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R Ferdowsian

A T. Ryder

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R. Ferdowsian
A. Ryder

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Table of Contents

Summary

Background, objectives and method

The Wamballup Swamp Catchment is 80 km north-west of Albany and covers the south-eastern corner of the Upper Kent Catchment.

Clearing the land for agriculture has increased runoff, flooding and the extent and severity of soil salinity.

The farmers in the catchment are keen to control salinity. The Department of Conservation and Land Management (CALM) also has special interests in this area because of the existence of an "A" class wetland that is in danger of salinisation. Because of the above factors, Agriculture WA considers this area a priority catchment. We have been called to investigate the salinity and hydrology of the area. This report is the result of our study. It contains recommendations and management options that will help reverse the salinity trend in the area.

The method 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 rainfall zones.

Landform Patterns and Hydrological Systems

There are 9 landform patterns (LFPs) in the study area and we have grouped them into five hydrological systems (HS; in bold):

- Broad crests and Gently undulating plains are in the Catchment Divides;
- Gently undulating plains with saline depressions and Very gently undulating plains are in the Plains with swampy floors;
- Lowland flats with well-defined drainage and Stagnant alluvial or sedimentary flats are in the Swampy terrains that have extremely low relief;
- Tertiary Floodplains and Flat-bottomed valleys with lake systems are in the Ancient drainage valleys;
- Lakes.

Geology

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

Salt storage

Salt storage varies between the HSs. In the Catchment divides, which have moderately shallow profiles, salt storages are generally low (<500t/ha). The highest salt storages (>3000t/ha) are in the Swampy terrains, which have deep clayey profiles.

Groundwater salinity

Groundwater salinity in the study area varied between 520 mS/m and 2500 mS/m. The aquifer under the Wamballup Swamp had the lowest salinities. The highest salinities were in bores that were in granitic areas near the catchment divides. These areas had low salt storages and coarse aquifer material.

Groundwater levels

The areas that are near the catchment divides have developed a permanent aquifer since clearing and their groundwater levels have risen between 5 and 6 m during that period. Groundwater levels in the other areas have risen by between 1.4 (near discharge sites) and 6.0 m (away from discharge sites) during the same period. In the Catchment divides and Plains with swampy floors, the rate of rise may be >0.20 m/annum. In the lower part of the catchment, groundwater levels are close to the soil surface and are discharging through root zones and capillary voids.

Aquifers

Areas near the Catchment Divides have local aquifers that are separated by granitic highs. The salinity and rising groundwater in these areas are on-site issues and may be controlled by respective landholders. Aquifers in other areas are regional ones. Salinity in areas with regional groundwater, is affected by both on-site and off-site management.

Hydrology of the Wamballup Swamp

The salinity of groundwater under Wamballup Swamp was 520 mS/m which is the freshest groundwater in the study area, but it is being replaced by more saline groundwater. The lake water is perching about 1 m above the present groundwater levels. This situation will change in future if groundwater levels rise above their present levels. The salinity of nine out of thirteen water samples from the lake was between 400 and 800 mS/m. The salt in the lake is mostly due to salty baseflow that is generated from the areas immediately to the east of the reserve.

Recharge

In a year with average rainfall (560 mm), about 70 mm of the annual rainfall bypasses the root zone of crops and adds to the groundwater. Recharge will be about 110 mm in wet years and about 45 mm in dry years.

Potential salinity

Large areas of some of the landform patterns in the study area may eventually become salt-affected. Without changes to the present management system, more than 27% of the catchment may become salt-affected.

Waterlogging

Between May and mid-August the rainfall in the study area exceeds the potential evaporation and there is widespread in situ waterlogging. Approximately 73% of the catchment is affected by waterlogging in typical years. The extent of waterlogging varies with the type of landform pattern. Waterlogged areas recharge the aquifer. Preventing waterlogging will reduce the final extent of salinity.

General management options to reduce recharge and the extent of salinity

Degradation problems in the Wamballup Swamp area are catchment issues. The best results will be achieved if management options are applied throughout the area. Patchwork solutions may have a localised effect but will not address the problem at a catchment level.

