	00

7.3. Groundwater levels

We measured groundwater levels early in June 1996 in a very dry season. Because there had been little rain and no recharge, the groundwater was lower than normal. In the *Crests*, groundwater levels are generally low while in the *Swampy Terrains* levels are close to the soil surface (Table 1; Figures 7a and 7b).

Before clearing the natural vegetation, groundwater levels in the study area were low and stable. Since clearing these levels have risen. The rate of rise has been estimated by three methods:

1. Original groundwater levels (before clearing) can be assessed by interpreting the salt storage profiles. Ferdowsian and Greenham (1992) found that in the Upper Denmark Catchment, profiles less than 8 m deep had had no permanent groundwater prior to clearing. The salt storage in the lower part of these profiles gradually increased down to basement rock. However, salt concentration reduced over basement rock in profiles deeper than 8 m, where groundwater had existed prior to clearing. In this study area, salt storages in profiles ML9/96, ML17/96, ML18/96 and ML19/96 increased gradually to basement rock (Appendix 1). We therefore, assume that these four sites had no permanent groundwater prior to clearing. ML19/96, being very shallow (4 m) still has no water. Bores ML18/96 (7 m deep), ML9/96 (11 m deep) and ML17/96 (14 m deep) have developed 1, 9, and 12 m of groundwater respectively. In deep bores (ML9/96 and ML17/96), groundwater levels have risen between 9 and 12 m since clearing (0.2 m per year; 50 years since clearing).

2. Original groundwater levels can also be estimated in bores sites that have had shallow groundwater on top of basement rock prior to clearing. The salt storage profiles in these bores show a sharp reduction over basement rock indicating the original groundwater levels. Bores ML15/96 and ML16/96 are of this type. These two bores show the groundwater has risen by 11 - 12 m (0.23 m during the 50 years).

3. Agriculture WA drilled six bores in or near the study area (bores J12, J13, J14, J15, J56 and J58) in 1990. These bores show rises of 0.05 to 0.40 m (average 0.19 m per year) since 1990.

The present rate of groundwater rise in an area depends on how far it is from discharge sites. In the lower parts of the catchment, groundwater levels are close to the soil surface and are discharging through root zones and capillary voids. The overall rate of rise in these areas is probably low but groundwater levels show strong seasonal fluctuations (bore J58; Figure 8a; southern parts of the study area).

In the **Crests**, **Plains with Swampy Floors** and **Very Gentle to Level Plains** the rate of rise may be about 0.20 m/year (bore J14; Figure 8b; eastern parts of the study area). Three segments can be seen in this hydrograph:

- Average annual rainfall between 1990 and 1991 was 470 mm which caused the groundwater to rise by approximately 0.20 m per year.
- Average annual rainfall between 1992 and 1993 was 555 mm which caused the groundwater levels to jump by approximately 0.55 m per year.
- Average annual rainfall between 1994 and 1996 was very low (280 mm). No or very little recharge occurred and groundwater levels dropped by 0.25 m/year.

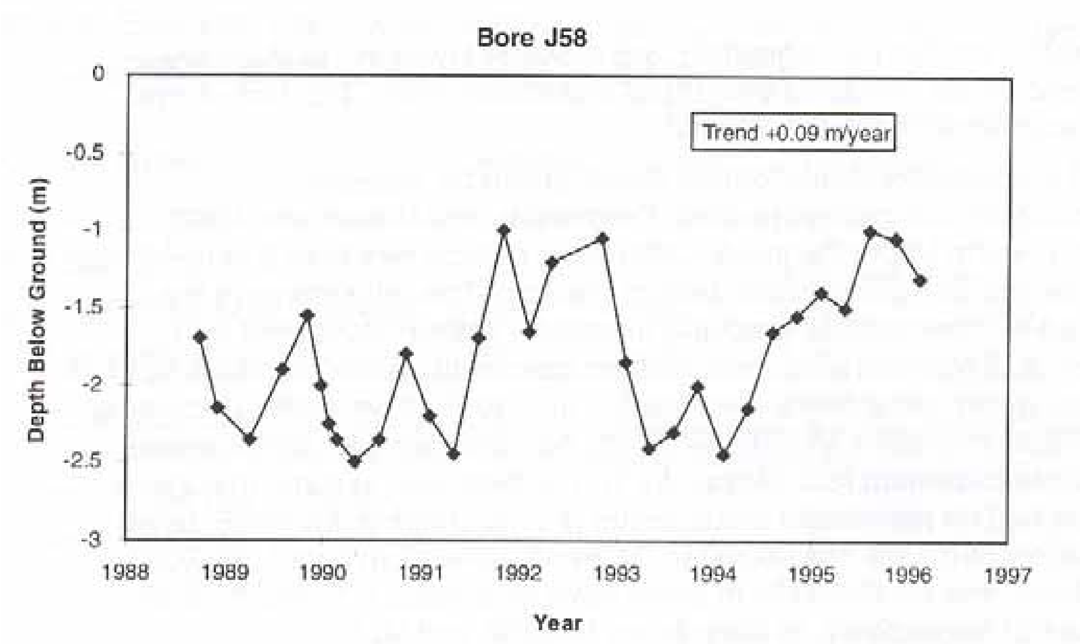

Figure 8a: Bores near discharge sites show seasonal fluctuations only

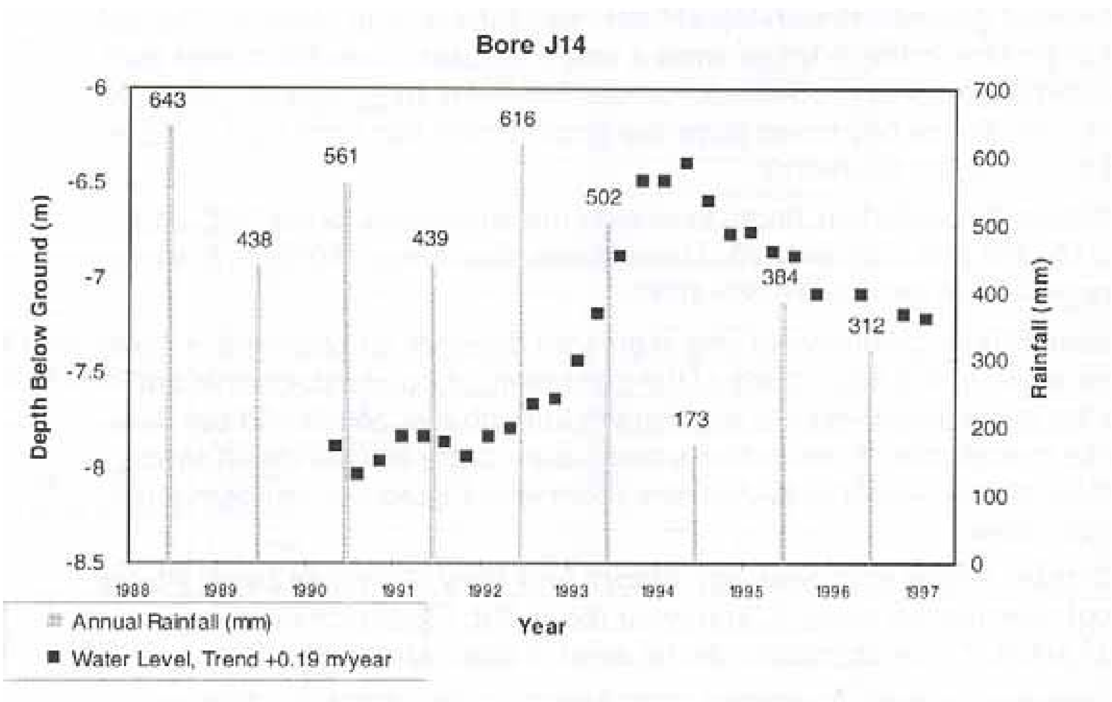

Figure 8b: Bores which are far from discharge sites showed overall groundwater level rises.

7.4. Hydrology of the Mills Lake and its relation to the regional aquifer

The Mills Lake receives surface runoff from the eastern parts of the study area in wet years (Decile 8 and 9). McAvan (1984) studied the Mills and the nearby Windmill Lakes as water supply sources for Ongerup and Jerramungup areas. He concluded that runoff was generated if their catchment was wet and rainfall exceeded 100 mm in a month or 50 mm in a day. He suggested that no significant inflow would occur in 80% of years. At the time of his study both of the lakes were fresh.

Since there is no salinity in the catchment area of the Mills Lake, the runoff is still fresh. The situation may change in future as groundwater levels rise. At the time of McAvan's study (1984) both the Mills Lake and Windmill Lake were fresh (120 mg/L; 22 mS/m) when full. Since McAvan's study, Windmill Lake has become saline (3940 mS/m on 22 July 1997; very low water level) and the Mills lake is in danger of becoming saline. The present situation in both lakes is because they are no longer perching above the regional groundwater but are intercepting it. Their salinity is caused by a regional aquifer which is discharging at these two sites. In this report, the interaction between the regional aquifer and the two lakes is discussed.

One of the sources of the Lakes water is groundwater flowing from the east to the west. We drilled two bores,10 and 23 m deep, in sand dunes that are 70 m east of the Mills Lake (bores ML10/96S and ML10/96D). These bores were in Tertiary sediments (Pallinup Siltstone over Werillup Formation). There were three main differences between these bores and others that we drilled in the study area:

1. The Pallinup Formation in the bores consisted of fine sand without any clay or loamy layers. Recharge in these material forms a lens of groundwater that is usually fresher than the underlying aquifer.

2. The groundwater level in the shallow bore was about 1.40 m higher than that in the deep one, confirming it as a recharge site.

3. Groundwater salinity in the shallow bore was 148 mS/m which is the freshest groundwater we found in the study area. As we drilled deeper, the fresh groundwater became mixed with deeper, more saline groundwater (Table 5) until 23 m, where the salinity of the groundwater was 2,700 mS/m.

Table 5: Groundwater salinity in bore ML10/96 increased with depth

Depth (m)	4.50	9.00	12.00	14.00	20.00
Groundwater salinity (mS/m)	148	1800	2620	2640	2710

Note: the water level of the perched aquifer was 4.00 m below the soil surface and the samples represent a mixed sample from groundwaters between 4.00 m and the drilled depths.

We concluded that:

- There is a *fresh groundwater mound* to the east of the Mills Lake that is perched on a saline regional aquifer (Figure 9).
- The *fresh groundwater mound* is discharging into the eastern side of the Lake (Figures 9 and 10). Small volumes of the regional, saline groundwater may also enter the Lake.
- While the eastern part of the Lake is discharging groundwater, the western portion is recharging the regional aquifer (Figure 10).
- There had been no permanent water in the Lake before or soon after, clearing (as indicated by the remnants of natural vegetation).
- In June 1996, the maximum depth of water in the Mills Lakes was 1.50 m. The present water level in the Mills Lake is controlled by regional groundwater levels. As these levels rise, the depth of water in the Mills Lake will also increase.
- The regional groundwater is flowing west towards the Windmill Lake, which has become an evaporation pan in recent years (Figure 9).
- There would be no recharge out of the Mills Lake if, due to excessive pumping, the Lake's water level is dropped below the regional groundwater levels (Figure 11). Then large amounts of saline groundwater and some fresh groundwater would discharge into the Lake. Consequently the salinity of the Lake will increase.

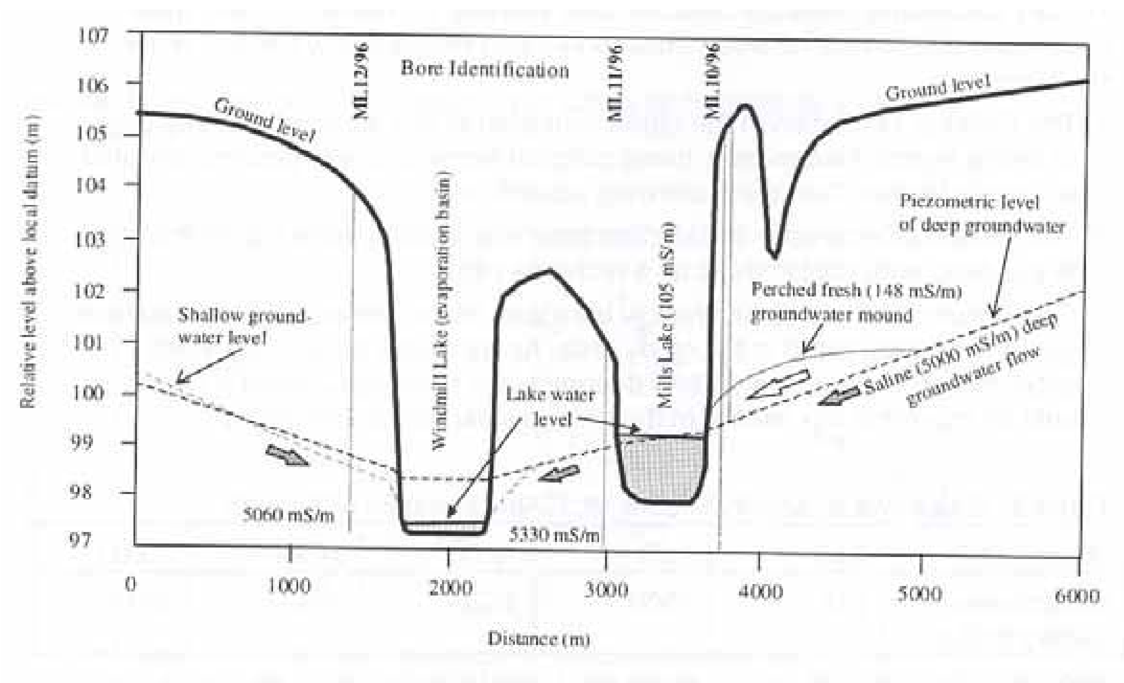

Figure 9: The Mills Lake is partly fed by a fresh groundwater mound from the east which keeps it fresh. The fresh groundwater is perching on a saline regional aquifer flowing towards Windmill Lake. Windmill Lake discharges saline groundwater over its entire area.

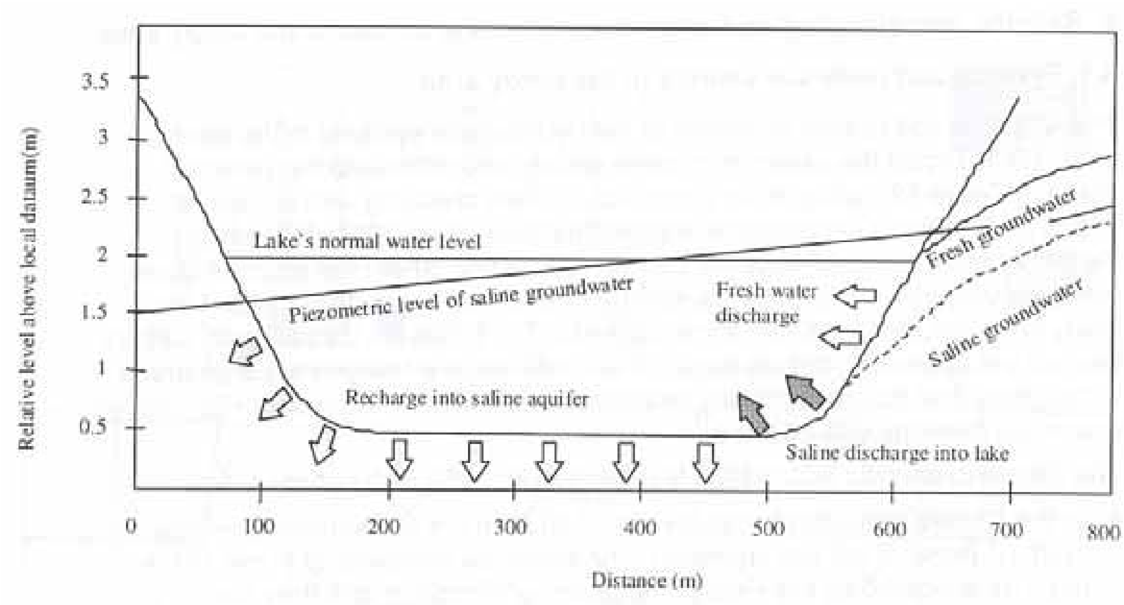

Figure 10: At high water levels, the Mills Lake receives a large discharge of fresh water and a small amount of saline groundwater. The pressure is such that the Lake's water recharges the saline aquifer on the western side. In this situation, the Lake's water remains reasonably fresh.

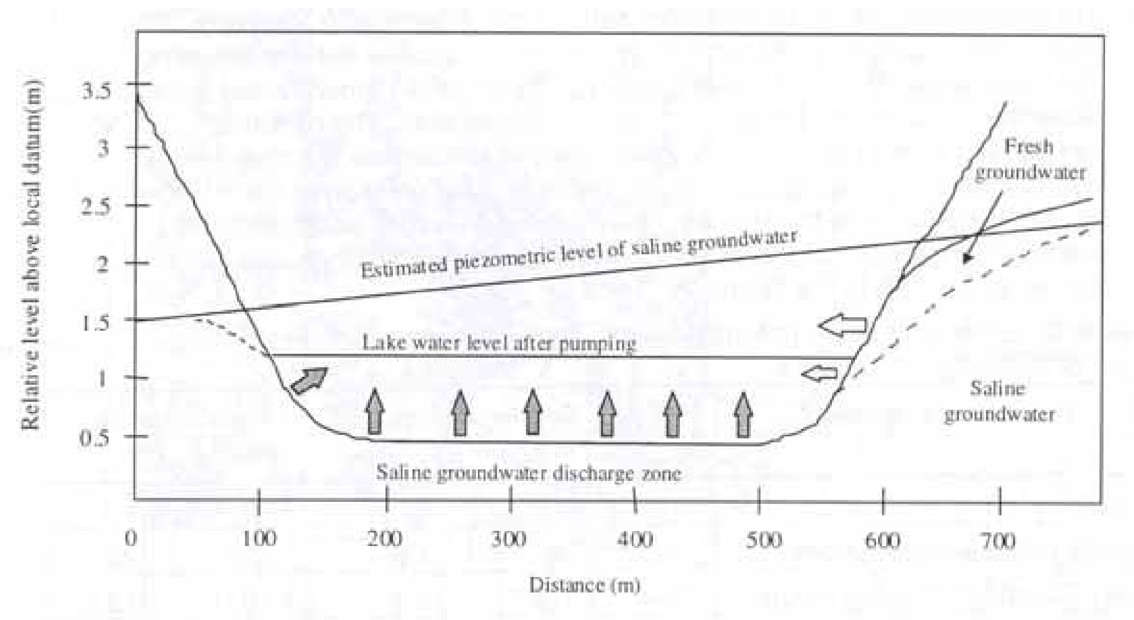

Figure 11: The situation changes when due to excessive pumping the lake's water level drops below the piezometric level of the saline aquifer. Then saline groundwater discharges into the lake and the Lake's water becomes saline.

8. Salinity, waterlogging and other environmental issues in the study area

8.1. Present and potential salinity in the study area

The extent of soil salinity is related to the hydrological systems in the study area. We mapped the extent of present salinity and estimated the potential salinity (Figure 12) using aerial photographs, field checking with a Geonic EM38 and drilling. Comparisons showed that more than 42% of Swampy Terrains may eventually become salt-affected, while other HSs such as Crests will have very little or no potential salinity (Table 6). The eastern parts of the study area include farms that were cleared in the 1960s. In these areas, salinity has not yet appeared, but we expect that it will within a few years. Large areas in this zone that do not show any indication of soil salinity at present will eventually become salt-affected.

The following specific information is related to the HSs in the study area:

- In the **Crests** groundwater levels are >5 m from the soil surface (average 10.8 m, Table 1) but are still rising. The hydraulic conductivity in this HS is high, as indicated by the yield of the bores while drilling and their fast recovery time. The groundwater is flowing into the lower HSs. The flow rate will increase as the hydraulic gradients increase. **Crests** probably have less runoff and waterlogging but a higher rate of recharge than other areas. The hydrological properties in this HS prevent groundwater rising as far as the soil surface. Therefore, there is **very little or no risk of soil salinity** in this HS (Table 6).

Table 6: Estimation of the potential salinity in the study area varies with the type of hydrological systems.