General management options to reduce recharge and the extent of salinity are discussed in the report. The topics include:

- 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; and
- pumping saline groundwater and discharging it into the creeks.

Specific management options

Specific management options that reduce recharge and the extent of salinity are related to HSs and LFPs. We suggest that the landholders find out which kind of landform patterns and hydrological systems they have and then read about specific management options that relate to their area.

1. Background

The Wamballup Swamp Catchment (WSC) is 80 km north-west of Albany (Figure 1) and covers the south-eastern corner of the Upper Kent Catchment. The WSC covers 6790 ha and approximately 85% is cleared. It contains a historical memorial site (37 ha) and the Wamballup Swamp Reserve (112 ha) which contains an A class wetland. This wetland, which is called Wamballup Swamp, is experiencing higher water levels than pre-clearing. These high water levels have changed the swamp to a permanent lake.

Average annual rainfall in the study area is 560 mm. Eighty percent of this falls between May and October. The annual precipitation in 30% of years (decile 3) falls below 530 mm and in 20% of years (decile 8) exceeds 680 mm.

Before land clearing, we believe the area was in a hydrological equilibrium. There was probably very little runoff and almost all of the annual rainfall was used by the natural vegetation. Since the land has been cleared for agriculture (approx. 50 years ago), the annual pastures and crops have not been using and intercepting as much of the rainfall as the natural vegetation. Consequently there has been more runoff, more flooding and recharge (which has caused groundwater levels to rise) and increased groundwater discharge. The rising groundwater levels have mobilised the salt which was stored in the soil profile. Groundwater levels in many low-lying parts of the catchment are now close to the ground surface. Saline groundwater is discharging through salt seeps and broad flats that have become salt-affected. Farmers fear, and it has been predicted (Evans et al., 1995), that without changes to the present management practices, many more parts of the study area will become salt-affected.

The farmers in the catchment area have formed an active group and want to control salinity. The Department of Conservation and Land Management has special interests in this area because of the A class wetland that is in danger of becoming saline. Because of the above factors, Agriculture WA considers the Wamballup Catchment a priority catchment.

We have been called to investigate the salinity and hydrology of the area and suggest management options that can help to reverse the salinity trend in this catchment. This report is the result of our salinity and hydrology study of the area.

2. Objective of this study

The objective of this study was to develop management strategies to overcome land degradation problems, especially salinity, in the catchment. To achieve this it was necessary to understand the hydrology of the catchment and suggest appropriate management options. To understand the hydrology of the catchment, it was necessary:

- to find if the aquifer is regional or local, which may affect the treatments needed;
- to investigate the geology of the area. Are there any sediments and palaeochannels in the area?
- to document the present groundwater levels and salinities in the study area;
- to facilitate future monitoring of the changes in groundwater levels and salinities and any effect that treatments may have;
- to compare the groundwater levels and salinities of various landform patterns LFPs) in the study area which have been mapped (Figure 2) by Ruhi Ferdowsian;
- to estimate the levels of groundwater near the wetlands and predict their effect on the health of wetland fringe vegetation;
- to predict any effect that deep drains would have on groundwater levels of the *Stagnant Flats* and *Tertiary Floodplains*;
- to investigate any effect that natural vegetation around Wamballup Swamp has on groundwater levels;
- to recommend sites for commercial and non-commercial trees;
- to identify areas that are in danger of becoming saline if left untreated;
- to recommend management options that will help reverse the salinity trend in the area.

Because salinity and hydrological properties vary from one landform pattern (LFP) to another, we have related these attributes to the LFPs of the study area.

3. Methods and Materials

- Landform pattern maps of the area that had been produced previously;
- Interpretation of aerial photographs to define areas in immediate danger of salinity and determine drilling sites;
- One metre contour maps to delineate the natural drainage lines and determine the elevation of the drilling sites;
- Ten deep bores (Figure 1) were drilled to bedrock and the geology described. Soil samples were taken every metre and their salt content measured.
- Salt storage profiles of the deep bores were interpreted to estimate the groundwater levels before clearing.
- Eight holes were drilled by the land holders (Appendix 2). These holes were used to find groundwater levels and salinities.
- Interpretation of Total Magnetic Intensity maps (Bureau of Mineral Resources; BMR).