Hydrological systems	Total area (ha)	Extent of present salinity		Potential salinity	
		(ha)	(%)	(ha)	(%)
Crests	6787	00	00	78	1.1
Plains with Swampy Floors	1399	58	4.8	308	22.0
Very Gently Undulating Plains	7534	158	2.1	1021	13.6
Undulating Dune Fields	116	00	00	8	6.5
Ancient Drainage Valleys	2987	191	6.4	777	26.0
Swampy Terrains	4171	503	12.1	1777	42.6
Lakes	828	828	100.0	828	100.0
Total	23827	1737	7.3	4796	20.1

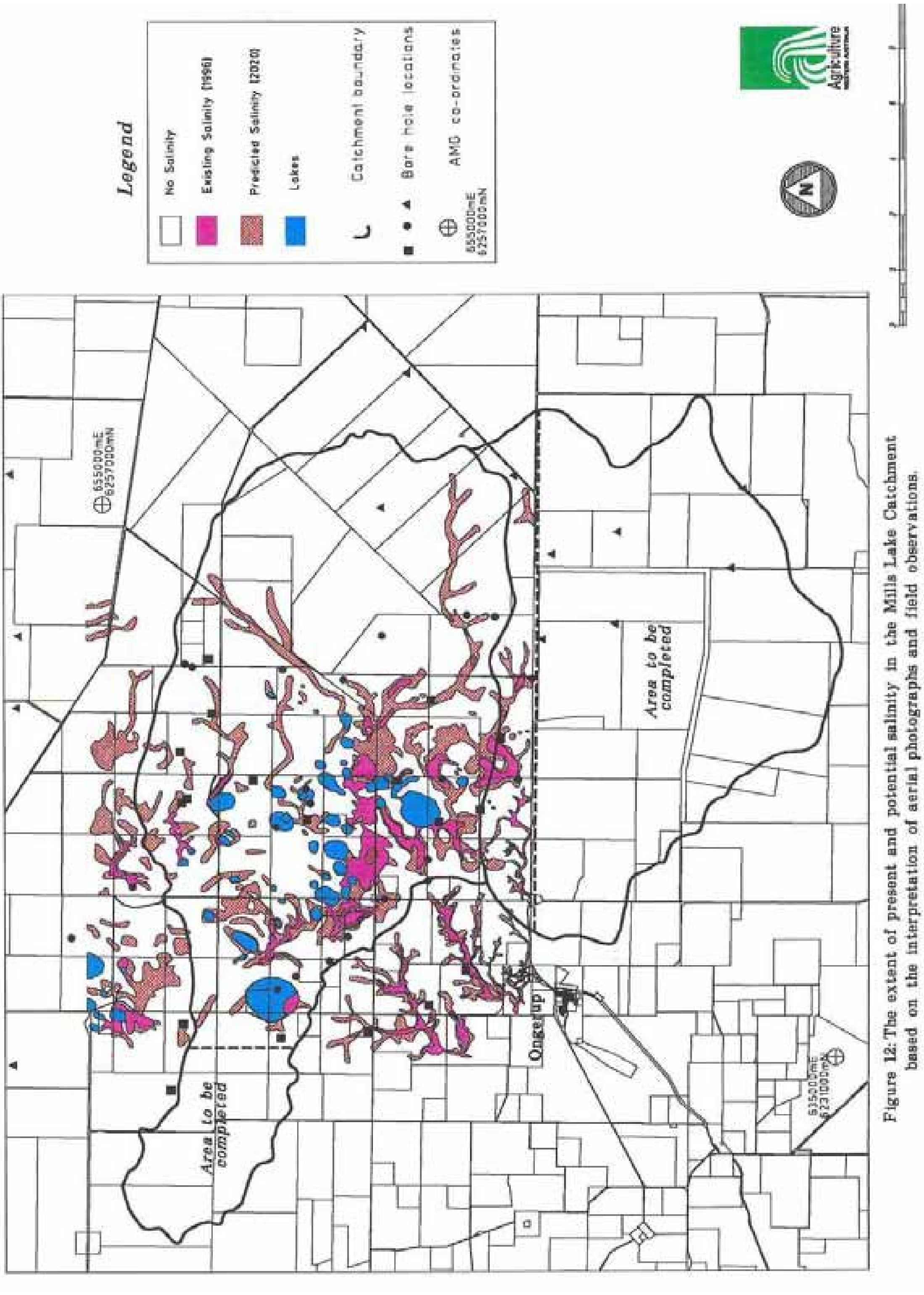

Figure 12: The extent of present and potential salinity in the Mills Lake Catchment based on interpretation of aerial photographs and field observation

- The groundwater levels under upper parts of the Plains with Swampy Floors are probably more than 3 m below the soil surface but are still rising. The lower areas of this HS have shallow to very shallow groundwater (<2 m below the soil surface, Table 1) and are discharge sites. The hydraulic conductivity in this HS is generally low near the soil surface but changes to high in a gritty layer which is on basement rock. This gritty layer leads water into the lower parts of the HS. As groundwater levels rise, soil salinity will expand. We expect that the extent of salinity in this HS will increase four fold, to about 20% in the future.
- The average groundwater level in 11 bores which were drilled in *Very Gently to Level Plains* was 1.75 m (range 1 to 3 m). Bores in this HS have tight, fine in grained material with a low hydraulic conductivity. Because the landscape is flat the hydraulic gradient is very low. These two factors inhibit movement of groundwater away from the area and cause groundwater levels to rise uniformly. Thus, large areas in this HS which are at present the best cropping areas may eventually become salt-affected. The extent of soil salinity in this HS is 2% at present but may grow to 15% in the future.
- The soil profiles in the **Undulating Dune Fields** consist of fine sand that historically has collected very little salt. There is a lens of fresh groundwater that is perching on a saline regional aquifer (Section 7.4). This lens will gradually join the regional aquifer, and as the regional groundwater levels rise, the perched fresh groundwater may rise and discharge into the depressions of this HS. With evaporation and concentration of salt, these depressions may become salt-affected. We estimate that approximately 7% of this HS may become salt-affected.
- Groundwater levels in the depressions and flats of the **Ancient drainage valleys** are at or near the soil surface (bores K349 and K301; Table 1). These areas are already discharge zones. There are also sand dunes in the **Ancient drainage valleys** that are few meters above the level of the depressions and flats. Groundwater levels under these sand dunes are well below the surface (bores ML12/96, 21/96, 22/96 and 8/96; Table 1). Pairs of bores drilled in the dunes showed that the groundwater levels in the shallow bores were higher than those in the deep ones, confirming that the dunes are recharge sites. Some of these dunes may also have a lens of fresh groundwater that is perching over the regional groundwater (Sections 7.3 and 7.4). **Ancient drainage valleys** are one of the main discharge areas for the regional aquifer in the study area. It is likely that due to the present agricultural practices, the regional groundwater levels are still rising. These rises will increase the extent of soil salinity in the HS. We expect that the extent of soil salinity in this HS will increase four fold, to about 25% in the future.
- **Swampy Terrains** have a very low hydraulic gradient and conductivity. An indication of the low conductivity was the length of time (a few days) it took for the water to recover after drilling. This low conductivity and low gradient mean that there is very little groundwater flow and the present and near future discharge sites will not be able to discharge enough groundwater to prevent the groundwater from rising. As a result**,** salt-affected areas will

continue to grow. About 12% of this HS is salt-affected at present. The figure may increase to 40% in the future.

8.2. Waterlogging in the Mills Lake Catchment

Waterlogging, which often goes unnoticed, reduces crop and pasture yields (McFarlane *et al.,*1992). Waterlogging is when free water can be found in the root zone of plants (usually within the top 0.3 m). Many farmers do not notice waterlogging until it has affected crops or pastures badly. When water fills the soil profile and appears on the soil surface it is called inundation or surface ponding. Waterlogging is classified as slight, moderate or severe to very severe depending on the duration and depth of free water found within 0.3 m of the soil surface.

The extent of waterlogging in the study area varies from one LFP to another and depends on the seasonal rainfall:

- In a year with decile 8 precipitation (460 mm; 2 wettest years out of every 10), rainfall during mid-May to mid-August will exceed the sum of plant water use and runoff. During these years, widespread waterlogging may occur in all LFPs in the study area. We estimate that in a year with decile 8 precipitation, approximately 60% of the catchment is affected by moderate to severe waterlogging.
- In a year with average rainfall (375 mm), rainfall during June and July will exceed the sum of plant water use and runoff and some waterlogging will occur. The extent of waterlogging in these years varies from one LFP to another. The most susceptible LFPs are the flat and low-lying areas.

Table 7: Extent of waterlogging* (during the 2 wettest years out of every 10), in hydrological systems, in the study area.

Hydrological system	Total area (ha)	Extent of severely to very severely waterlogged areas		Extent of moderately waterlogged areas	
		(%)	(ha)	(%)	(ha)
Crests	6787	19.7	1336	21.8	1480
Plains with Swampy Floors	1399	25.8	361	30	421
Very Gently Undulating Plains	7534	30.4	2289	30	2260
Undulating Dune Fields	116	10	12	5	6
Ancient Drainage Valleys	2987	27.2	811	30	894
Swampy Terrains	4171	63.2	2636	20.7	864
Lakes	828	00	00	100.0	828
Total	***23827***	***31.3***	***7451***	***28.0***	***6663***

***** These figures do not include the slightly waterlogged areas.

(Further information on waterlogging can be found in: Effects of waterlogging on crops and pasture production in the Upper Great Southern, Western Australia. Technical Bulletin No.86 Dept. of Agriculture, D.J. McFarlane, G.A. Wheaton, T.R. Negus, J.F. Wallace).

- In exceptionally dry years (<320 mm; 2 driest years out of ten), waterlogging is confined to the discharge sites only (Figure 12). These areas will increase as the salt-affected areas grow.

8.3. The state of the existing native vegetation in the study area

The study area has all aspects of a semi-desert (low rainfall, denuded landscape which is eroded by wind and is salt-affected) with active desertification in progress. Natural vegetation covers less than 3% of the study area and is confined to small patches, usually associated with the salt lakes and valley floors, or occasionally on ridges that have rock outcrops. The small patches of on-farm native vegetation are in various stages of deterioration and some blocks are completely dead. The on-farm native vegetation that has deteriorated probably uses very little water and thus has very little (or a *negative*) impact in preventing salinity.

Factors contributing to the deterioration of isolated remnant vegetation on hillcrests and hillslopes (**Crests**) are likely to be: grazing pressure; exposure to cold and wind; pests and disease; weeds; isolation (small gene pool, low diversity); excess nutrients and fire. Grazing pressure is probably the most severe factor. Stock prevent trees regenerating by eating seedlings, young shoots and saplings, and by ring barking the older trees. In addition, grazing eliminates the lower stratum and exposes the trees. Grazing can also adversely affect the root environment by puddling the soil around the trees.

Degeneration of isolated remnant vegetation on footslopes, valley flats and water coarses is primarily caused by rising groundwater, but grazing pressure, exposure, disease, and isolation also contribute.

The dead natural vegetation that is in, or surrounds, the wetlands, swamps and playas is mainly killed by the rising saline groundwater which drowns their roots. Inundation and grazing pressure may exacerbate the problem, but in most cases are not the main cause.

8.4. Future salinity of the Mills Lake

We think that the Mills Lake is in danger of becoming saline. However it is possible to prevent this (Section 9.6). There are four factors that may increase the salinity of this Lake in the future:

- Soil salinity in its catchment area is the biggest threat. The groundwater levels in the low lying areas of the catchment are within 2 m of the soil surface and rising (Sections 7.2 and 7.3). As they rise, some areas will become discharge sites. The salinity and volume of surface runoff will increase as discharge areas expand. This saline runoff may threaten the future of the Mills Lake.

- As groundwater levels rise, the water in the Mills Lake will deepen and a larger portion of the Lake's volume will be influenced by the flow path of the saline regional aquifer. This will increase the salinity of the Lake.
- If the perched, fresh groundwater mound is maintained, the salinity of the Mills Lake will probably remain brackish (ie 300 to 900 mS/m). As soon as the mound is removed, the Mills Lake will turn salty.
- Excessive pumping will cause the water level to drop and the Mills Lake will change into a discharge site for the saline regional groundwater. This will also increase the salinity of the Lake.

9. Management options to reduce recharge and the extent of salinity

Degradation problems in the study area are catchment issues. It will be possible to reverse the degradational problems in the Mills Lake Catchment. If the management options are applied throughout the area. Patchwork treatments may have a localised effect but will not address the problem at the catchment level. We suggest the landholders have a vision. They should consider what they want their landscape to look like in 20 or 30 years time; a denuded desert or a productive farming area.

Management options that can reduce degradation, especially the extent of salinity, and improve sustainability, have been placed into six groups:

- General management options - these will help reduce groundwater levels in the agricultural areas;
- Specific options - these relate to the hydrological systems;
- Management of surface runoff;
- Management and use of fresh and saline groundwater;
- Specific options for lakes and small depressions;
- Specific options for the Mills Lake.

These issues are discussed in Sections 9.1 to 9.6. Section 10 discusses “Where these findings and management options may be applied.

9.1. General management options to reduce recharge in the agricultural areas

To reverse the increasing salinity, the present rates of recharge need to be reduced. This reduction can be made by:

- Reducing recharge and increasing surface and sub-surface runoff (using surface drains);
- Increasing the area under perennial pastures;
- Introducing phase cropping;
- Improving the productivity of existing crops and pastures;
- Increasing water use by revegetating selected areas;
- Regenerating existing native vegetation;
- Pumping saline groundwater and lowering groundwater levels.

In the following discussions (Sections 9.1.1 to 9.1.7), these issues have been related to the HSs and LFPs of the study area.

9.1.1.Reducing recharge and increasing surface and sub-surface runoff using drainage

Between mid-May and mid-September in 20% of years, rainfall exceeds the sum of plant water use and runoff. In these wet years, 60% of the study area becomes moderately to very severely waterlogged (Table 7). Some areas may even become inundated for more than one or two weeks. Surface drains help to reduce the incidence of waterlogging and inundation and so improve cropping capability.

The results of the following study are relevant to the Mills Lake Catchment.

Effect of drains on production

Cox (1988) studied the effect of graded interceptor drains on waterlogging and crop yield between 1984 and 1985 in a catchment 3 km north-east of Narrogin. The annual and growing season (May to October) rainfalls, in Narrogin, during those three years are comparable with decile 8 and average annual rainfalls in the study area (Tables 8 and 9). Cox's findings on waterlogging and the effect of drains will be applicable to the study area in years that have above average rainfall.

Table 8: Annual and growing season rainfall and drain flow in Narrogin between 1984 and 1986

	1984	1985	1986
Annual rainfall (mm)	462	435	377
Seasonal rainfall (mm)	330	356	267
Drain flow (mm)	7.6	8.1	4.0

Table 9: Variation in annual and growing season rainfall in the study area

Rainfall (mm)	Wet years (decile 8 rainfall)	Mean rainfall	Dry years (decile 3 rainfall)
Annual rainfall	460	375	320
Seasonal rainfall	351	262	212

Cox concluded that:

- Low seasonal rainfall was sufficient to cause *in situ* waterlogging in areas with a shallow topsoil.
- Drains in pasture generated more runoff than those in crops. This indicated that crops may be using more water than the pasture.
- The drains became increasingly effective as rainfall increased.

- Recut drains produced more runoff than drains that had not been maintained.
- The drains removed between 4 and 8 mm of the growing season's rainfall (drain spacing was 102 m).
- There was less waterlogging up to 50 m downslope and 7 m upslope of the drains in wet years, provided drain channels were cut into the clay subsoil.
- There was a positive return on investment in drains, even when the future benefits were discounted and inflation was taken into account. The greatest benefits occurred when the area was frequently cropped and the probability of waterlogging was high.
- The income generated by the improved yields over 20 years at the Narrogin site far outweighed the costs of drain installation, maintenance and loss of productive land.
- The optimum drain spacing, based on maximum net present value over 20 years, was 40, 60, 80, and 100 m for areas with 90, 70, 50, and 30% waterlogging probability (for a crop-crop-pasture rotation).

In the Mills Lake Catchment, drains may remove between 4 mm (in an average year) and 8 mm (in a year with decile 8 rainfall) of the annual rainfall. Removing this water will reduce waterlogging and improve plant growth and water use. The net effect is a reduction in recharge. This reduction is greater than the amount of water the drains remove.

Type of drains for the study area

We found that in the low lying areas of the **Swampy Terrains, Ancient Drainage Valleys**, and **Plains with Swampy Floors**, the soil profile was composed of very heavy clay. The hydraulic conductivity of near surface material (subsoil only) is very low and any attempt to construct deep drains (>0.6 m deep; open or sub-surface) may not be technically or economically feasible. Ferdowsian et al. (1997) studied a deep drain that was constructed in the North Stirling area in 1985. They found that the income from the reclaimed area (8 ha) was not enough to recover the construction expenses (more than $30,000).

All subsequent references to drains refer to well-designed, open surface drains built by graders or occasionally by a scraper.

Selection of drains and drain spacing should be based on the attributes of the LFPs and HSs (Table 10). In deep gravely sands or sandy soils with a clayey sub-soil more than 0.60 m deep, it is not feasible to construct surface drains. Waterlogging of these soils is not common enough to warrant the expense.

9.1.2. Reducing recharge by growing perennial pastures

Various workers (Nulsen and Baxter 1982; Carbon *et al*. 1982; Nulsen 1984; and Joffre *et al*. 1988), found that perennial pastures used more water than annual pastures. Their ability to use more water could be attributed to their deeper root zone (Ferdowsian and Greenham, 1992), denser root system and their ability to intercept and use the summer rainfall provided they were not dormant. However, some perennial pastures such as perennial ryegrass (*Lolium perenne*) and cocksfoot

Table 10: Types, spacing and cost of drains in relation to the hydrological systems of the study area

Hydrological systems	Functional drains	Spacing (m)	Costs * $/km	Costs * $/ha
Crests	V-shaped conventional interceptor drains on upper slopes	100 to 120	500	50 to 42
	Flat bottomed interceptor drains on lower slopes	80 to 120	700	88 to 59
	No drains in deep sands			
Plains with Swampy Floors	V-shaped conventional interceptor drains on upper slopes	100 to 120	500	50 to 42
	Flat bottomed interceptor drains on lower slopes	80 to 120	700	88 to 59
	No drains in depressions			
Very gently to Level plains	V-shaped conventional interceptor drains on upper slopes	80 to 120	500	63 to 42
	Flat bottomed interceptor drains on lower slopes	80 to 120	700	88 to 59
	W drains and grass or tree covered waterways**	2000	2000	10
	No drains in deep sands			
Undulating Dune Fields	No drains	N/A (Not applicable)	N/A	N/A
Ancient Drainage Valleys	Spoon drains and	100	750	75
	W drain in flats	1000	1500	15
	No drains in dune fields			
Stagnant Terrains	Spoon drains	100	750	75
	W drains	1000	1500	15
Lakes	No drains	N/A	N/A	N/A

* Costs are for grader built drains. The most expensive drains ($/ha) are flat-bottomed, graded interceptor drains, and spoon drains, because the soil must be transported away from the cutting point. To construct these drains, scrapers may be a cheaper option if the volume of work is large. For small sections or for a few drains, graders may be the most economic choice.

** Grass or tree covered waterways are strips of land that receive runoff from graded interceptor or spoon drains. They have one or two embankments along each side to contain water and avoid inundation of the adjacent areas. In flat areas they may have a W drain in the middle to facilitate the movement of surface runoff. Waterways should be fenced off and controlled grazing used when necessary.

(*Dactylis glomerata*) may not use more water than the annual pastures because they also have a shallow root system. The extra water that a mixture of annual and perennial pastures uses is equal to the available water in the additional depth that their roots occupy plus out of season rainfall (summer active perennials). The available water in the additional depth of root zone may be as much as 50 mm for deep rooted perennials (eg. kikuyu). It is recommended that a mixture of annual and perennial pastures is grown to reduce recharge. Table 11 shows the recommended perennial pastures for different Land Management Units (LMUs) of the study area.

Table 11: The recommended perennial pastures for different Land Management Units (soils) in the study area. Numbers (between 1 and 5) are in order of decreasing preference.