Drilling method and profiles

Bores were sited (Figure 1) using aerial photographs and LFPs and then drilled using a Gemco HM12 Rotary Air Blast drill rig. All the holes were cased with 40 mm PVC pipe (piezometers with 2 m of slotted pipe) for future monitoring. Drill logs of these holes (WS1/96 to WS10/96) are presented in Appendix 1. These logs show groundwater levels and salinities, salt storage, depth to bedrock and lithology

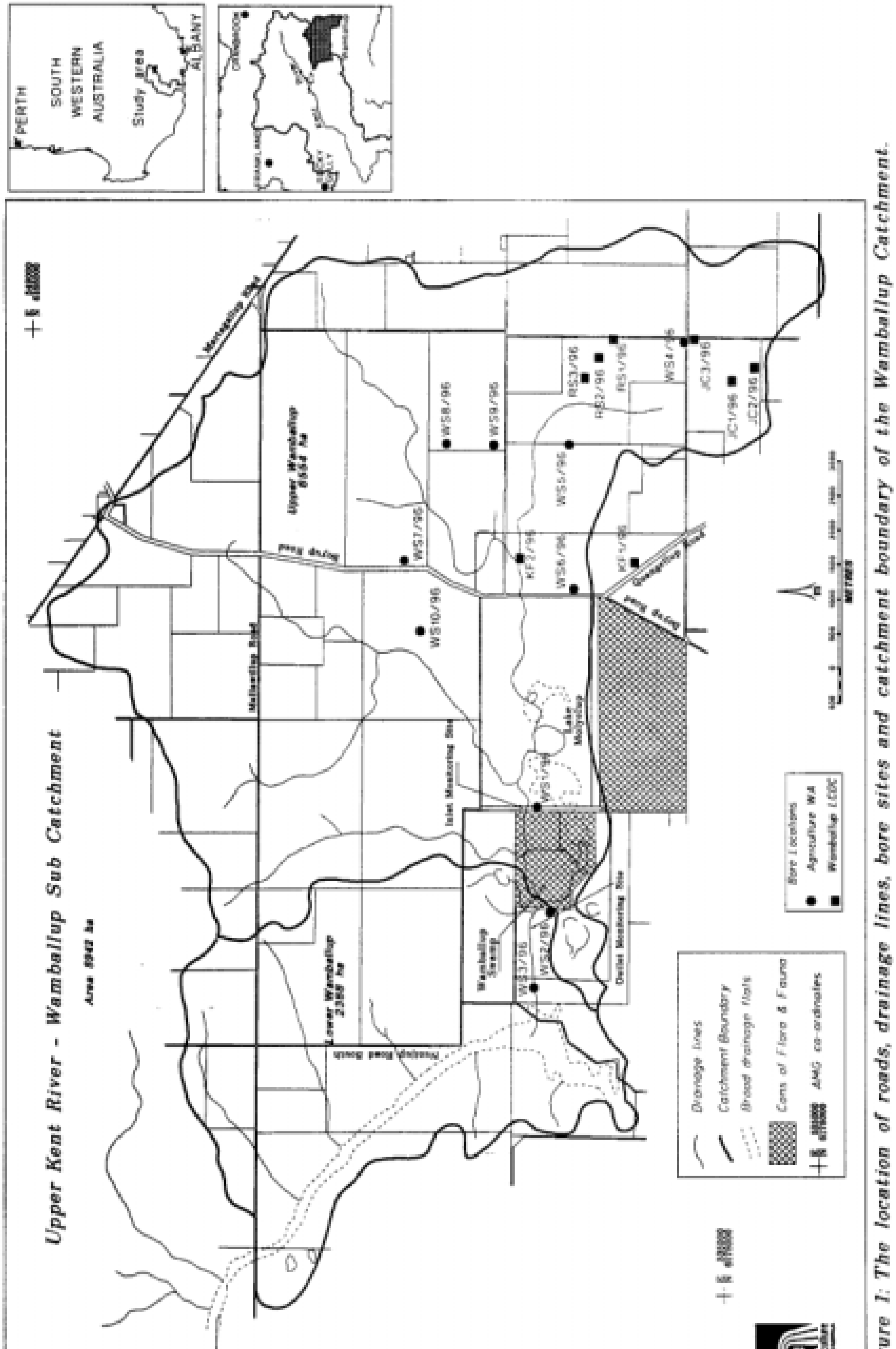


Figure 1: The location of roads, drainage lines, bore sites and catchment boundary of the Wamballup Catchment

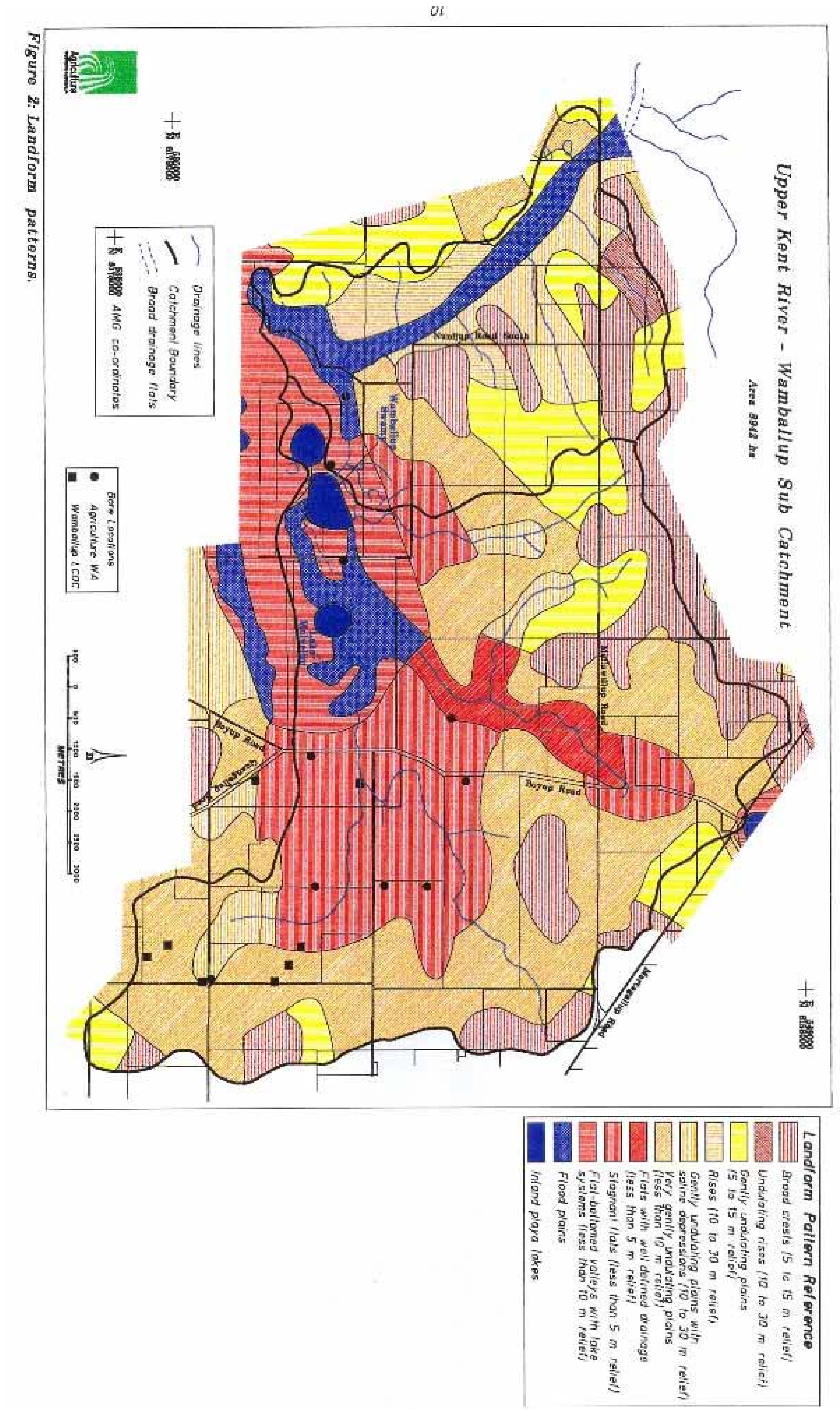


Figure 2: Landform patterns

4. 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 degradational problems associated with its use (Figure 2).