Land Management Units	Recommended perennials	
Deep well-drained white sand (>0.50 m)	Tagasaste (1)	Perennial veldt grass (2)
Deep well-drained yellow or brown sand (>0.50 m)	Tagasaste (1) Perennial veldt grass (2)	Lucerne (1)
0.50 to 0.60 m gravelly sand over clay	Tagasaste (2) Cocksfoot (2)	Lucerne (2) Perennial veldt grass (3)
0.30 to 0.50 m gravelly sand over clay	Lucerne (1) Tagasaste (2)	Cocksfoot (2) Perennial veldt grass (3)
Well-drained loamy sand or clay close to the soil surface	Lucerne (1) Cocksfoot (2) Phalaris (3)	Tall wheatgrass (2) Tall fescue (3)
Deep waterlogged sand (>0.50 m)	Tall wheatgrass (1) Kikuyu (2)	Tall fescue (1) Phalaris (3)
Waterlogged loamy soil	Strawberry clover (1) Tall fescue (2)	Tall wheatgrass (1) Phalaris (2)
Waterlogged clayey soil	Strawberry clover (1) Tall fescue (2)	Tall wheatgrass (1) Phalaris (2)
Slightly to moderately salt-affected soil	Strawberry clover (1) Tall fescue (2)	Tall wheatgrass (1) Phalaris (2)
Moderately to strongly salt-affected soil	Puccinellia (1) Tall wheatgrass (3)	Salt bush (1)
Active discharge sites	Saltwater couch (1) Tall wheatgrass (3)	Puccinellia (2)

For more information on perennial pastures refer to Bulletin 4253; “Perennial pastures for areas receiving less than 800 mm annual rainfall” (1994), by R.A. Sudmeyer, C. Saunders, I. Maling and T. Clark. WA Department of Agriculture.

9.1.3. Reducing recharge by phase cropping

In areas that have a low annual rainfall (<500 mm) and low rates of recharge (<50 mm), farmers have managed to reduce the extent of soil salinity by phase cropping. Phase cropping is a rotation in which a few years of cropping (cereals or pulses) are followed by a few years of pasture (lucerne or any other perennial mixed with annual pasture) that in turn are followed by cropping. The cropping phase may be between two and three years in areas that receive >500 mm of rain per annum, and four years in areas that have very low rainfall (<400 mm). The economic life of lucerne is considered to be between four and six years. This period may be reduced if the land is required for cropping. During the cropping phase, recharge will build up moisture in the soil profile. This storage can then be used by lucerne. Most of the success stories are related to growing a mixture of lucerne with other perennial pastures such as phalaris, tall wheatgrass and annuals. There are many success stories where lucerne has lowered groundwater levels and the following two cases are applicable to most areas of the hydrological systems found in the Mills Lake Catchment (*Crests* and non-waterlogged areas of the other HS with the exception of sand dunes). In both cases, lucerne continues to persist with volunteer annual clover and grasses. Grazing has been continuous over winter and rotational over summer; 1 week on and 5 weeks off.

Case 1: The effect of lucerne on groundwater levels in the *Catchment Divide* and *Plains with Swampy Floors*

Lucerne was sown in July 1992 into a 70 ha paddock on a property near Jacup (60 km east of the study area, 350 mm annual rainfall). The site had been cleared in 1964. Salinity first appeared in 1981 and had expanded to 3 ha by 1992. The salt-affected area has stabilised since 1992 or has reduced slightly (Geoff Bee; the land holder, personal communication). Agriculture. WA had drilled two bores in this area in 1989. The first bore is in **Crests** and the second one is in upper areas of **Plains with Swampy Floors**. Groundwater levels in both bores have dropped since lucerne was planted. Figure 13 shows groundwater trends in one of those bores as well as the annual rainfall. It also shows groundwater level trends in bores which were in similar HSs, but under annual pastures and crops. Figure 13 indicates that:

- Groundwater levels under three sites were within 1 m of the soil surface and experienced similar fluctuations between 1990 and 1993.
- Annual rainfall was lower than normal in 1994,1995 and 1996.
- Groundwater levels under annual pastures have stayed almost the same and show a seasonal fluctuation.
- Crops, which use more water than the annual pastures, have lowered the groundwater levels by 1.5 m during the dry years (1994 – 1996).
- Groundwater levels under lucerne have dropped to 3.0 m below the original levels; this is 1.5 m more than the water level reduction under crops.

Case 2: The effect of lucerne on groundwater levels in *Ancient Drainage Valleys*

Rob and Ann Smart are farming near Fitzgerald, 75 km east of the study area (350 mm rainfall per annum). The lower parts of their property are in the **Ancient Drainage Valleys**. They have two neighbouring paddocks in this HS. One bore was drilled in each paddock in 1983. Both paddocks were under crop and annual pasture rotation (1:4) prior to 1987. Crop : pasture rotations had continued in one paddock until November 1996. The second paddock (50 ha), was changed to alley farming system in September 1987. Alleys have 4 rows of trees, in belts that are 80 m apart. Trees are a mixture of *Eucalypt, Acacia and Melaleuca species*. Lucerne was sown in the same year in 80 m strips which were between the alleys. This system has been continued to the present.

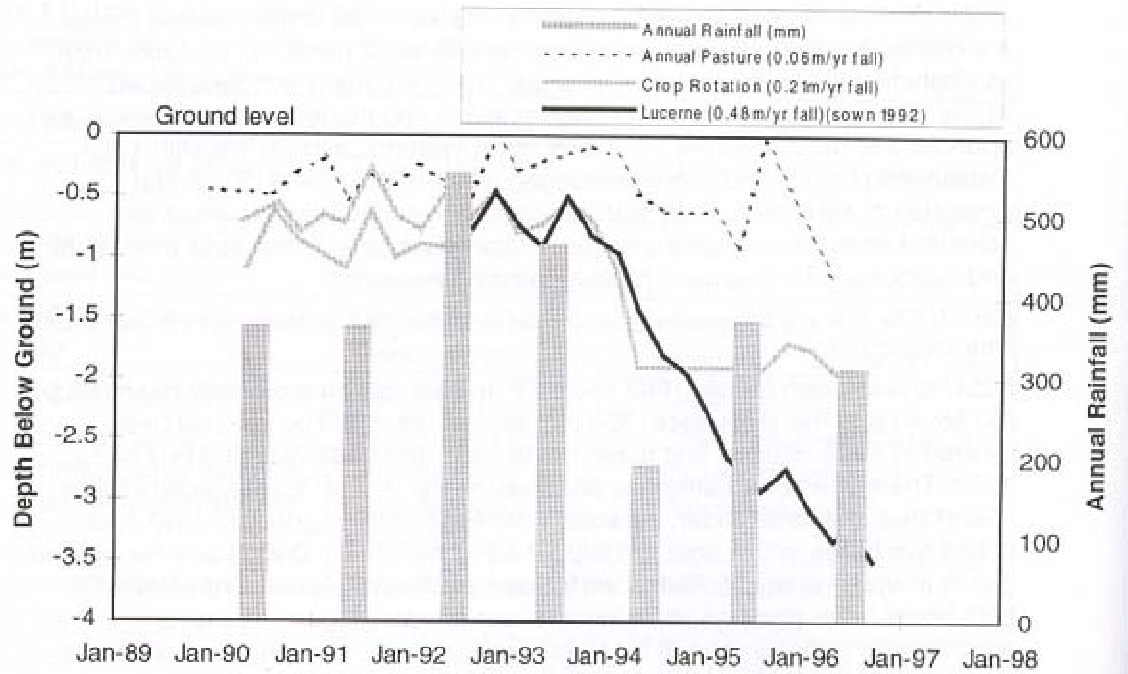

Figure 13: In undulating areas, lucerne has lowered groundwater levels more than annual pastures and crops during last four years (three of which were low rainfall years).

Rob and Ann have regularly monitored groundwater levels in the two bores since 1983 (Figure 14). The monitoring results show that:

- Groundwater levels in the two bores have had a strong seasonal fluctuation.
- Until 1987, when lucerne was planted, the difference in water levels between the two systems was negligible. Groundwater levels in both paddocks behaved similarly and were within 2 m from the soil surface.
- The bore under the crop/pasture rotation showed a continuous rise in groundwater levels until 1994. From then onwards it dropped slightly,

probably because of the low annual rainfall. This bore has an overall rising trend of 0.1 m per year.

- Groundwater levels in the bore under the lucerne and alley farming system started to drop after 1987, when the management changed.
- In response to high rainfall in 1992 and 1993 and temporary flooding, water levels in both bores rose close to the soil surface (Rob and Ann Smart, personal communication). Soon after the flooding, the groundwater levels under the lucerne and alley farming dropped to pre-flooding levels.
- Groundwater levels under the lucerne and alleys have been about 1.7 m below the levels under the crop and annual pasture treatment.

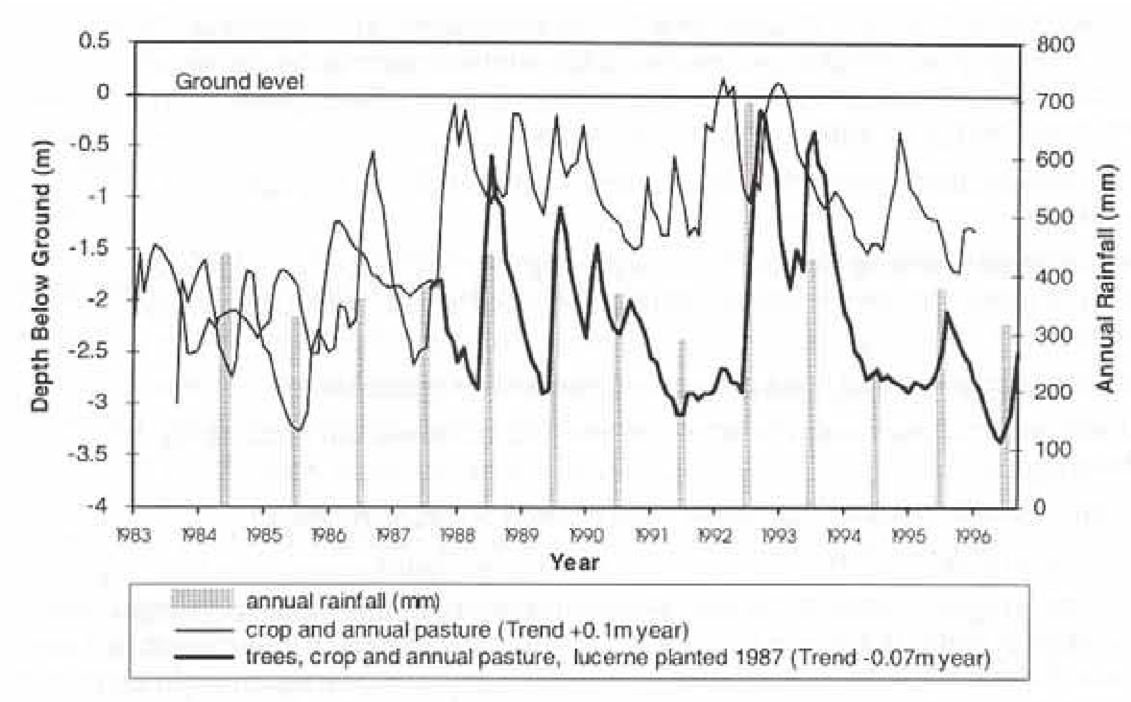

Figure 14: In Ancient Drainage Valleys, a lucerne and alley farming system has lowered groundwater levels by 1.7 m in comparison with the traditional crop and annual pastures rotation.

Suitable areas for lucerne and phase cropping

Phase cropping should be considered as the *best* option for controlling soil salinity in the study area. Where the unsaturated soil profile is reasonably deep (>2 m) and there is no severe waterlogging, lucerne will do well because of the depth of soil available for its roots. All areas that are cropped regularly are suitable for phase cropping: *Crests, Very Gentle to Level Plains,* the high grounds of *Plains with Swampy Floors* and the high ground of *Ancient Drainage Valleys*. We estimate that >70% of the study area is suitable for phase cropping. However, lucerne does not tolerate severe waterlogging and will not do well in acidic soils. Inoculating the seeds prior to planting will improve lucerne's performance. Lucerne is slightly salt tolerant and has very deep roots that can penetrate sodic subsoils and deplete the moisture stored in the soil profile.

9.1.4. Reducing recharge by using better management practices

Any management strategy that increases pasture and crop growth presumably also increases evapotranspiration. Options include:

- high yielding packages;
- any measures that can defer grazing of annual pastures in autumn;
- maintaining optimum pasture mass;
- applying nitrogen to grassy pastures;
- strip grazing and other measures.

Advisers from Agriculture WA can give further information on these issues. These management options are only likely to benefit farmers willing to adjust their management practices and those farmers with high stocking rates who experience feed gaps early in the growing season.

9.1.5. Revegetating selected areas and limitations caused by the salinity of groundwater.

Tree and shrub planting is one of the necessary treatments for the study area. There are three reasons for revegetating of selected areas, related to salinity. Revegetation:

- reduces recharge and trees cannot use very saline groundwater;
- stabilises sand dunes and lunette systems and increases the productivity of deep sands;
- creates shelter belts and prevents wind erosion on cropping areas.

(a) Trees only reduce recharge and cannot use saline groundwater

Trees use water and reduce the overall recharge in an area and consequently the volume of water that the aquifer has to handle. Any reduction in recharge will also reduce the extent of soil salinity. However, the groundwater in most of the study area is too saline for the trees to use. Thus trees will only use the fresh water that is stored within the soil profile and to a lesser extent, any relatively fresh water that may be resting on top of the aquifer. When planting trees to reduce salinity, the following points should be considered:

- salinity in a catchment cannot be eliminated if large blocks of natural or planted vegetation are in one part of the catchment and nothing is on the rest;
- if trees are required for using excess water they must be scattered as widely as possible throughout the area;

- strip plantations are the best option because isolated trees are difficult to protect;
- if the strip plantations are to be self-supporting and self-pruning (for timber production), they have to be at least six rows wide;
- the tree spacing in strip plantations should be as close as possible to encourage deep root penetration and good forms (shape).
- at least 20% of the landscape should be under shelter belts. to ensure the long-term sustainability of the study area;

Creek lines and water courses, swamps, lakes and salt-affected areas and their fringes should be fenced off and revegetated. Before fencing, a Geonics EM38 should be used to mark the areas that are in immediate danger of salinity ie readings of (EC_a >60 mS/m). Trees for salt-affected areas may have a small commercial or grazing value. Their main benefit is in reclaiming land and helping reduce the extent of salinity in the other parts of a catchment. Planting trees and shrubs on or near, salt-affected areas may only have a temporary effect if other measures to control salinity are not in place. Without other treatments, salt will accumulate in the root zone of these trees and eventually kill them.

Tree selection (Table 12) must be based on the attributes of land management units (LMU). More information may be obtained from Agriculture WA, at the Katanning and Narrogin Offices.

Further information on agroforestry and alley farming can be found in the Journal of Agriculture No 3 and No 4 1994, Dept. of Agriculture.

(b) Stabilising sand dunes and lunette systems and increasing their productivity

Sand dunes and lunette systems became mobile units as soon as their natural vegetation was removed. Two factors affect the mobility of the units:

- They are composed of fine silty sand that is subject to wind erosion.
- The undulation of the land units that surround them gives a wave-shaped motion to the wind making it more erosive than elsewhere.

Erosion of sand dunes is usually accompanied by the deposition of a blanket of white sand that may cover large areas and degrade agricultural land. On September 18, 1996, we observed one of these events during which the pasture in half of a paddock was covered by a blanket of white sand. The sand dunes and areas blanketed by sand are the least productive areas of the Mills Lake Catchment. Bare sandy ground with low water holding capacity results in high rates of recharge and is a hydrological disaster.

It is recommended that these sand dunes and the areas that have had sand deposited on them be revegetated. Perennial veldt grass and tagasaste (Tables 16 and 17) should be planted to protect these areas.

(c) . Creating shelter belts and preventing wind erosion on cropping areas

Shelter belts reduce recharge by using groundwater from the unsaturated soil profile and by creating a better environment for pastures and crops to grow and use more water. Other benefits of shelter belts are in reducing the velocity of erosive winds, timber production and creating a shelter for crops and stock. Wind erosion could become an annual event on duplex soils derived from granite and on the Tertiary sandplains of the study area. “Wind will erode the soils if its surface is loose and dry and not protected by at least 50% ground cover “(Dr. Dan Carter, Agriculture, WA. Albany). These conditions are produced when the soils are cultivated dry and also by overgrazing stubbles or pastures during summer and autumn. Sheep destroy the cover and disturb the soil surface to the point where it can erode in winds above 28 km/hour.

Erosive winds occur many times during the year, so if the soil surface is in a poor condition, serious wind erosion is likely every year (Dan Carter, pers. communication).

Two things must be done to reduce the incidence of wind erosion:

- maintain at least 50% ground cover;
- create wind breaks to reduce the wind velocity.

Shelter belts can also have some commercial values. Selection of tree species for timber is limited in this area because of the low rainfall. There are a few isolated Bluegums (*Eucalyptus globulus*) in the study area that have done very well because their roots spread over a large area. They will not do well in a shelter belt which has more than two rows. *E. sideroxylon* (ironbark), which has evolved in areas that receive 450 mm annual rainfall, may be a better choice.

9.1.6. Regeneration of the existing native vegetation in the study area

The on-farm native vegetation that has deteriorated probably uses very little water and thus has very little (**or a negative**) impact in preventing salinity. Regeneration of the natural vegetation will improve water use and can be expected to have an impact on reducing salinity.

It is suggested that remnant vegetation which is in a reasonable condition should be fenced and protected.

Death of the natural vegetation that is in or surrounds the wetlands, swamps and playas is not preventable because of increasing inundation and the rising saline groundwater, which drowns their roots. A new fringe vegetation will naturally establish in the high water mark zone. Fencing the wetlands will protect the young saplings from grazing pressure and ensure their survival. The fences should be erected well above the high water mark to establish a wide and self-supporting belt of fringe vegetation.

Table 12: Recommended trees and shrubs for land management units of the study area (information from David Bicknell, Agriculture WA, Narrogin).

Rating: 1 = very suitable, 5 = not suitable

LMU	Trees and shrubs (rating)	
Deep well drained white sand (>0.5 m)	1 *Chamaecytisus proliferus* (tagasaste) 1 *Acacia saligna* (golden wreath wattle) 2-3 *Eucalytpus platypus* var *heterophylla* (coastal moort)	3 *Pinus pinaster* (maritime pine) 2-4 Banksia spp. (*B prionotes, B baueri*)
Deep well drained yellow or brown sand (>0.5 m)	1 *Chamaecytisus proliferus* (tagasaste 1 *Acacia saligna* (golden wreath wattle) 2 *Pinus pinaster* (maritime pine) 2 *Eucalytpus platypus* var *heterophylla* (coastal moort) 2-3 *Allocasuarina huegeliana* (rock sheoak) 2-3 *Banksia prionotes* (acorn banksia)	2-3 *Eucalyptus argyphea* (silver mallet) 2-3 *Eucalytpus camaldulensis* (river red gum) 2-3 *Eucalyptus kochii* ssp. *kochii* (oil mallee) 2-3 *Santalum acuminatum* (quandong) 2-3 *Santalum spicatum* (sandalwood) 3 *Eucalyptus cladocalyx* (sugar gum)
0.3-0.5 m gravelly sand over clay	1-3 *Acacia acuminata* (jam) 1-3 *Allocasuarina huegeliana* (rock sheoak) 2-3 *Calothmanus quadrifidus* (one-sided bottlebrush) 1-3 *Dryandra* spp. 1-2 *Eucalyptus argyphea* (silver mallet) 2 *Eucalyptus astringens* (brown mallet) 1-2 *Eucalyptus cappillosa* (inland wandoo)	1-3 *Eucalyptus lesouefii* (Goldfield's blackbutt) 1-2 *Eucalyptus sideroxylon* (red iron bark) 2 *Eucalyptus leucoxylon* ssp. *leucoxylon* (SA blue gum) 2 *Eucalyptus leucoxylon* ssp. *megalocarpa* (large fruited SA blue gum)
0.5 m or more gravelly sand over clay	As above plus 1 *Eucalyptus leucoxylon* ssp. *leucoxylon* (SA blue gum) 1 *Eucalyptus leucoxylon* ssp. *megalocarpa* (large fruited SA blue gum)	2-3 *Verticordia chrysantha* (golden featherflower) 2-3 *Verticordia eriocephala* (common cauliflower)
Well drained loamy sand	As above plus	1 *Eucalytpus platypus* var *platypus* (round leaved moort)

LMU	Trees and shrubs (rating)	
Deep waterlogged sand (>0.5 m)	1 *Casuarina obesa* (salt sheoak) 1 *Melaleuca cuticularis* (salt paperbark) 1-2 *Eucalyptus camaldulensis* (river red gum)	Nearly all the species on waterlogged loamy soils (below).
Waterlogged loamy soil	1 *Casuarina obesa* (salt sheoak) 1 *Melaleuca cuticularis* (salt paperbark) 1 *Melaleuca uncinata* (broombush) 1 *Melaleuca lateriflora* (oblong leaf honey myrtle) 1 *Melaleuca acuminata* (broombush) 1-2 *Callistemon phoeniceus* (fiery bottlebrush) 1-2 *Eucalyptus camaldulensis* (river red gum)	1-2 *Eucalyptus occidentalis* (flat topped yate) 1-2 *Melaleuca brevifolia* (white flowered honey myrtle) 1-3 *Acacia saligna* (golden wreath wattle 1-3 *Boronia* spp. 1-2 *Eucalyptus spathulata* (swamp mallet) 1-2 *Eucalytpus sargentii* (salt river gum)
Waterlogged clayey soil including gilgai soils	1-2 *Casuarina obesa* (salt sheoak) 1-2 *Melaleuca cuticularis* (salt paperbark) 1-2 *Melaleuca uncinata* (broombush) 1-2 *Melaleuca lateriflora* (oblong leaf honey myrtle) 1-2 *Melaleuca acuminata* (broombush)	1-3 *Acacia saligna* (golden wreath wattle) 1-3 *Callistemon phoeniceus* (fiery bottlebrush) 1-3 *Eucalytpus occidentalis* (flat topped yate) 1-3 *Eucalyptus spathulata* (swamp mallet) 2-3 *Eucalytpus sargentii* (salt river gum)
Slightly to moderately salt-affected soils	1-3 *Acacia acuminata* (raspberry jam wattle) 1-3 *Acacia merrallii* (Merrall's wattle) 1-2 *Acacia redolens* 1-2 *Acacia saligna* (golden wreath wattle) 1-2 *Eucalyptus astringens* (brown mallet) 1-2 *Eucalytpus camaldulensis* (river red gum) 1-2 *Eucalytpus famelica* (salt mallee) 1-2 *Eucalytpus kochii* ssp. *kochii* (oil mallee)	2 *Eucalytpus loxophleba* (York gum) 1-2 *Eucalyptus platypus* var *heterophylla* (coastal moort) 1-2 *Eucalyptus platypus* var *platypus* (round leaved moort) 1-3 *Melaleuca* spp. Nearly all the species below.

LMU	Trees and shrubs (rating)	
Moderately to strongly salt-affected soils	1-3 *Acacia cyclops* (coastal wattle) 1-3 *Acacia saligna* (golden wreath wattle) 1-2 *Atriplex* spp. (saltbush) 1-2 *Casuarina obesa* (salt sheoak) 2-3 *Eucalyptus halophila* (salt lake mallee) 2-3 *Eucalytpus kondininensis* (Kondinin blackbutt)	2-3 *Eucalytpus occidentalis* (flat topped yate) 2-3 *Hakea preissii* (needle leaved hakea) 2-3 *Melaleuca cuticularis* (salt paperbark) 2-3 *Melalecua hamulosa* (broom bush honey myrtle) 2-3 *Melaleuca thyoides* (salt lake honey myrtle) 1-3 *Melaleuca uncinata* (broom bush)
Active discharge sites	Depends on salinity and waterlogging. See table above.	

For more information on wind erosion and monitoring refer to:

“Wind Erosion-Monitoring the paddock status" Farmnote No. 45/93, G. Moore and P. Needham.

“Preventing wind erosion" Farmnote No. 35/96, Dan Carter.

“No-till sowing machinery to control win erosion" Farmnote No. 61/96, Paul A. Findlater.

Further reading on managing remnant bush: Journal of Agriculture No3 1994 Dept. of Agriculture.

9.1.7. Pumping saline groundwater

Pumping is an engineering solution that does not remove the cause of the problem but removes its symptoms. It is technically possible to pump saline groundwater from coarse sands in the Werillup Formation and lower the groundwater levels. The possibility of pumping is limited to one hydrological system (*Ancient drainage valleys)*. The pumping will lower groundwater levels only in the areas that surround the pumping bores. The extent and radius of the effect may be calculated by further drilling and pump tests.

Pumping saline groundwater presents three problems:

- continuity of practice;
- high costs; and
- disposal of saline groundwater.

Pumping as a solution is discussed in Section 9.4.

9.2. Specific management options in relation to the hydrological systems of the study area

Specific management options that reduce recharge and the extent of salinity are related to land management units and also to hydrological systems.

9.2.1. Specific management options for deep gravelly sands over clay that are found in the Crests and in Very Gentle to Level Plains

In Section 9.1.5b, we talked about stabilising the sand dunes and lunette systems and increasing their productivity. Here we talk about the deep sands and gravelly sands in other parts of the study area. Some parts of the study area have deep (>0.50 m) sand or gravelly sand (A horizon) over the clayey B horizon (subsoil). These areas generate no runoff. The water holding capacity of the sandy layer is low (<25 mm; Table 3). Due to the low water holding capacity and no runoff, deep sandy areas will have between 20 and 60 mm more recharge than those that have a shallower A horizon and loamy soils. The recharge from deep sandy areas will increase the salinity problem of the lower HSs. It is expensive (and not recommended) to construct surface drains in areas that have deep gravelly sands. The main options to reduce recharge in these areas are better management, perennial pastures, phase cropping and strip planting of trees.

9.2.2. Specific management options for the Plains with Swampy Floors

The main options to reduce recharge in these areas are surface drains, better management of crops and pastures, perennials, phase cropping and strip planting of trees. The slopes of these areas will also benefit from graded interceptor drains. The drains should discharge their water into the waterways and on to natural drainage lines.

The lower parts of this HS have reasonably well-defined depressions to contain runoff. These areas are already or are becoming salt-affected. It is recommended that the well-defined water courses are fenced and the natural vegetation allowed to regenerate. Fenced areas should include a wide strip of land each side of the natural waterway to enclose the potentially saline areas.

9.2.3. Specific management options for the Swampy Terrains

The *Flats with well-defined drainage* have a natural water course that is either salt-affected or will be affected. These depressions should be fenced off and planted with salt-tolerant trees. Planting should cover a wide belt, the width of which may be defined using of a Geonics EM38 (an instrument that can indicate salinity in the top one metre of a soil profile). Slightly salt-affected areas will have EM38 readings that are between 60 and 80 mS/m (Ferdowsian and Greenham, 1992). Moderately affected area will have readings between 81 and 110 mS/m. Planting trees and shrubs in these areas should coincide with treatments on other parts of the landscape. If the other parts of the catchment are not treated, salt may accumulate in the root zone of trees in these discharge areas and eventually kill them.

The *Stagnant flats* need spoon drains which are relatively expensive ($150/ha). Spoon drains should discharge into W drains that may be constructed in the middle of waterways. Soil from the spoon drains should be used to fill the small depressions (playas) that occur in the *Stagnant flats*. Waterways and W drains should be placed in areas prone to salinity and then fenced off and planted with trees. Trees and shrubs that can tolerate salinity and waterlogging should be selected. Ripping of lines and high mounds are essential for the success of trees in this landform pattern.

Phase cropping with lucerne is not recommended in stagnant parts of this HS because lucerne is very sensitive to waterlogging. Other perennial pastures that suit these waterlogged and probably salt-affected areas (Table 11; specially tall wheatgrass) may be used to improve productivity and water use.

9.2.4. Specific management options for the Ancient Drainage Valleys

The undulating areas of this HS should be dealt with like the *Plains with Swampy Floors* and *Very Gentle to Level Plains*. The stagnant parts of this HS have many similarities with the *Stagnant flats*. The main difference to remember is that soil salinity is a difficult problem to tackle, as the saline areas have become permanent discharge sites and their salinity is almost wholly due to off-site problems. There is very little recharge to flush salt from the root zone of trees. This means that trees will be struggling to live in an increasing salty environment. We suggest that drains can improve the condition as a first step. Salt-tolerant pastures are also useful (Table 11). Other treatments should be deferred until the rest of the catchment has been treated and the overall salinity condition of the catchment has improved.

9.3. Management of surface runoff

One of the biggest threats to the future of the Mills Lake Catchment is increasing surface runoff, especially from the undulating eastern parts and to a lesser extent from the undulating western part of the study area. Increasing runoff in the study area is due to:

- Rising groundwater increases the area of the discharge sites. These sites generate more runoff than the non-affected areas and consequently the surface runoff increases.
- Soil structure decline in the area. This deterioration is due to cultivation and occurs in soils that are sodic or behave like sodic soils. For more information on sodic soils refer to Technote Number 14/93, by Ferdowsian and Dellar.
- The eastern part in particular has broad, long depressions and long slopes that may generate large volumes of runoff. The soil profile in the depressions can easily become saturated. Any rain that falls after saturation will become surface runoff and add to the runoff that is generated on the long slopes. There are no natural features in these areas that trap or store

runoff, and so water would eventually flood the *Stagnant flats* on the basin floor.

- It is likely that the graded interceptor drains that were suggested in Section 9.1.1 will increase the volume of runoff in the study area.

The undulating areas west of the study area have shorter slopes than those in eastern parts and so the volume of their runoff will be less.

In both the western and eastern parts of the study area, it is technically possible to divert surface runoff (storm water) before it reaches the *Lakes* and *Stagnant Flats* and discharge it into Warperup Creek, which is close to the Ongerup-Jerramungup Road. However, before embarking on this option, a feasibility study of the diversion is needed. The engineer designing the project should consider the volume of runoff, diversion routes, flow velocity, free board and spillways to ensure safety of the layout, road crossing, inundation of agricultural land and other technical issues. The Catchment Hydrology Group or a consultant may be asked to design the drainage system.

9.4. Management and use of fresh and saline groundwater

Four out of the six major discharge sites in the study area (Figure 6) are rapidly becoming very salty lakes. The regolith at these four sites consists of a full Tertiary profile. The Werillup Formation, which starts at about 23 m below the soil surface consists of coarse sand with a high hydraulic conductivity, so it is possible to pump large volumes of water from the Werillup Formation. The salinity of groundwater in four bores that we drilled in the Werillup Formation varied between 4600 and 5600 mS/m. These salinities (which are just below sea water salinity) are suitable for salt water inland fish and so It may be possible to pump the groundwater into large ponds and produce fish. The most suitable areas for the ponds are the gilgai soils. However, gilgai soils are not suitable for pumping because it is unlikely that they have the Werillup Formation underneath them. It is possible to select pump sites which are reasonably close to gilgai or other soil profiles suitable for the construction of ponds.

Salinity in the ponds will increase gradually due to evaporation. This means that eventually, very saline water will need to be removed from the ponds. This water could be disposed into evaporation ponds where the salt would eventually crystallise. The feasibility and environmental consequences of this practice should be investigated and if it proves acceptable, it can be used to draw down the groundwater levels and improve salinity in the *Ancient Drainage Valleys.* This pumping will have no effect on the extent of soil salinity in other hydrological systems.

9.5. Specific management options for the Lakes and small depressions

The natural vegetation that covered the floors and surrounds of the wetlands, swamps and playas has been killed mainly by the rising saline groundwater, which drowns their roots and inundates for longer periods than in pre-clearing times.

Before clearing, lakes were part of a balanced ecosystem. As reasonably fresh water recharged the aquifer, it leached salt from the root zone of the lake's vegetation. After clearing, as groundwater levels rose, the wetlands have become permanent discharge sites and their salinity has increased. Some of the lakes also receive saline baseflow from salt-affected areas and this further increases their salt concentration. There are several management options that can help these lakes and swamps:

- Fence well away from the present high water mark, keep stock away from lakes and swamps and actively or passively revegetate inside the fence to create a new fringing vegetation.
- Large lakes may be the only possible places to discharge runoff and shallow seepage if there are no creeks and rivers to take excess water out of the area. Lakes that hold water and have become discharge sites (Figure 6) are the best for receiving surface waters. Avoid discharging the surface runoff into small lakes.
- Lower the groundwater levels by reducing recharge in the catchment.
- Fresh water lakes could be used for stock, human consumption or irrigating perennial pastures before they recharge the regional aquifer.
- Small areas that become inundated every few years should be drained. If inundation continues, seed burst occurs and those areas become bare, summer camping grounds for stock. Wind consequently blows their disturbed silty soils. If this process continues the areas eventually grow larger and deeper and become perfect recharge sites. These areas should be drained if possible. Revegetate and fence these depressions wherever possible.

9.6. Specific management options for the Mills Lake

The Mills Lake is the freshest water resource in the area. The surface area of the Lake was 18.5 ha in June 1996 and its maximum depth about 1.50 m. Its volume was probably >90,000 m^3 and its salinity 283 mS/m (1550 mg/L, TSS). This level of salinity is the upper limit of water quality for human consumption. A pumping station on the north-western bank of the Lake and a pipe line are used to pump water to Ongerup (12 km south-west) in dry years.

There are several management options that will help protect the Mills Lake from becoming saline:

- At present, the surface runoff that fills the Mills Lake is fresh. However, as the Lake's catchment becomes salt-affected, the baseflow will become saline. This salty water should be prevented from entering the Mills Lake and be diverted into the Windmill Lake. Flash floods that are fresh could still be used to fill the Mills Lake. This could be achieved using control gates.

- One of the sources of the fresh water for the Mills Lake is the recharge under the *Undulating Dune Fields*, east of the Lake. These areas should not be revegetated to ensure the continuous recharge and fresh water supply.
- Excessive recharge in the *Undulating Dune Fields* will cause the regional groundwater levels to rise but this may be an acceptable trade-off if it helps to maintain the fresh water resource. To minimise recharge entering the aquifer, avoid excessively high water levels in the Lake. This could be achieved by pumping and maintaining water levels to an acceptable level.
- It is equally important to realise that excessive pumping could also endanger the future of the Mills Lake. However, there may be a safe volume that can be pumped out of the Lake. If the water level in the Lake falls below the regional groundwater levels, the salinity of the inflow will increase (Figure 11); the lower it drops, the saltier the inflow. To avoid excessive pumping, groundwater levels in the two bores closest to the lake (ML10/96D and ML11/96D) should be measured. The mean water levels in these two bores should be marked on a depth board in the Lake. Water levels in the Lake should not drop below the mean groundwater levels in those bores.
- Water level in the Lake should be kept at acceptably high levels, for as long as possible. If water is to be pumped out it should be done as late in the season as possible. Pumping in spring should be avoided. This will reduce the period that saline groundwater would discharge into the lake. If excessive saline groundwater accumulates in the lake, it should be pumped into Windmill Lake before the winter rains begin.
- The thickness of the fresh perched aquifer is not known. The boundary between the shallow and deep aquifers is not well defined. Groundwater salinity probably increases by depth. Bore ML10/96 is on top of a lunette. In this bore, the groundwater level (perched aquifer) was 4.00 m below the soil surface in June 1996. Away from this bore, ground levels fall and the perched groundwater levels decrease. This situation may make it possible to skim off the fresh groundwater and drain it into the lake, improving the Lake’s water quality and increasing the useable volume of water. It will also prevent the perched aquifer from recharging the regional aquifer. The fresh groundwater could be skimmed off using a well-designed drainage system, but we do not have enough information to make a firm recommendation at this time. Further studies and drilling are required in the Undulating Dune Fields.

10. Application of these findings to other areas

In the absence of detailed studies, the general findings from this report can be applied to three other areas which have the same rainfall and hydrological systems as the Mills Lake Catchment. These are:

- the North Stirling Basin, which is 65 km south-west of the Mills Lake;
- the Ancient Drainage Valleys north of the study area;
- the Upper Warperup Catchment (Figure 1) which has almost all the HSs that are in the Mills Catchment with the exception of the *Ancient Drainage Valleys*.

We have estimated the extent of the present and potential salinity of the Upper Warperup Catchment (Table 13) based on the Mills Lake Catchment. Our estimates show that more than 21% of this catchment could become salt-affected in future.

Table 13: Potential salinity in the Upper Warperup Catchment varies with landform patterns (from Figure 3) and hydrological systems (from Figure 5).

Landform patterns and Hydrological systems (LFPs)	(HSs)	Total area (ha)	Extent of salinity (ha)	(%)	Potential salinity (ha)	(%)
Gently undulating plains	CR	1298	00	00	22	1.7
Gently undulating plains with shallow bedrock	CR	1213	00	00	7	0.6
Gently undulating plains with saline depressions	PSF	1378	366	26.6	881	64
Gently undulating broad depressions	PSF	292	1	0.3	40	13.8
Valleys with U-shaped channels	PSF	567	85	15	113	20
Very gently undulating plains	VGP	4542	90	2.0	595	13.1
Plains	VGP	2031	36	1.8	238	11.7
Flats with well defined drainage	ST	895	26	2.9	347	38.8
Stagnant flats	ST	2176	278	12.8	914	42.0
Total		14671	981	6.7	3157	21.5

11. Future monitoring

Monitoring the salinity and groundwater levels in the Mills Lake Catchment is essential. Long-term monitoring of groundwater levels at regular intervals will give an indication of groundwater trends and the effectiveness of treatments. The following monitoring is recommended:

- Groundwater levels in bore ML10/96 and ML11/96 and water levels in the Mills Lake should be measured on a monthly basis. This information will help to predict the future of the Lake as a water resource.
- Groundwater levels should be measured seasonally. Monitoring other bores that Agriculture WA drilled in the study area in 1989-90 is also recommended.
- Groundwater salinities should be measured once every other year, preferably in April. Samples should be collected only after flushing the holes (3 to 10 times the volume stored in the casing).
- Water levels and salinity of the major discharge sites (Figure 6 and 12) should be monitored.
- Mapping areas that are occasionally inundated or excessively waterlogged would provide useful information for future decision making.
- The eastern parts of the study area do not have enough bores to monitor changes in their groundwater levels. A few lines, perpendicular to the broad valleys, should be selected for further drilling and monitoring. Three or four shallow bores (to water level) should be drilled along each line and in different parts of the landscape. Bores in the valley floors will only show that the groundwater levels are very close to the soil surface. The bores along slopes will be more useful for long-term monitoring.
- Before any major management changes are implemented, bores should be drilled in the target areas as well as in similar areas that do not have treatments. This will help monitor any effects the management changes have.

If the Mills Lake is essential as a future water resource, more bores should be drilled in the *Undulating Dune Fields* which are on the eastern side of the Lake. These bores are necessary to map the extent, depth and gradient of the perched aquifer and its relationship with the regional groundwater.

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Appendix 1

The following pages show the drill logs from the 22 bores that we drilled in the study area in April 1996. The location of these bores is marked on Figures 1 and 3. The drill logs contain the following information:

- Eastings and Northings (Australian Map Grid; AMG) of sites;
- Salt concentration (kg/m^3) in bores, which ranged from 5.7 to 33.0. The maximum salt concentration in a depth interval was 100 kg/m^3 (bore ML3/96);
- Total salt stored (TSS; t/ha) in the whole profile, which ranged from 340 (in a 4 m deep hole) to >15,000 in a 45 m deep hole in *Stagnant Flats*;
- Groundwater salinity (mS/m), which varied from 150 (fresh groundwater mound under a dune field) to 7,800 (under a *Lunette System*);
- Water level (m) which ranged from -1.00 to -17.4 ;
- Which hydrological system and landform pattern it was drilled in;
- Interpreted geology;
- A full description of the soil profile (lithology).

Appendix 2

Bores drilled by landholders in the study area, showing water levels and groundwater salinities (March 1996).