Hydrological systems (HS) are combinations of LFPs that have similar hydrological properties and may be grouped together as one unit. The LFPs of the study area have been grouped into five hydrological systems: Catchment Divides; Plains with swampy floors; Swampy terrains; Ancient drainage valleys; and Lakes (Figure 3).

4.1 Catchment Divides

This group contains two LFPs (Table 1): *Broad crests* (BC) and *Gently undulating plains* (GUP). Landform patterns of this system have very low relief (5 m-30 m within a radius of about 300m). Their crests and slopes are eroded and they have aggraded open depressions that gradually become swampy downstream. Waterlogging is limited to the floors of open depressions and flat crests. Soil salinity is rare but these areas do contribute to salinity in the lower LFPs. Almost all of the areas are recharge areas, especially waterlogged sandy depressions. Thus these LFPs have higher recharge than the other LFPs in the study area. The underlying granitic rocks are shallow to moderately deeply (< 20m) weathered.

4.2 Plains with swampy floors;

This group is in mid-catchment positions and includes three LFPs: *Gently undulating plains with saline depressions* (GUSaP); and *Very gently undulating plains* (VGUP). These LFPs have continuous and active erosion and aggradation. Waterlogging and salinity are confined to the floors of their open depressions. Their groundwater is more saline than that of the *Catchment Divides* but less than that of the *Swampy Terrains* with extremely low relief. Saline groundwater reaches the surface in the depressions through root channels and spreads over the land causing soil salinity. The bedrock is moderately deep (10 to 20m) and only very few rock outcrops are found on the upper slopes. The attributes of these two LFPs are given in Table 2.

4.3 Swampy terrains that have extremely low relief

These LFPs have extremely low relief (< 10m). Stream channels are sparse to widely spaced and insufficient to drain the LFP. Erosion and aggradation is continuously active to frequently active. Salt storages and groundwater salinities of these LFPs are greater than those in other LFPs. Potentiometric levels of the groundwater are often above or near the soil surface. Groundwater comes to the surface through root channels and capillary pores causing soil and stream salinity. The underlying granitic rocks are deeply weathered and rock outcrops are very rare.

This group contains two LFPs with variable attributes (Table 3): *Lowland Flats with well defined drainage* (DraiF) and *Stagnant alluvial or sedimentary flats* (StF).

Table 1: Attributes of LFPs on Catchment Divides that have very low relief

Landform attributes	**Landform patterns**	
	Broad crests (BC) (12.2% of total area)	**Gently undulating plains (GUP) (6.7% of total area)**
Terrain	level to very gentle LFP standing above the adjacent areas	gently undulating LFP set on catchment boundaries
Landform Elements (LFEs)		
Typical	Plain	Gentle crest,
Common	Gentle crest	Slope, Open depression, Rock outcrops,
Occasional	Upper slope, Rock outcrops	Gully, Closed depression
Relief (m)	5 - 15	5 - 15
Modal terrain slope*	LE - VG	LE - VG
Channel development **	absent	absent
Channel or depression characteristic:		
spacing (m)***	absent	500 - 1200
pattern		tributary
Mode of geomorphological activities	eroded	eroded and aggraded
Status of geomorphological activities	continuously active	continuously active
Occurrence of rock outcrops	occasional	seldom to occasional (frequent in GUPRo)
Form of salinity and saline LFEs	none	very little; in lower part of their open depressions

Note: These abbreviations and symbols apply to the following four tables as well.

* Modal terrain slopes are: LE = level (< 1%); VG = very gently inclined (1%-3%); GE = gently inclined (3%-10%); MO = moderately inclined (10%-32%) and; ST = steep (>32%).

** Channel development is referred to existence of defined channelled flow in the major depressions of a LFP. Channel developments are:

absent = no traces of channelled flow;

incipient = has started (traces of channelled flow are very shallow, narrow and mostly discontinuous);

erosional = continuous linear channels occur (their width and depth are considerable).