Owner	Bore No.	Location Number	Location Easting, Northing	Water Level (m; DBG*) 18/3/96	Salinity (mS/m)	Depth Drilled (M)	Landform pattern and hydrological systems (LFP)	(HS)
Steve Jones	1	K1350	644226, 6254272	1.45	5700	7.2	Plains	VGP
	2			1.4	2760	3.2		
	3			1.03	3170	7.2		
	4		644458, 6254026	dry	dry	1.1		
Norm Curtin	1	K356	646127, 6254273	0.5	5080	7.2	Plains	VGP
	2			1.4	3520	3.2		
John Harding	1	K1456	647959, 6245342	1.12	6400	7.2	Stagnant flats	ST
	2			1.15	2310	1.8		
	3		646567, 6242870	1.05	1293	3.2		
Graham Stewart	1	K302	643960, 6243662	1.12	4680	6.8	Stagnant flats	ST
	2			1.22	1310	3		
	3			1.08	8230	7.2		
	4		643561, 6245098	1.17	7530	3.2		
Peter Mattner	1	K301	645051, 6246544	1.8	4620	7.2	Flat bottomed valleys	ADV
	2			1.8	4160	3.2		
Kelly O'Neil	1	K1211	636287, 6254203	1.3	6760	7.2	Plains	VGP
	2			1.3	2360	2.1		
	3	K1368		4	6950	7.2		
	4		633885, 6254653	dry	dry	3.2		
Len Faulkner	1	K743	645021, 6251717	1.06	3670	5.2	Very gently undulating plains	VGP
	2			0.9	4710	3.1		

Owner	**Bore No.**	**Location Number**	**Location Easting, Northing**	**Water Level (m; DBG*) 18/3/96**	**Salinity (mS/m)**	**Depth Drilled (M)**	**Landform pattern and hydrological systems (LFP)**	**(HS)**
Ross Strahan	1	K363	649472, 6253290	dry	dry	7.2	Gently undulating plains	CR
	2			dry	dry	3.2		
	3	K361	647525, 6253132	4.08	5230	7.2		VGP
	4			dry	dry	3.2		
	1	K349	643614, 6249752	1.6	NA**	7.2[1]	Flat bottomed valleys with lakes	ADV
	2			NA	NA	3.2[1]		
	1	K283	638223, 6244107	NA	NA	7.2[1]	Gently undulating plains	CR
	2			NA	NA	3.2[1]		
	1	K280	636921, 6245479	NA	NA	7.2[1]	Gently undulating plains with saline dep.***	PSF
	2			NA	NA	3.2[1]		
	3			NA	NA	7.2[1]		
	1	K271	635782, 6250728	2.04	NA	7.2[1]	Gently undulating broad dep.	PSF
	2			NA	NA	3.2[1]		
	1	K276	636039, 6247602	NA	NA	7.2[1]	Gently undulating plains	CR
	2			NA	NA	3.2[1]		
	3			NA	NA	7.2[1]		

*BGL= below ground level; **NA = data not available; ***dep. = depression

7.2[1] = assumed depth

Appendix 3: Terminology and abbreviations used in this report

Term	Description
Aeolian	Material that is deposited by wind.
Aggradation	The process of building up surfaces by depositing sediments.
Alluvial or alluvium	Material that is deposited in floodplains by water.
AMG	Australian Map Grid (National reference system).
Aquifer	A water-bearing underground layer (stratum), that water can be extracted from. A saturated soil capable of yielding useful supplies of water.
Archaean	Early Precambrian era (Precambrian period was between 600 and 4,500 million years ago).
Baseflow	The extended, low flow in a creek after surface runoff has finished and when groundwater is the sole contributor to the flow.
Basement rock	(or bedrock) Hard rocks that are at the base of the soil profile
CALM	Department of Conservation and Land Management.
Capillarity	Rise of groundwater above water table, due to surface tension.
Capillary	Fine spaces between soil particles through which water moves.
Closed depression	A depression (basin) in the landscape that is lower than the surrounding areas and collects runoff.
Colluvial	Material which has rolled down hills by gravity and has been deposited on the lower slopes.
Conductivity (electrical)	Ability of a solution, soil or rock to conduct an electrical current.
Conglomerates	Rounded or sub-rounded rock fragments which are cemented together.
Degradation	Decline in the condition of natural resources commonly caused by human activities.
Depression	A low lying area.
Discharge	Groundwater loss through evaporation or seepage.
Drainage pattern	Pattern and arrangement of creeks. Direction of creeks in relation to each other and the way they join.
Drill log	A record of material and findings obtained while drilling a bore.
Fault	A long (sometimes many kilometres) fracture or system of fractures (fault zone) in rock that shows a displacement between the two sides.
Flash flood	Large volume of runoff that only occurs for a short time.

Term	Description
Flat	An area that is almost level (<1% slope) and is not a crest or a depression. When a large area of level land is higher than most of the surrounding areas it is called a plain or plateau.
Fluvial	Material deposited by water.
Flow lines	In a laminar flow (flow that is not turbulent), molecules of liquid flow along predictable lines which are called flow lines.
Geology	Science of learning about the earth (its origin, structures, composition, historical changes and processes).
Geomorphology	Science of describing and interpreting landform patterns and processes of landscape formation.
Geophysics	The science of studying the earth's physical properties such as magnetism, conductivity and density.
Gneiss	A metamorphosed rock that, like granite, has quartz, feldspars and mica but in which the grains are organised (bands). Banding is due to recrystallisation while cooling was in process. Gneisses are generally coarse-grained. A mass of gneiss that has coarse crystals may have pockets with finer material.
Granite rock	A rock that has an irregular, granular texture and its grains can be seen. Composed of quartz (10-20%), feldspars (70%), mica (5-10%) and other minor minerals
Gravel	Rock particles 2-4 mm in diameter.
Hydraulic conductivity	The ability of soil or a rock to transmit water.
Hydraulic gradient	Slope between water levels in two bores that have been drilled at different sites but into the same aquifer. If the bores are along the same flow line, the gradient will be the maximum gradient of that aquifer in that area.
Hydro	Water
Hydrogeology	The study of geological factors in relation to flow of water.
Hydrograph	Graphical representation of flow rate or water level during a measuring period.
Hydrological equilibrium	When an area has become stable hydrologically ie long-term recharge equals long-term discharge.
Hydrological system (HS)	Areas that have similar hydrological properties and may be grouped together as one unit.
Hydrology	The study of water movement on the land surface and in the soil profile.
In situ; in situ weathered material	In place; Weathered material that has stayed in its place of weathering.

Term	Description
Isopotential	A line on a map connecting all spots with the same groundwater level (above a known bench mark). The relevant level is usually marked on the isopotential line.
Landform element (LFE)	Small part (20 to 30 m in radius) of the landscape described by its slope, morphology and degradational problems associated with its use.
Landform pattern (LFP)	A toposequence (valley floor, hillside and ridge) described by its relief, slope, landform elements and degradational problems associated with its use.
LMU	Land management unit.
LFP	Landform pattern.
Leaching	The removal of some chemical components of a rock or soil by water.
Lignite	Low grade brown coal, silt with weathered organic material.
Lithology	Characteristics (composition and texture) of sedimentary material that may vary from one layer to another.
LMU	
Local aquifer	An aquifer that exists at a local scale (hill slope, small valley) and has formed because of local recharge.
Lacustrine	Formed at the bottom, or along the shore, of lakes.
Lunette	Elongated, convex, low sandy ridges built up by wind, usually on the east-south-east margins of playas. They have moderately inclined (10 to 32%) inner slopes (towards the lake) and gently inclined (3 to 10%) outer slopes.
Marine sediments	Sediments laid down under the sea.
Mobilisation of salt	Movement of salt by groundwater. Salt in unsaturated soil profiles is attached to clay by water (in a thin film of water that is held tightly to soil particles). As groundwater levels rise, some of this salt may enter the macropores and be moved by flowing water.
mg/L	Milligrams per litre (equal to parts per million).
Mottles	Mottles are spots, blotches or streaks in a soil profile which have different colours from the rest of the soil.
mS/m	Milli Siemens per metre (a measure of electrical conductivity of water). To convert to mg/L, multiply by 5.5.
Open depression	A valley or depression that has an outlet through which water can move out of that area.
Palaeochannels	Ancient river channels that have been filled with sediments.
Pallinup siltstone	Silts that were deposited in a marine environment on the south coast of Western Australia during the Eocene (age ~ 40 million years).

Term	Description
Pebble	A rock particle between 4 and 60 mm in diameter.
Permeability	The characteristic of a soil which affects the rate at which water flows through a soil or a rock.
Physiography	The branch of geography that deals with the interpretation and mapping of features of the land surface.
Piezometer	A tube inserted into a water saturated material to measure the pressure (piezometric level) at that specific point.
Plant available water (PAWC)	Difference between field capacity and wilting point of a soil. Water that plants can obtain from unsaturated soil.
Quartz dyke	An almost vertical sheet-like body of mainly quartz that cuts across the bedding or structural planes of the host rock.
Quartz vein	An almost vertical quartz intrusion into host rocks. When fractured, quartz veins have very high hydraulic conductivities. They are found in gneiss including schist, basement rocks, sediments and a baked margin of rocks that envelope a dolerite dyke. In areas that have fresh groundwater and have low yields such as schists, quartz veins are likely to have good yields. In salinity prone areas, some saline seeps may be associated with quartz veins.
Recharge	The component of rainfall that drains below the root zone of vegetation and joins the groundwater.
Regional aquifer	An aquifer that is large (more than one hillside) and is fed by on-site as well as off-site recharge. Groundwater levels in a regional aquifer do not follow the undulations or slopes of the soil surface. Flow lines in an aquifer are almost straight and parallel.
Regolith	All weathered or sedimentary material that lies over the basement rock.
Relief	Changes in elevation within a specified distance.
Root zone	Near surface part of a soil profile where roots are active.
Salt-affected	An area where the growth of crops, pastures or natural vegetation is reduced by excessive salt in the root zone.
Salt bulge	A zone in the profile of a regolith that has the highest concentration of salt.
Salt storage	Salt storage is the amount of salt held in a soil profile. Salt storage is measured in terms of kg per cubic metre (kg/m^3) or tonnes per hectare (t/ha). Salt storage depends on landform patterns and rainfall.
Saprolite	Soft, disintegrated, decomposed rock, remaining in its original place.
Scald	A patch of bare ground which is a seepage zone but has dried on the surface.

Term	Description
Shear zone	A fractured zone in the earth's crust that is caused by tectonic movement and between the sides of which there is no observable relative movement.
Silt	Soil particles that are between 0.002 and 0.02 mm in diameter. They are larger than clay and smaller than fine sand.
Sinkhole	Sinkholes are steep-sided, closed depressions which occur in areas that have limestone or spongolite. A sinkhole is formed when soluble material dissolves and leaches out of a soil profile forming an underground cavity. A large cavity may become connected to the ground surface if its overlying material collapses. If surface runoff is discharged into these sinkholes, the water immediately recharges the aquifer causing a rapid rise in the groundwater level.
Sodic soil	A soil that has high levels of sodium associated with the surface of its clay particles. The exchangeable sodium percentage (ESP) in a sodic soil is >6%. Clay in sodic soils disperse when exposed to water.
Spongolite	A siltstone full of sponge spicules that has probably formed along the beaches of an Eocene sea.
Subsoil	The B horizon (below the topsoil) of a soil profile. A soil horizon is a layer of soil, approximately parallel to the soil surface, with morphological properties that are different from layers below or above. The B horizon is usually a zone of accumulation (of clay, ions etc).
System	A group of elements (land, rocks, methods) that are interrelated and have some common attributes or functions.
Tertiary	A geological period that extended between 2 and 65 million years ago. This period is characterised by active erosion and sedimentation.
Texture	Size, shape and relationship between grains of a soil or rock. The proportion of sand, silt and clay in soil.
Toposequence	Combination of hill top, upper slope, mid-slope, footslope and valley floor that form the shape of a landscape.
TSS/ TDS	Total soluble salts or total dissolved salts, usually measured in water, as milligrams per litre (mg/L).
Unsaturated soil profile	A zone in the soil profile where the pores are not filled with water and the soil contains some air in its larger pores.
Water balance	A state of equilibrium when rainfall or irrigation water in a landscape is accounted for by the sum of runoff, plant water use, evaporation, recharge and changes in soil moisture content (where all inputs equal outputs).

Term	Description
Water holding capacity	(or field capacity) water that is held in the soil immediately after gravity has drained away the excess water.
Waterlogging	A soil condition in which excess water in the root zone inhibits gas exchange with atmosphere. In a waterlogged soil, free water can be found in the root zone of plants (usually within the top 0.3 m). Waterlogging reduces plant growth.
Water table	The upper surface of an unconfined aquifer. Water level in soil profile at atmospheric pressure.
Werillup Formation	Sequence of pebbles, sand and lignite deposited on low lying parts of the south coast of Western Australia prior to the invasion of the Eocene Sea.
Weathering	Chemical, physical and biological decomposition of rocks. This can result in the formation of a soil profile.
Wilting point	Moisture content of a soil when the suction force of plant roots cannot overcome the soil-water tension and so the plants wilt.
Zone	A region, area or a portion of something that has specific or distinctive features or attributes.

Drilling Log Mills Lake 1996

ML1/96

Easting: 645046 **Northing:** 6242265 **Salt Storage (TSS t/ha):** 4236
Groundwater salinity (mS/m): 6090 **Water level below ground (m):** -1.75
Date: 6/5/96 **Slotted depth (m):** -23.5 to -25.5
Hydrological System: Swampy terrains that have extremly low relief.
Interpreted Lithology: 0-4 m Quaternary sediments transported from nearby granite hills, 4-23 m Tertiary silts, 23-25.5 m *in situ* weathered granitic material, 25.5 m bedrock.

Drilling log

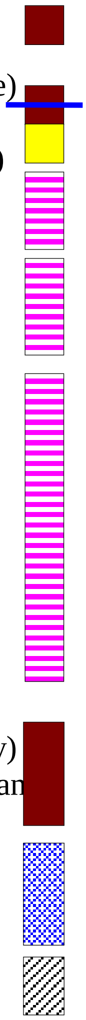
0-1 m gravelly sandy clay 10YR 7/1 (white)
1-2 m sandy heavy clay 10YR 7/1 (white) and mottles 2.5YR 5/8 (red)
2-3 m sandy clay loam 10YR 7/2 (white)
3-4 m silty clay 2.5Y 8/0 (white)
4-6 m silty clay 2.5Y 8/0 (white) with mottles 10R 5/4 (weak red)
6-9 m silty clay 10YR 8/2 (white)

9-19 m silty clay 10YR 8/2 (white)

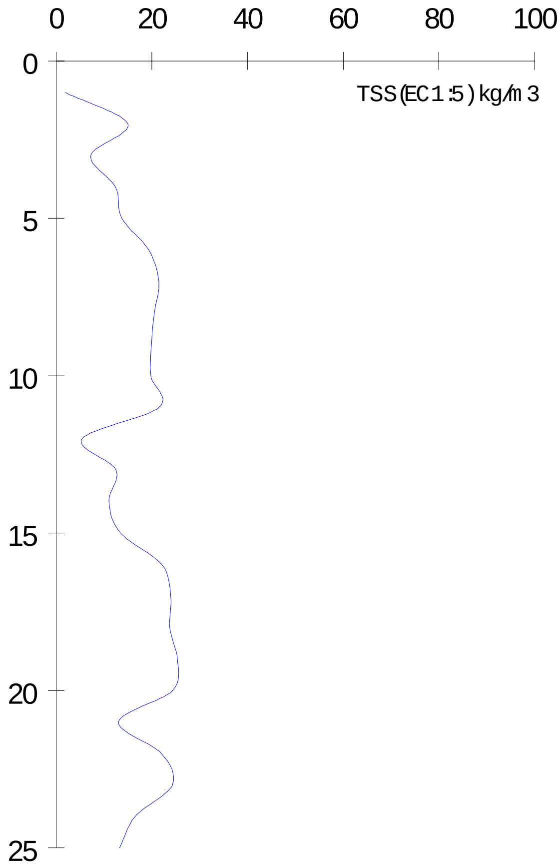
19-23 m sandy clay 10YR 6/1 (light grey) the top of Werillup profile, more sand than layers above

23-25.5 m coarse sandy clay 10YR 6/1 (light grey), sharp edged sand

25.5 m Bedrock



Salt Storage Profile



Legend

- heavy sandy clay, sandy clay
- coarse sandy clay
- heavy silty clay
- reddish or pinkish silt, silty clay
- fine sand, loamy sand, loamy clay sand
- hardpan
- *in situ* weathered material
- water-table
- bedrock
- coarse sand
- lignite

Drilling Log Mills Lake 1996

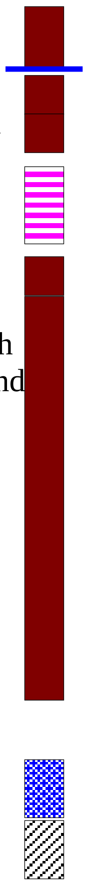
ML2/96

Easting: 645080 **Northing:** 6244983 **Salt Storage (TSS t/ha):** 6859
Groundwater salinity (mS/m): 7000 **Water level below ground (m):** -1.75
Date: 7/5/96 **Slotted depth (m):** -20 to -22
Hydrological System: Swampy terrains that have extremly low relief.
Interpreted Lithology: 0-4 m Quaternary, 4-20 m Tertiary silts, 20-22 m *in situ* weathered granitic material, 22.1 m bedrock.

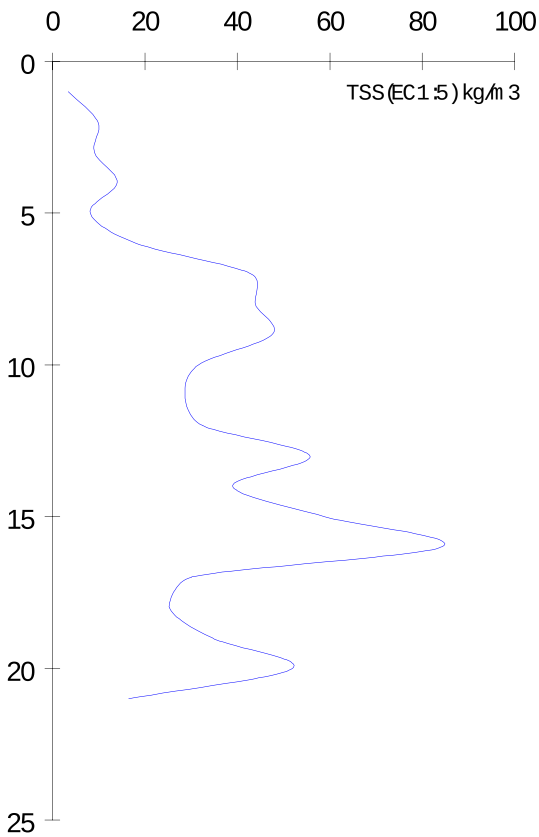
Drilling log

0-2 m heavy clay 5Y 7/1 (light grey)
2-3 m heavy clay 10YR 6/2 (light brownish grey) and 20% mottles 2.5YR 3/6 (dark red), some are very hard gravel
3-4 m sandy clay 10YR 8/1(white)
4-6 m silty clay 5YR 8/1 (white) with some sharp sand, developed water at 5m
6-7 m sandy clay 10YR 8/1 (white) and 5% mottles 10R 6/6 (light red)
7-20 m sandy clay 10YR 8/1 (white) with some yellow mottles, layers of coarse sand in tight clay

20-22 m grey material, 10YR 6/1 (light grey), mineral schist
22 m bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML3/96

Easting: 642203 **Northing:** 6245348 **Salt Storage (TSS t/ha):** 15125
Groundwater salinity (mS/m): 7360 **Water level below ground (m):** -1.81
Date: 7/5/96 **Slotted depth (m):** -43 to -45
Hydrological System: Swampy terrains that have extremly low relief.
Interpreted Lithology: 0-1 m Quaternary, 1-29 m Tertiary sediments, 29-45 m *in situ* weathered granitic material, 45 m granitic bedrock.