*** As measured from 1:50 000 sheets

Table 2: Undulating LFPs in *Plains with swampy floors*

	Landform patterns	
Landform attributes	**Gently undulating plains with saline depressions (GUSaP)** **(3.6% of total area)**	**Very gently undulating plains (VGUP)** **(37.5% of total area)**
Terrain	gently undulating LFP with very gently inclined saline open depressions	level to VG undulating plains on catchment boundaries or lower slopes
Landform elements (LFEs)		
Typical	Hillslope, Slope, Saline valley flats	Gentle crest, Open depression, Plain
Common	Gentle crest, Upper slope	Valley flats
Occasional	Gully, Playa	Upper slope, Closed depression
Relief (m)	10 - 30	< 10
Modal terrain slope*	VG - GE	LE
Channel development *	absent to incipient	absent
Channel or depression characteristic:		
spacing (m)*	300 – 800	not defined
pattern	tributary	tributary
Mode of geomorphological activities	eroded and aggraded	eroded and aggraded
Status of geomorphological activities	continuously active	continuously active
Occurrence of rock outcrops	occasional on upper slopes	none
Form of salinity and saline LFEs	depressions and the adjacent LFEs	depressions

* Refer to footnotes of Table 1.

Table 3: LFPs in *Swampy terrains* that have extremely low relief

Landform attributes	**Landform patterns**	
	Flats with well defined drainage (DraiF) **(6.0% of total area)**	**Stagnant flats (StF)** **(22.7% of total area)**
Terrain	level flats or plains on lower slopes that are dissected by gullies and streams	wide, level flats that have no defined streams
LFEs:		
Typical	Stream channel, Valley flats	Valley flats
Common	Plain, Saline valley flats	Saline valley flats
Occasional	Gentle crest, Footslopes, Gully, Open depression, Playa	Gentle crest, Stream channel, Gully, Open depression, Playa
Relief (m)	< 5	< 5
Modal terrain slope*	LE	LE
Channel development*	Incipient	absent
Channel or depression characteristic:		
spacing (m)*	not applicable	not applicable
pattern	not applicable	not applicable
Mode of geomorphological activities	eroded and aggraded	eroded and aggraded
Status of geomorphological activities	frequently active	frequently active
Occurrence of rock outcrops	None	none
Form of salinity and saline LFEs	lower flats	lower flats

* Refer to footnotes of Table 1.

4.4 Ancient drainage valleys;

This group is formed on Tertiary material and includes two LFPs:

- *Tertiary Floodplains* which resemble *Swampy terrains* and have extremely low relief (< 10m). *Tertiary Floodplains* have no defined stream channels and runoff inundates most of these areas. Inundation and salinity hazards of this LFP are greater than those of the other LFPs.
- *Flat-bottomed valleys with lake systems* resemble the LFPs with swampy floors. Their depressions are swampy and salt-prone but their other areas may be gently to very gently undulating.

The attributes of these two LFPs are presented in Table 4.

Areas of this HS have a complete Tertiary Profile (ie. all sequences of Tertiary sediments are present). The profiles consists of Pallinup Siltstone (between 7 to 10 m deep), over Werillup Formation lignite (< 1 m thick) over Werillup coarse sand. The coarse sandy layer has a very high hydraulic conductivity. This HS (*Flat-bottomed valleys with lake*), not only covers the south-western part of the study area but it continues further south covering Kwornicup Lake. We expect that the area of Tertiary sediments is large and may include Kwornicup Lake. Thus the aquifer of the study area extends far beyond the physical catchment boundary and includes that of Kwornicup Lake.

4.5 Lakes

Lakes cover 1.6% of total the area and include all closed water bodies that are more than 500 m in diameter.

5. Physiography and Geology

Tertiary sediments that are found in some parts of the study area consist of the Werillup Formation and overlying Pallinup Siltstone. The Werillup Formation was first deposited over bedrock in a swampy environment. These sediments consist of lignite (dark-coloured clayey silt that has high organic material) and medium to coarse sand. The dark-coloured silt usually overlies the sand. The sand has mostly coarse grains and a higher hydraulic conductivity than the silts and clay. The lowest layer of the Werillup Formation may contain very coarse material including rounded pebbles that were 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 underlain by moderately deep Tertiary sediments. Occasional sinkholes may appear in areas that have thick spongolite because lime, which was in the spongolite, has been leached out leaving behind cavities.