Drilling log

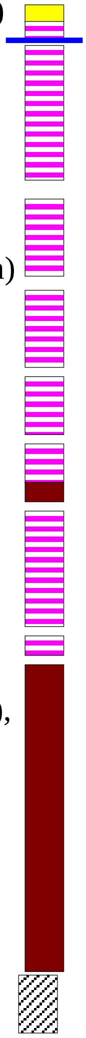
0-1 m sandy clay loam 10YR 7/2 (white)
1-2 m silty clay 10YR 8/1 (white) and mottles 10YR 6/3 (pale brown)
2-8 m silty clay 10YR 8/1 (white)

8-12 m silty clay 10YR 8/1 (white) and mottles 10YR 6/4 (light yellowish brown)
12-16 m silty clay 10YR 8/1 (white)

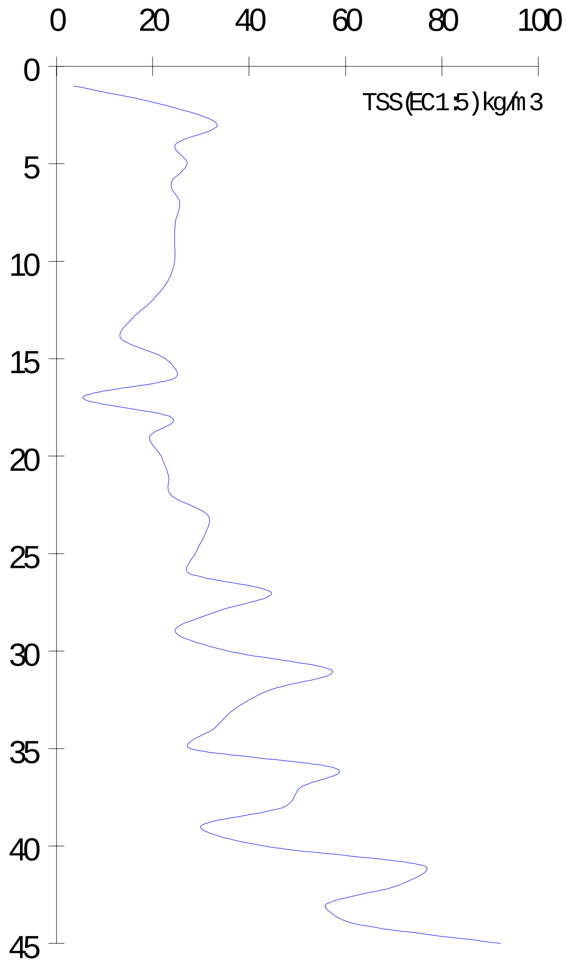
16-19 m silty clay 2.5Y 6/0 (grey)

19-21 m silty clay 10YR 6/2 (light brownish grey)
21-22 m sandy clay 10YR 6/2 (light brownish grey)
22-28 m silty clay 10YR 8/6 (yellow) to 7/2 (white)
28-29 m silty clay 2.5Y 7/2 (light grey)
29-45 m sandy clay 2.5Y 7/2 (light grey), mixed samples

45 m Bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

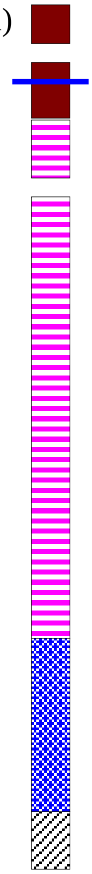
Drilling Log Mills Lake 1996

ML4/96

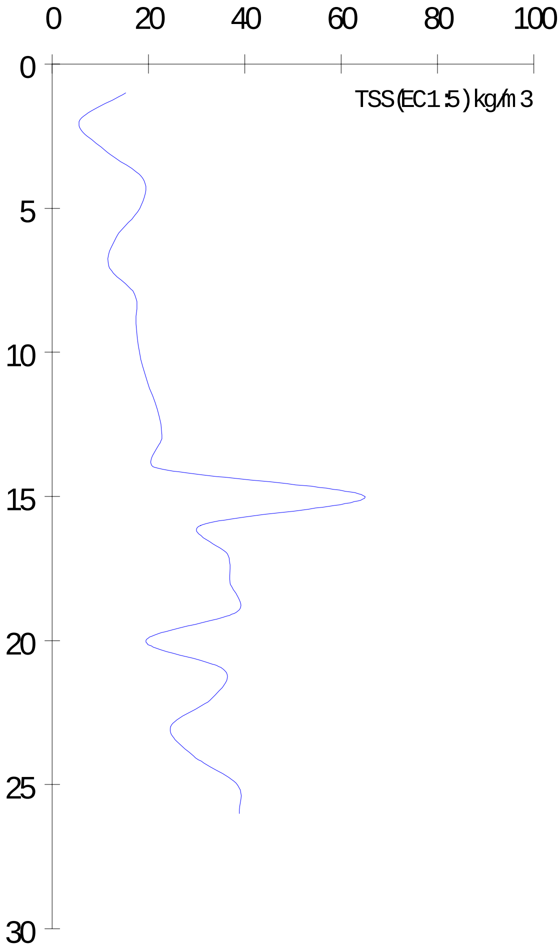
Easting: 641430 **Northing:** 6245350 **Salt Storage (TSS t/ha):** 6588
Groundwater salinity (mS/m): 6850 **Water level below ground (m):** -1.6
Date: 7/5/96 **Slotted depth (m):** -24 to -26
Hydrological System: Very gentle to level plains.
Interpreted Lithology: 0-2.5 m Quaternary colluvial, 2.5-5 m Tertiary silt, 5-26 m *in situ* weathered granitic material, 26 m bedrock.

Drilling log

0-1 m sandy clay 7.5YR 6/2 (light brown)
1-2.5 m sandy clay 2.5YR 6/6 (light red)
2.5-5 m silty clay 7.5YR 8/0 (white)
5-20 m silty clay 7.5YR 8/0 (white)
20-26 m silty clay 2.5Y 7/2 (light grey)
26 m Bedrock



Salt Storage Profile



Legend

- heavy sandy clay, sandy clay
- coarse sandy clay
- heavy silty clay
- reddish or pinkish silt, silty clay
- fine sand, loamy sand, loamy clay sand
- hardpan
- *in situ* weathered material
- water-table
- bedrock
- coarse sand
- lignite

Drilling Log Mills Lake 1996

ML5/96

Easting: 640787 **Northing:** 6246989 **Salt Storage (TSS t/ha):** 8001
Groundwater salinity (mS/m): 7290 **Water level below ground (m):** -1.18
Date: 8/5/96 **Slotted depth (m):** -24 to -26
Hydrological System: Very gentle to level plains.
Interpreted Lithology: 0-10 m Tertiary silt, 10-26 m *in situ* weathered coarse-grained granitic material, 26 m bedrock.

Drilling log

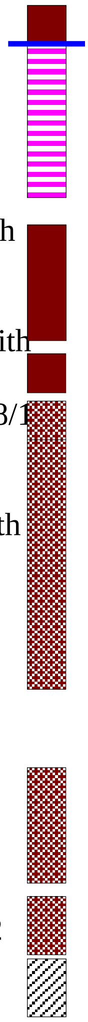
0-1.2 m heavy clay 2.5Y 6/2 (light brownish grey)
1.2-7 m silty clay 10YR 8/1 (white)

7-10 m sandy clay 10YR 8/1 (white) with 5% mottles 2.5Y 6/6 (olive yellow)

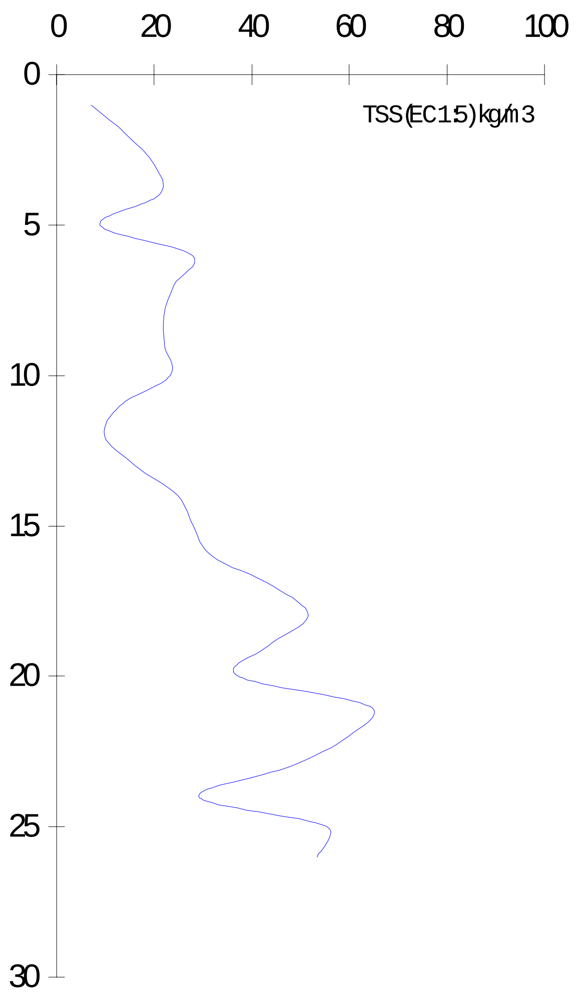
10-11 m sandy clay 10YR 8/1 (white) with 40% mottles 2.5Y 6/6 (olive yellow)
11-12 m coarse sandy gritty clay 10YR 8/1 (white) with mottles 2.5Y 6/6 (olive yellow)
12-21 m coarse sandy clay 10YR 8/1 with some weathered rock fragments

21-25 m coarse sandy clay 10YR 8/1 gradually changing to 2.5Y 6/0 (grey)

25-26 m very gritty sandy clay 2.5Y 7/2 (light grey)
26 m Bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML6/96

Easting: 639425 **Northing:** 6248306 **Salt Storage (TSS t/ha):** 9144
Groundwater salinity (mS/m): 6810 **Water level below ground (m):** -2.12
Date: 8/5/96 **Slotted depth (m):** -33 to -35
Hydrological System: Swampy terrains that have extremly low relief.
Interpreted Lithology: 0-18 m Tertiary silt and fine sand, 18-35 m *in situ* weathered coarse-grained granitic material, 35 m bedrock.

Drilling log

0-1.2 m heavy clay 10YR 6/2 (light brownish grey)
1.2-5 m sandy clay 7.5YR 8/2 (pinkish white)

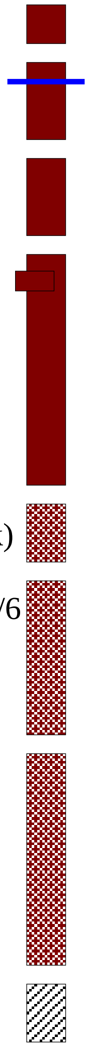
5-7 m sandy clay 7.5YR 8/2 (pinkish white) with mottles 10R 6/6 (light red)
7-8 m sandy clay 10YR 8/1 (white)
8-18 m sandy clay 5YR 8/4 (pink)

18-20 m coarse sandy clay 5YR 8/4 (pink)

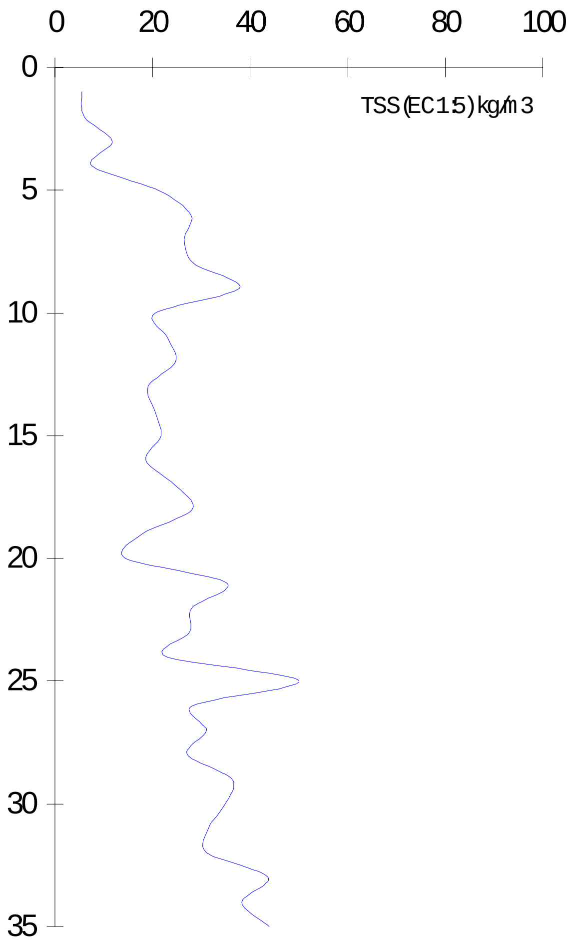
20-26 m coarse sandy gritty clay 10YR 7/6 (yellow)

26-35 m coarse sandy gritty clay 2.5YR 6/2 (pale red)

35 m Bedrock



Salt Storage Profile



Legend	
heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML7/96

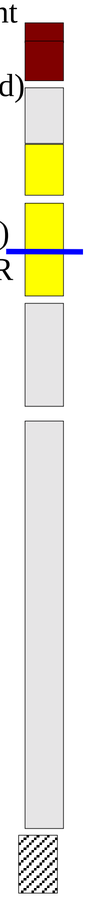
Easting: 638522 **Northing:** 6248980 **Salt Storage (TSS t/ha):** 3660
Groundwater salinity (mS/m): 7090 **Water level below ground (m):** -6.58
Date: 9/5/96 **Slotted depth (m):** -19 to -21
Hydrological System: Catchment Divides.
Interpreted Lithology: 0-7 m Colluvial material, 7-21 m *in situ* weathered granitic material, 21 m bedrock.

Drilling log

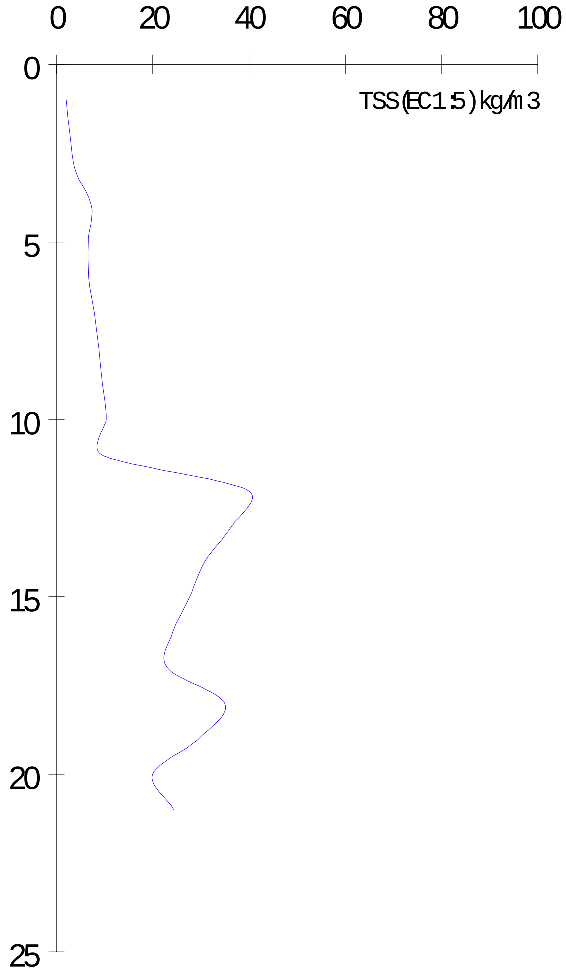
0-0.5 m sandy heavy clay 10YR 6/2 (light brownish grey)
0.5-1.5 m sandy clay 2.5YR 6/6 (light red)
1.5-3 m coarse sandy clay 7.5YR 8/2 (pinkish white)
3-4 m sandy clay 5YR 7/4 (pink)
4-5.5 m clayey sand 2.5Y 7/2 (light grey)
5.5-7 m fine to medium loam sand 7.5YR 6/6 (reddish yellow)
7-10 m coarse sand 10YR 6/6 (brownish yellow)

10-21 m coarse sand 10YR 6/4 (light yellowish brown)

21 m Bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML8/96

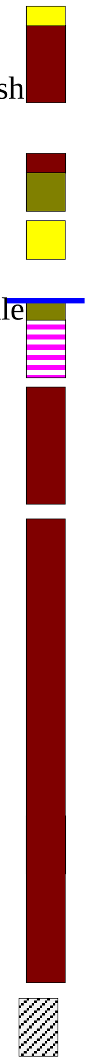
Easting: 638000 **Northing:** 6250151 **Salt Storage (TSS t/ha):** 7836
Groundwater salinity (mS/m): 7780 **Water level below ground (m):** -9.51
Date: 9/5/96 **Slotted depth (m):** -38 to -40
Hydrological System: Ancient drainage valleys.
Interpreted Lithology: 0-14 m Tertiary silt, 14-43.5 m *in situ* weathered granitic material, 43.5 m bedrock.

Drilling log

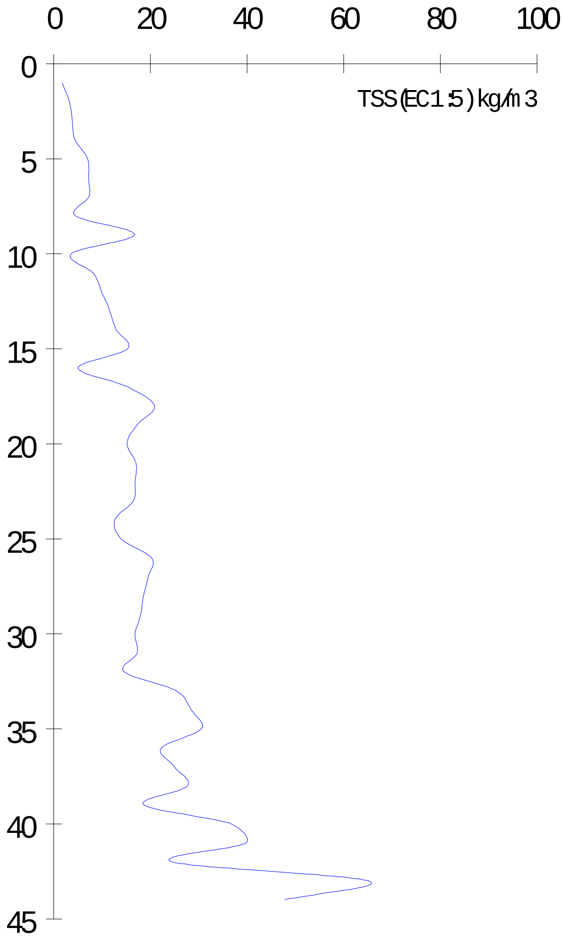
0-1 m sandy loam 7.5YR 7/6 (reddish yellow)
1-5 m sandy clay 2.5Y 6/2 (light brownish grey)
5-6 m sandy clay 10YR 6/4 (light yellowish brown)
6-8.5 m silty heavy clay 2.5Y 7/2 (light grey)
8.5-10 m clayey sand 10YR 7/3 (very pale brown)
10-11 m silty heavy clay 5Y 6/1 (grey)
11-14 m silty clay 2.5Y 8/1 (white)
14-20 m sandy clay 10YR 8/6 (yellow)

20-43.5 m sandy clay 10YR 7/2 (white)

43.5 m Bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered material
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML9/96

Easting: 637416 **Northing:** 6250779 **Salt Storage (TSS t/ha):** 1235
Groundwater salinity (mS/m): 5260 **Water level below ground (m):** -2.00
Date: 9/5/96 **Slotted depth (m):** -9 to -11
Hydrological System: Lakes
Interpreted Lithology: 0-6 m Alluvial and colluvial sand and clayey material transported from nearby granitic hills, 6-11 m *in situ* weathered coarse-grained granitic material, >11 m weathering profile continues.

Drilling log

0-1 m sandy heavy clay 10YR 6/3 (pale brown)

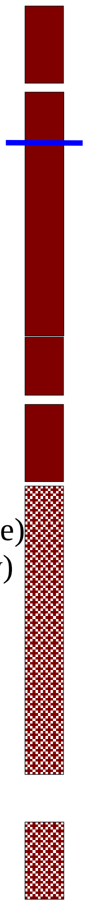
1-4 m sandy clay 2.5Y 8/1 (white)

4-5 m sandy clay 2.5Y 8/1 (white) with mottles 10YR 6/8 (brownish yellow)

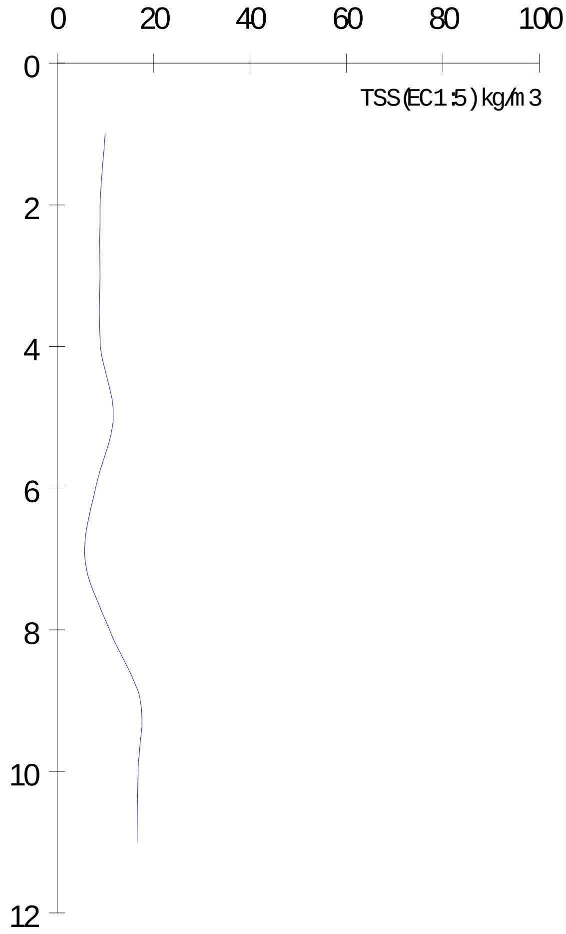
5-6 m sandy clay 2.5Y 8/1 (white)

6-10 m coarse sandy clay 2.5Y 8/1 (white) with mottles 10YR 6/8 (brownish yellow)

10-11 m coarse sandy clay 2.5Y 8/1 (white)



Salt Storage Profile



Legend

- heavy sandy clay, sandy clay
- coarse sandy clay
- heavy silty clay
- reddish or pinkish silt, silty clay
- fine sand, loamy sand, loamy clay sand
- hardpan
- *in situ* weathered material
- water-table
- bedrock
- coarse sand
- lignite

Drilling Log Mills Lake 1996

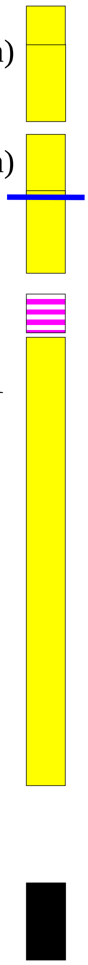
ML10/96

Easting: 644727 **Northing:** 6249746 **Salt Storage (TSS t/ha):** 1611
Groundwater salinity (mS/m): 1835 **Water level below ground (m):** -5.32
Date: 10/5/96 **Slotted depth (m):** -7 to -9
Hydrological System: Undulating dune fields in Tertiary areas.
Interpreted Lithology: 0-5 m fine sand and silt, wind deposited, 5-8 m Tertiary silt (Pallinup silt), 8-23 m Tertiary fine to medium grained sand (Pallinup), 23-23.5 m Lignite, >23.5 m medium sand.

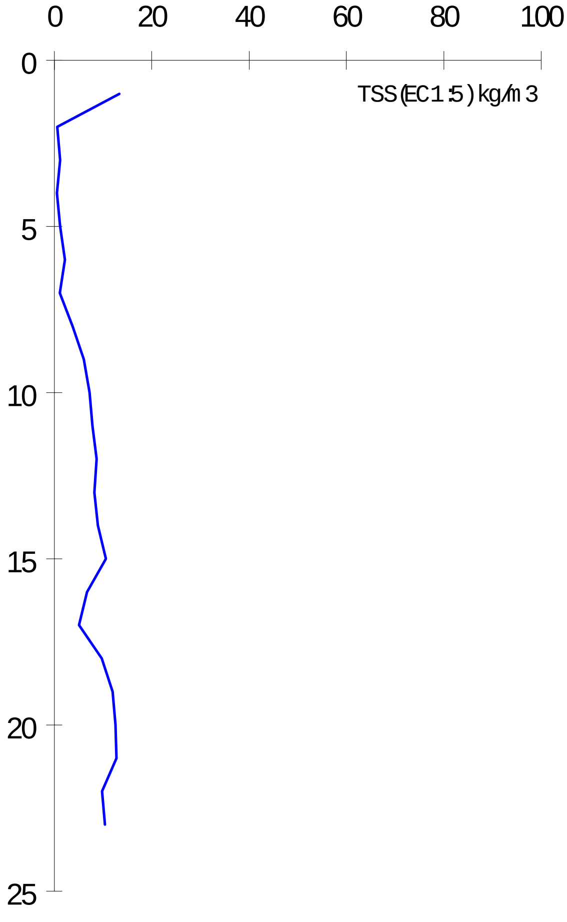
Drilling log

0-1 m fine sand 10YR 8/1 (white) with mottles 10YR 4/4 (dark yellowish brown)
1-4 m fine sandy clay 10YR 8/1 (white)
4-5 m fine sand 10YR 8/1 (white) with mottles 10YR 4/4 (dark yellowish brown) some silicified hard material
5-7 m coarse fine sand 10YR 6/2 (light brownish grey)
7-8 m silty clay 10YR 5/1 (grey)
8-23 m fine sand colour changing from 10YR 6/8 (brownish yelow) to 10YR 5/1 (grey)

23 m Lignite



Salt Storage Profile



Legend

- heavy sandy clay, sandy clay
- coarse sandy clay
- heavy silty clay
- reddish or pinkish silt, silty clay
- fine sand, loamy sand, loamy clay sand
- hardpan
- *in situ* weathered material
- water-table
- bedrock
- coarse sand
- lignite

Drilling Log Mills Lake 1996

ML11/96

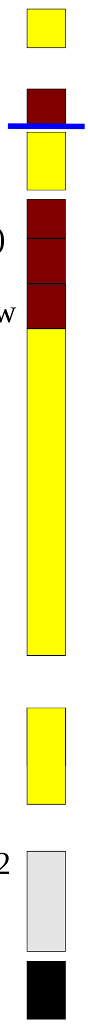
Easting: 644183 **Northing:** 6249614 **Salt Storage (TSS t/ha):** 2238
Groundwater salinity (mS/m): 5330 **Water level below ground (m):** -1.96
Date: 11/5/96 **Slotted depth (m):** -7.5 to -9.5
Hydrological System: Undulating dune fields in Tertiary areas.
Interpreted Lithology: 0-2 m Quaternary silt, clay and fine sand, 2-5 m medium clayey sand (Pallinup), 5-23 m fine sand (Pallinup), 23-23.5 m lignite (Werillup), >23.5 m medium to coarse sand (Werillup).

Drilling log

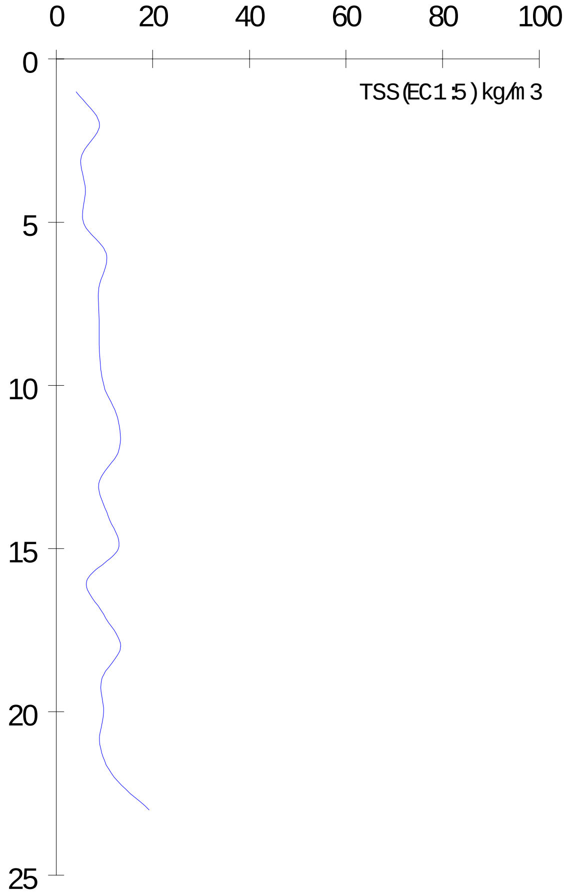
0-1 m fine sandy loam 10YR 6/3 (pale brown)
1-2 m fine sandy clay 10YR 8/2 (white)
2-4 m clayey sand 2.5Y 8/2 (white) medium- grained (1.5mm)
4-5 m clayey sand 2.5Y 8/2 (white)
5-6 m sandy heavy clay 2.5Y 8/2 (white)
6-7.5 m clayey sand 2.5Y 8/2 (white)
7.5-17 m fine sand 2.5Y 8/2 (white), flow rate at 17m is approx 2 L/sec

17-20 m fine to medium sand 2.5Y 8/2 (white)

20-23 m medium to coarse sand 2.5Y 8/2 (white)
23 m hole was collapsing, Werillup on drill bit



Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered material
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML12/96

Easting: 643330 **Northing:** 6250872 **Salt Storage (TSS t/ha):** 1578
Groundwater salinity (mS/m): 5060 **Water level below ground (m):** -5.84
Date: 15/5/96 **Slotted depth (m):** -15 to -17
Hydrological System: Ancient drainage valleys.
Interpreted Lithology: 0-11 m Tertiary silt (Pallinup), 11-12 m Tertiary fine sand (Pallinup), 12-13.5 m fine sand (Pallinup), 13.5-14 m lignite (Werillup), 14-20 m fine to medium sand (Werillup), >20 m profile continues, bedrock unknown.

Drilling log

0-0.5 m fine sandy loam 10R 6/1 (reddish grey)
0.5-1 m sandy heavy clay 10R 6/ (pale red)
1-3 m silty clay 10YR 8/4 (very pale brown)

3-6 m clayey fine sand 10YR 8/4 (very pale brown)

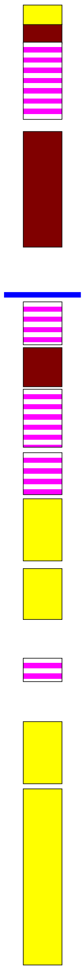
6-7 m silty clay 10YR 7/1 (white)
7-8 m clay sand 10YR 7/6 (yellow)
8-9.5 m silty clay 10YR 7/1 (white)

9.5-11 m silty clay 5YR 7/4 (pink)

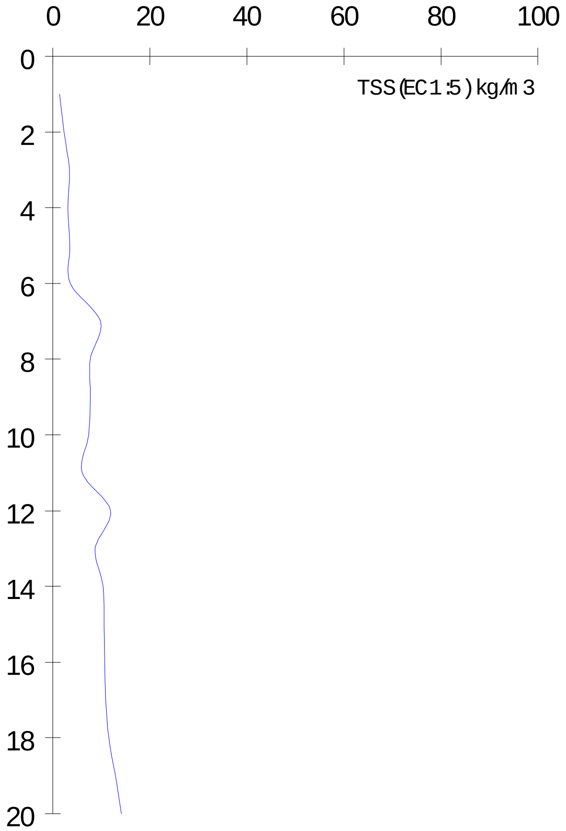
11-12 m fine sand 10YR 8/3 (very pale brown)
12-13.5 m medium sand 10YR 7/6 (yellow)
13.5-14 m silty clay 10YR 4/1 (dark grey)

14-15.5 m very fine sand 10YR 8/1 (white)
15.5-20 m very fine sand gradually changing to fine or medium sand 10YR 8/1 (white)

20 m hole was collapsing, too much water.



Salt Storage Profile



Legend

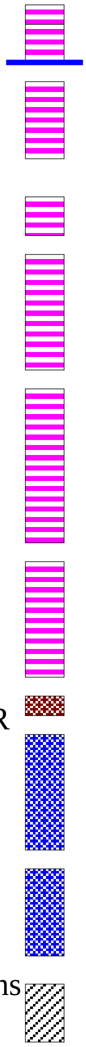
heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML13/96

Easting: 649049 **Northing:** 6250638 **Salt Storage (TSS t/ha):** 11866
Groundwater salinity (mS/m): 4770 **Water level below ground (m):** -2.9
Date: 15/5/96 **Slotted depth (m):** -41 to -43
Hydrological System: Very gentle to level plains.
Interpreted Lithology: 0-10 m Tertiary silt (Pallinup), 10-33 m grey Tertiary silt (Pallinup), 33-45.5 m fine greenish sandy clay, (*in situ* weathered dolerite), 45.5 m dolerite bedrock.

Drilling log



0-1.5 m silty clay 10YR 7/6 (yellow)
1.5-4 m silty clay 2.5Y 7/0 (light grey)
4-7 m silty clay 10YR 8/4 (very pale brown)

7-10 m silty clay 5YR 8/3 (pink)

10-16 m silty clay 10YR 5/2 (greyish brown)

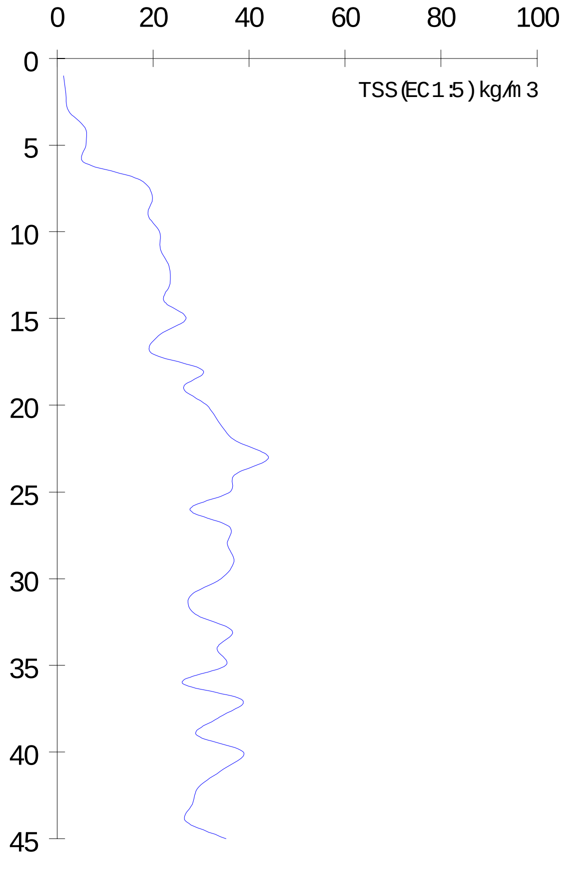
16-25 m silty clay 10YR 7/2 (white)

25-32 m fine silty clay 10YR 8/2 (white)

32-33 m fine silty clay with very coarse semi- rounded quartz and sandstone 10YR 8/2 (white)
33-40 m fine silty clay 5G 5/2 (greyish green)

40-43 m fine silty clay 10YR 8/2 (white)
43-45.5 m fine silty clay with coarse grains of dolerite in it 5G 5/2 (greyish green)

Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered material
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML14/96

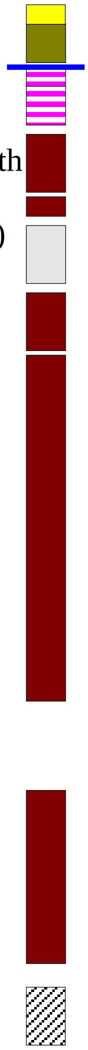
Easting: 648700 **Northing:** 6248470 **Salt Storage (TSS t/ha):** 4558
Groundwater salinity (mS/m): 4120 **Water level below ground (m):** -2.08
Date: 16/5/96 **Slotted depth (m):** -9.7 to -11.7
Hydrological System: Very gentle to level plains.
Interpreted Lithology: 0-10 m Tertiary silt and fine sand (Pallinup), 10-35 m reddish sandy clay with rounded sand grains (sediments derived from nearby Gabbro), 35 m bedrock.

Drilling log

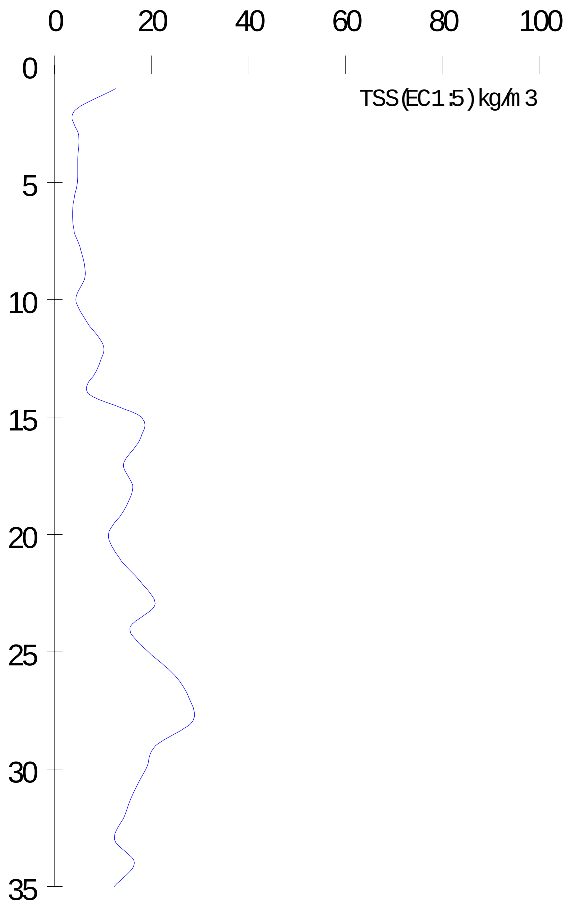
0-1 m fine sand 10YR 8/2 (white)
1-2.5 m silty heavy clay 10YR 8/4 (very pale brown)
2.5-3.5 m silty clay 10YR 8/1 (white)
3.5-4 m sandy clay 10YR 8/1 (white) with mottles 7.5YR 5/8 (strong brown)
4-7 m clayey fine sand 10YR 8/1 (white)
7-8 m sandy light clay 10YR 7/2 (white)
8-10 m sand 10YR 7/2 (white)
10-13 m fine sandy clay 5R 4/1 (dark reddish grey)
13-28 m sandy heavy clay 5R 6/2 (pale red)

28-35 m sandy heavy clay 5R 4/1 (dark reddish grey)

35 m bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

ML15/96

Easting: 650309 **Northing:** 6247089 **Salt Storage (TSS t/ha):** 3359
Groundwater salinity (mS/m): 3910 **Water level below ground (m):** -12.19
Date: 16/5/96 **Slotted depth (m):** -21 to -23
Hydrological System: Catchment Divides.
Interpreted Lithology: 0-5 m Alluvial and colluvial sediments (Quaternary), 5-23 m fine silty clay, *in situ* weathered fine grained granitic material, 23 m fine grained granitic bedrock.

Drilling log

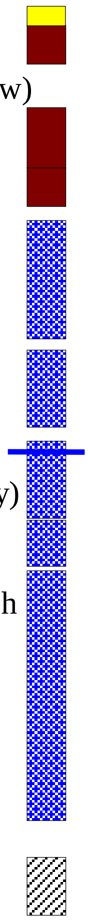
0-0.5 m clayey fine sand 10YR 8/6 (yellow)
0.5-2 m fine sandy clay 10YR 7/8 (yellow)
2-4 m fine sandy clay 10YR 8/1 (white) with mottles 2.5YR 5/6 (red)
4-5 m fine sandy clay 10YR 8/1 (white)
5-9 m fine silty clay 10YR 8/1 (white)

9-12 m fine silty clay N6 (grey)

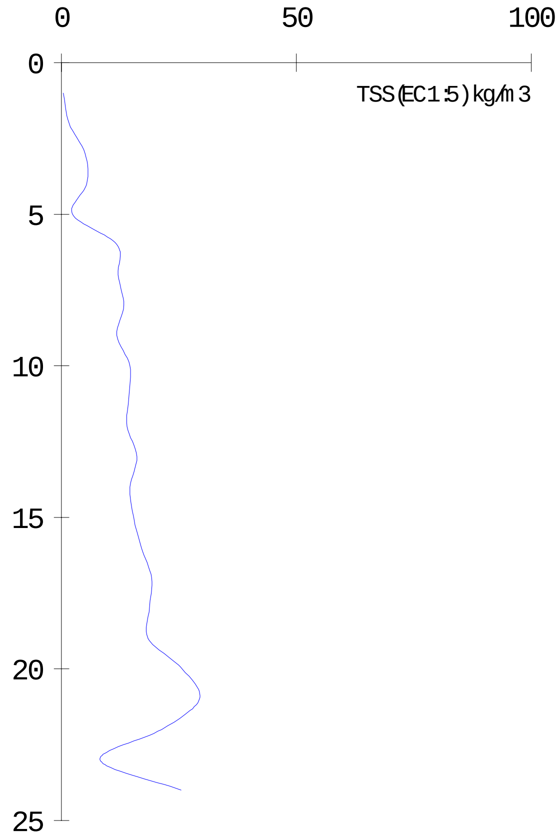
12-14 m fine silty clay N5 (grey)
14-15 m fine silty clay 5Y 7/1 (light grey)

15-23 m fine silty clay 5GY 6/1 (greenish grey)

23 m bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered material
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML16/96

Easting: 648686 **Northing:** 6241747 **Salt Storage (TSS t/ha):** 3325
Groundwater salinity (mS/m): 5750 **Water level below ground (m):** -2.00
Date: 16/5/96 **Slotted depth (m):** -12 to -14
Hydrological System: Plains with swampy floors.
Interpreted Lithology: 0-1.5 m Alluvial and colluvial material, 1.5-10 m Tertiary silt (Pallinup), 10-13.8 m *in situ* coarse-grained granitic material, 13 m bedrock.