Table 4: Attributes of landform patterns which are in the *Ancient drainage valleys*

Landform attributes	Landform patterns	
	Tertiary Floodplains (FIP) **(3.9% of total area)**	**Flat-bottomed valleys with lake systems (Vlak)** **(6.1% of total area)**
Terrain	aggraded and eroded floors of the lateritic plateau or alluvial flats	flats in palaeo-channels with saline lakes
LFEs:		
Typical	Saline valley flats, Closed depression	Lakes, Valley flats, Gentle crest, Open depression
Common	Open depression and Playa	Closed depression, Playa, plain, Saline valley flats
Occasional	Gully	Stream channel, swamp, Lunette
Relief (m)	< 5	< 10
Modal terrain slope*	LE	LE -VG
Channel development *	absent to incipient (and migrating)	absent
Channel or depression characteristic:		
Spacing (m)*	not applicable	not applicable
Pattern	non-tributary to uni-directional	not applicable
Mode of geomorphological activities	eroded and aggraded	eroded and aggraded
Status of geomorphological activities	continuously active	continuously active
Occurrence of rock outcrops	none	none
Form of salinity and saline LFEs	all affected or potentially affected	lakes and swampy floors

* Refer to footnotes of Table 1.

5.1 Physiography

There are two faults and two sets of shear zones that affect the hydrology of the area (Figure 4). The faults probably existed before the Tertiary sediments were deposited. The first one is about 1.5 km wide, has an east-west orientation and crosses the Boyup Road north of the Boyup and Quangellup (Eulup) Roads (Figure 4). The second fault has a NE-SW orientation and passes through the Martagallup Lake and Martagallup Swamp which are north of the Boyup and Martagallup Road crossing (Figure 4). Further south this fault passes through Kwornicup Lake.

The second fault is composed of a few discontinuous but parallel faults that appear to be displaced by westward movement of the area. Major swamps and deep Tertiary sediments of the study area coincide with the intersection of the two faults. It seems that deep depressions had formed before the formation of these swamps that were later infilled by the Tertiary sediments (Figure 5). The top of the Werillup Formation as identified by the dark silt (lignite), gains about one metre elevation as we go from the eastern boundary of the Wamballup Swamp Reserve to the western side. When deposited, this material presumably had the same elevation. The difference in elevation of the Werillup Formation and elevated bedrock at the outlet of the study area (Figure 5) shows that this area, at one time, has been uplifted.

5.2 Geology

The geology of the area can be related to the landform patterns and hydrological systems:

5.2.1. Geology of Catchment Divides (CD)

Landform patterns of this HS have developed on *in situ* weathered granitic and gneissic material. The weathering profiles are moderately shallow (<15m) and change from sand or loamy sand near the soil surface to sandy clay (or heavy sandy clay), to moderately weathered bedrock with coarse grit and then to bedrock.

5.2.2. Plains with swampy floors (PSF)

This HS is the transitional zone between *Catchment Divides* and *Swampy Terrains*.

Weathering profiles in the higher parts of this HS resemble the profiles in the *Catchment Divides* with layers of sandy clay over a thin layer of gritty material over the bedrock. Weathering is generally moderately shallow but in some areas can be moderately deep. The lower areas of this HS have a few metres of Pallinup silty clay near the soil surface. These sediments are often buried by about 1 - 1.5 m of sandy clay or sandy loam (alluvium). The alluvium is derived from the higher grounds, including the granitic hills, and has covered the Pallinup sediments during recent geological periods. WS4/96 is a good example of a weathering profile in these LFPs.

5.2.3. Swampy terrains (ST)

Flats with well defined drainage and *Stagnant flats* have deeply (>25m) weathered profiles that consist of 1 to 2 m of alluvium over 4 to 10 m of Pallinup Siltstone, over sandy clay (that is, *in situ* weathered material) over bedrock. The Pallinup clay and silts in these areas have weathered to very heavy silty clay which prevents movement of water. Bores WS5/96, WS6/96, WS7/96 WS8/96, WS9/96 and WS10/96 are typical of these profiles.