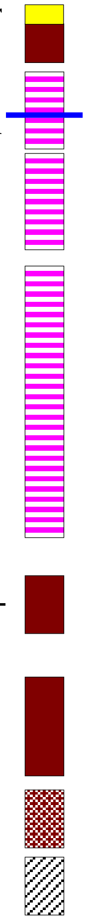
Drilling log

0-0.5 m fine sand with no organic matter 10YR 7/1 (white)
0.5-1.5 m heavy clay 10YR 7/1 (white)
1.5-3 m silty clay 10YR 8/1 (white) with mottles 2.5YR 5/6 (red)
3-5 m silty clay 10YR 8/1 (white)

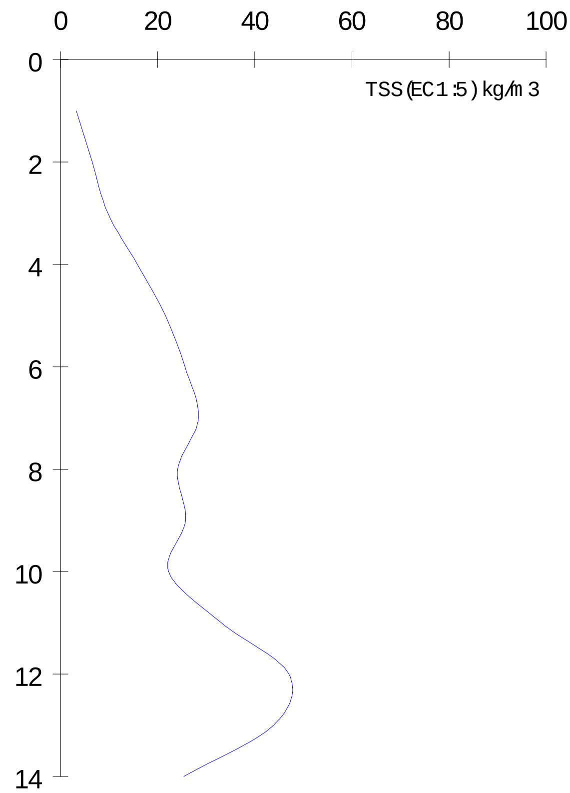
5-10 m silty clay 5YR 7/2 (pinkish grey) added water at 8m

10-11 m sandy clay 5YR 8/2 (pinkish white) with some semi-rounded quartz 2-4mm
11-13 m sandy clay 5YR 8/2 (pinkish white) with quartz up to 10mm

13-13.8 m coarse clayey sand 10YR 8/2 (white)
13.8 m bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay material
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML17/96

Easting: 651025 **Northing:** 6244074 **Salt Storage (TSS t/ha):** 1842
Groundwater salinity (mS/m): 5100 **Water level below ground (m):** -2.20
Date: 16/5/96 **Slotted depth (m):** -12 to -14
Hydrological System: Very gentle to level plains.
Interpreted Lithology: 0-14 m *in situ* weathered granitic material, 14 m bedrock.

Drilling log

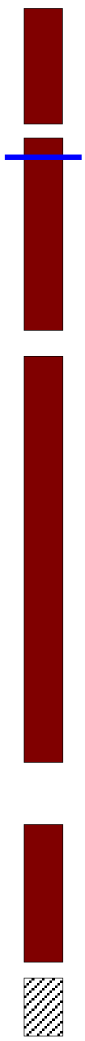
0-2 m heavy clay 10YR 6/2 (light brownish grey)

2-5 m sandy clay 10YR 8/2 (white) sand < 0.8mm diameter

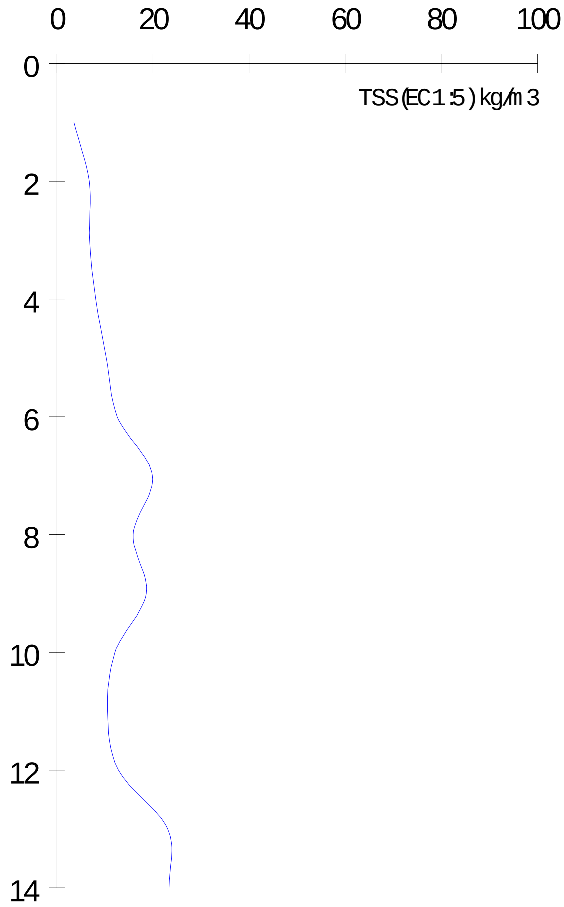
5-12 m sandy clay 10YR 8/1 (white)

12-14 m sandy clay 10YR 7/1 (white)

14 m bedrock



Salt Storage Profile



Legend			
	heavy sandy clay, sandy clay		hardpan
	coarse sandy clay		*in situ* weathered material
			water-table
	heavy silty clay		bedrock
	reddish or pinkish silt, silty clay		coarse sand
	fine sand, loamy sand, loamy clay sand		lignite

Drilling Log Mills Lake 1996

ML18/96

Easting: 650977 **Northing:** 6243065 **Salt Storage (TSS t/ha):** 396
Groundwater salinity (mS/m): 6380 **Water level below ground (m):** -6.14
Date: 16/5/96 **Slotted depth (m):** -5 to -7
Hydrological System: Catchment Divides.
Interpreted Lithology: 0-7 m *in situ* weathered granitic material, 7 m bedrock.

Drilling log

0-1 m sandy heavy clay 10YR 7/2 (white)

1-1.5 m sandy heavy clay 2.5YR 5/6 (red)

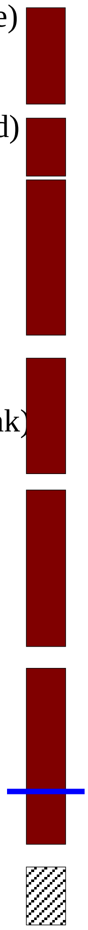
1.5-3 m medium clayey sand 10YR 8/1 (white)

3-4 m medium clayey sand 5YR 7/3 (pink)

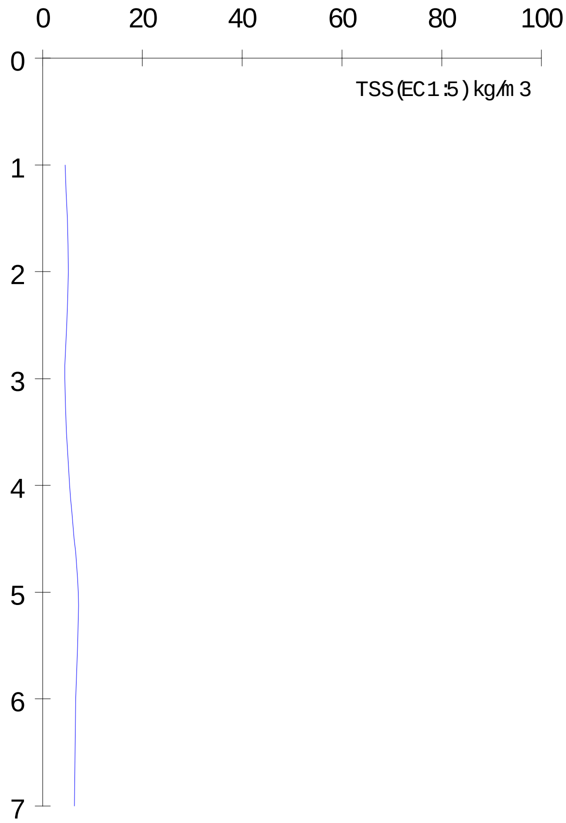
4-5.5 m medium clayey sand 2.5Y 7/2 (light gray)

5.5-7 m medium clayey sand 10YR 6/6

7 m bedrock



Salt Storage Profile



Legend

- heavy sandy clay, sandy clay
- coarse sandy clay
- heavy silty clay
- reddish or pinkish silt, silty clay
- fine sand, loamy sand, loamy clay sand
- hardpan
- *in situ* weathered material
- water-table
- bedrock
- coarse sand
- lignite

Drilling Log Mills Lake 1996

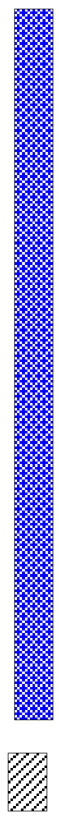
ML19/96

Easting: 649206 **Northing:** 6253822 **Salt Storage (TSS t/ha):** 338
Groundwater salinity (mS/m): dry **Water level below ground (m):** dry
Date: 17/5/96 **Slotted depth (m):** no pipe installed
Hydrological System: Catchment Divides.
Interpreted Lithology: 0-4.2 m *in situ* weathered granitic material, 4.2 m bedrock.

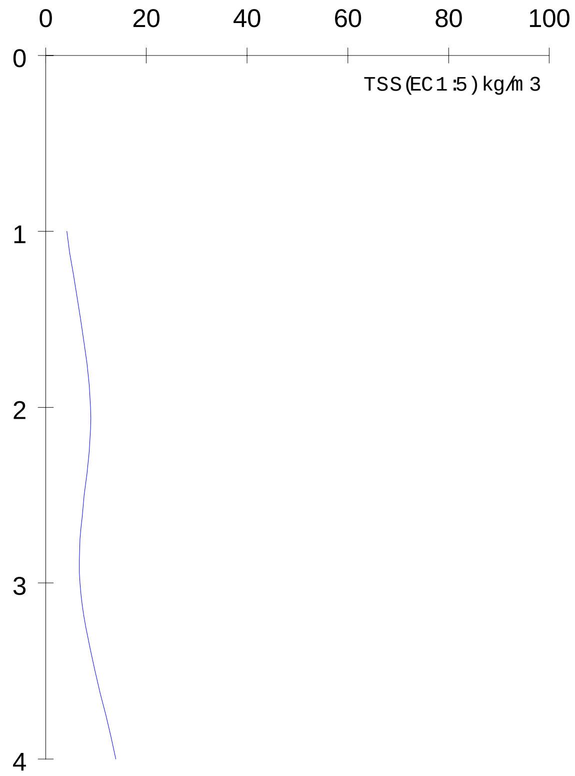
Drilling log

Salt Storage Profile

0-4.2 m *in situ* weathered granite



4.2 m bedrock



Legend

heavy sandy clay, sandy clay
coarse sandy clay material
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered
water-table
bedrock
coarse sand
lignite

Drilling Log Mills Lake 1996

ML20/96

Easting: 649289 **Northing:** 6254110 **Salt Storage (TSS t/ha):** 2783
Groundwater salinity (mS/m): 6100 **Water level below ground (m):** -17.35
Date: 18/5/96 **Slotted depth (m):** -18 to -20
Hydrological System: Catchment Divides.
Interpreted Lithology: 0-12 m Tertiary sediments (Pallinup silt), 12-20 m *in situ* weathered coarse grained granitic material, 20 m bedrock.

Drilling log

0-1 m heavy clay 5Y 6/1 (grey)
1-2 m heavy clay 5Y 6/1 (grey) with 60% mottles 7.5R 6/4 (pale red)
2-4 m silty clay 10YR 8/1 (white) with 20% mottles 7.5R 6/4 (pale red)
4-7 m silty clay 10YR 8/3 (very pale brown)

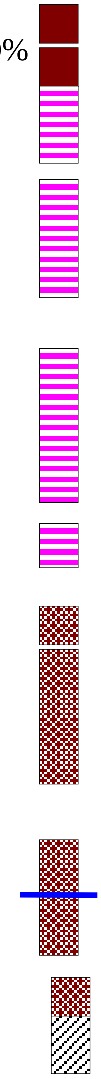
7-11 m silty clay 10YR 8/1 (white)

11-12 m silty clay 5GY 6/1 (greenish grey)

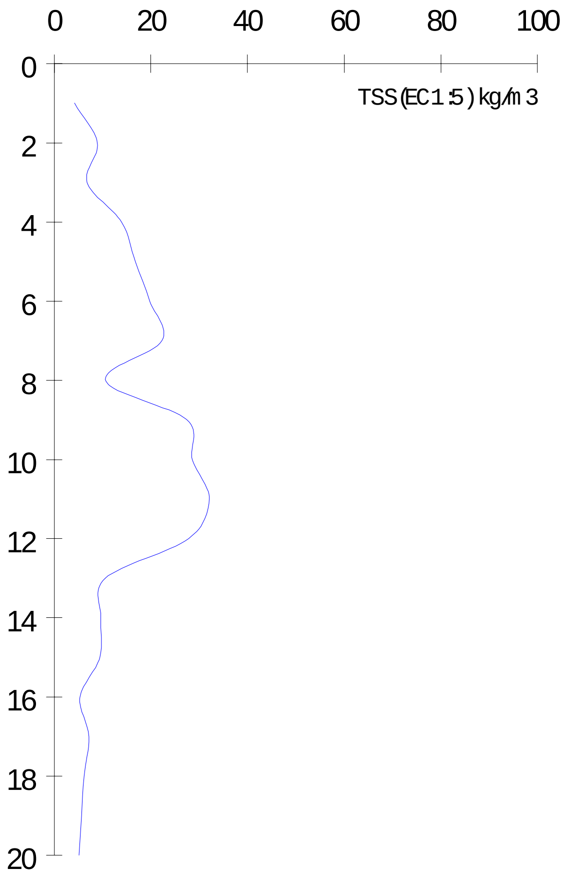
12-13 m coarse sandy clay 10YR 8/2 (white)
13-16 m clayey coarse sand 7.5YR 6/4 (light brown)

16-19 m clayey coarse sand 10YR 6/3 (pale brown)

19-20 m clayey coarse sand 10YR 7/2 (white)
20 m bedrock



Salt Storage Profile



Legend

heavy sandy clay, sandy clay	hardpan
coarse sandy clay	*in situ* weathered material
	water-table
heavy silty clay	bedrock
reddish or pinkish silt, silty clay	coarse sand
fine sand, loamy sand, loamy clay sand	lignite

Drilling Log Mills Lake 1996

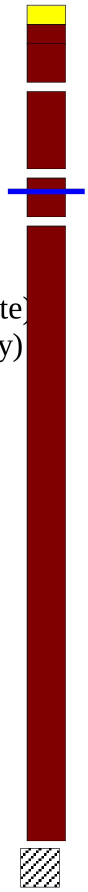
ML21/96

Easting: 641263 **Northing:** 6255987 **Salt Storage (TSS t/ha):** 4710
Groundwater salinity (mS/m): 5610 **Water level below ground (m):** -7.51
Date: 17/5/96 **Slotted depth (m):** -8.6 to -10.1
Hydrological System: Ancient drainage valleys.
Interpreted Lithology: 0-3.5 m sandy clay built up by wind deposition, 3.5-8 m silty clay, Tertiary silt, clay and fine sand (Pallinup), 8-34 m dark clayey fine to medium sand (Pallinup Formation), 34 m bedrock.

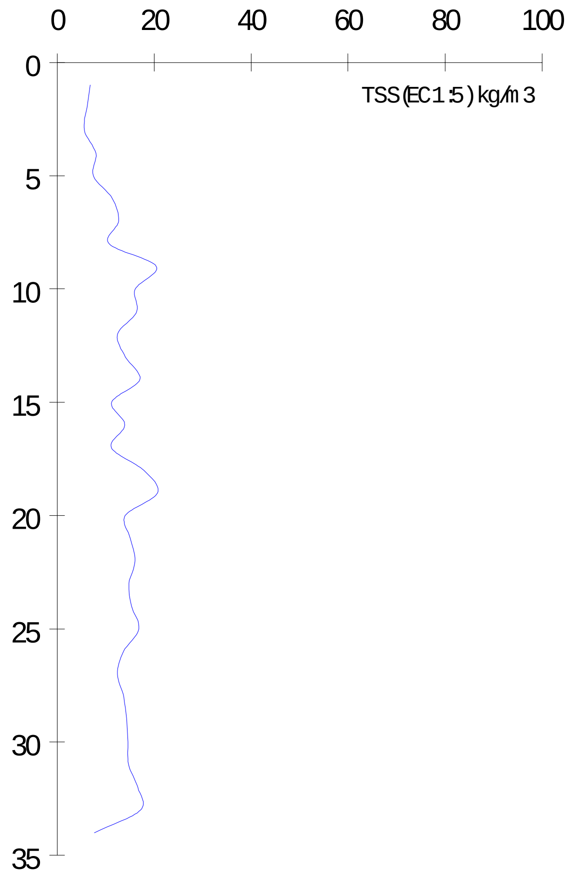
Drilling log

0-0.2 m loamy sand 10YR 4/2 (dark greyish brown)
0.2-1 m sandy clay 10YR 7/3 (very pale brown)
1-3.5 m sandy heavy clay 5GY 6/1 (greenish grey)
3.5-7 m sandy heavy clay 10YR 8/8 (yellow)
7-8 m heavy clayey sand 10YR 8/2 (white)
8-34 m clayey sand 10YR 4/1 (dark grey)

34 m bedrock



Salt Storage Profile



Legend

	heavy sandy clay, sandy clay		hardpan
	coarse sandy clay		*in situ* weathered material
			water-table
	heavy silty clay		bedrock
	reddish or pinkish silt, silty clay		coarse sand
	fine sand, loamy sand, loamy clay sand		lignite

Drilling Log Mills Lake 1996

ML22/96

Easting: 639410 **Northing:** 6258172 **Salt Storage (TSS t/ha):** 1108
Groundwater salinity (mS/m): 4490 **Water level below ground (m):** -4.2
Date: 17/5/96 **Slotted depth (m):** -11 to -13
Hydrological System: Ancient drainage valleys.
Interpreted Lithology: 0-8 m Tertiary silt and clay (Pallinup), 8-14 m clayey sand (Pallinup), >14 m bedrock.

Drilling log

0-2 m silty heavy clay 5Y 6/1 (grey)

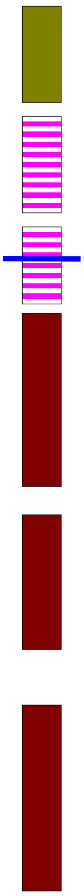
2-3.5 m silty clay 5Y 7/1 (light grey)

3.5-5 m silty clay 5G 6/1 (greenish grey)

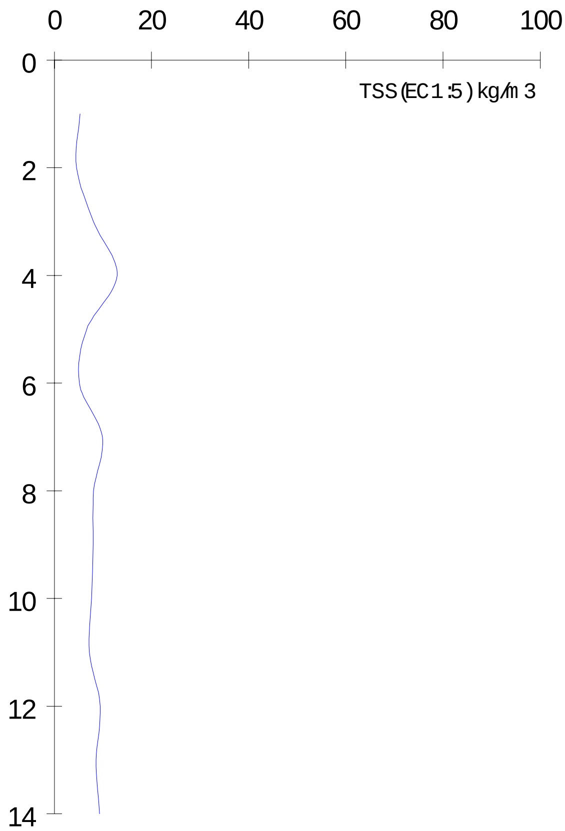
5-8 m heavy clay 5Y 7/1 (light grey)

8-11 m clayey heavy sand 10YR 8/6 (yellow)

11-14 m clayey heavy sand 10YR 8/2 (white)



Salt Storage Profile



Legend

heavy sandy clay, sandy clay
coarse sandy clay material
heavy silty clay
reddish or pinkish silt, silty clay
fine sand, loamy sand, loamy clay sand
hardpan
in situ weathered
water-table
bedrock
coarse sand
lignite