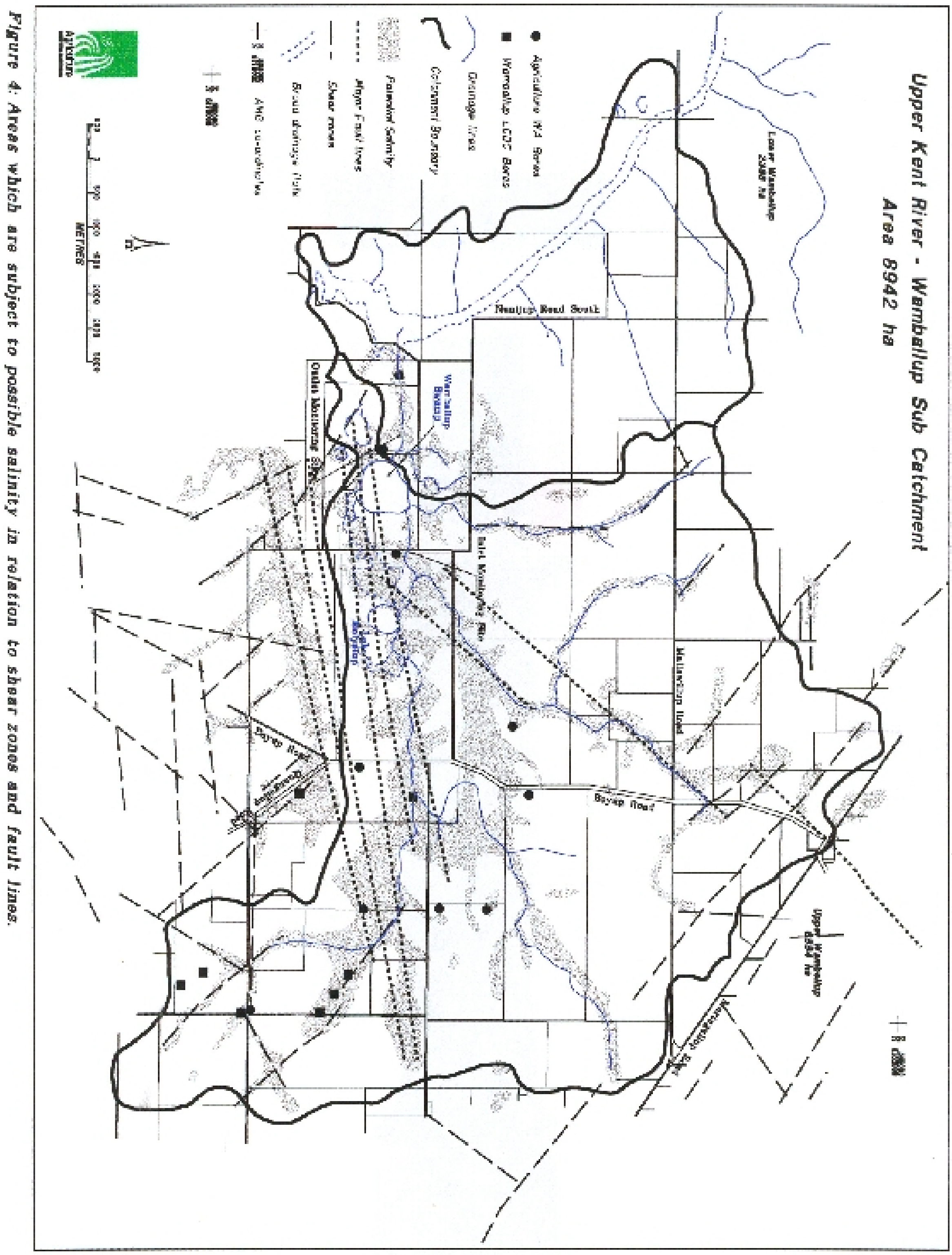


Figure 4: Salinity

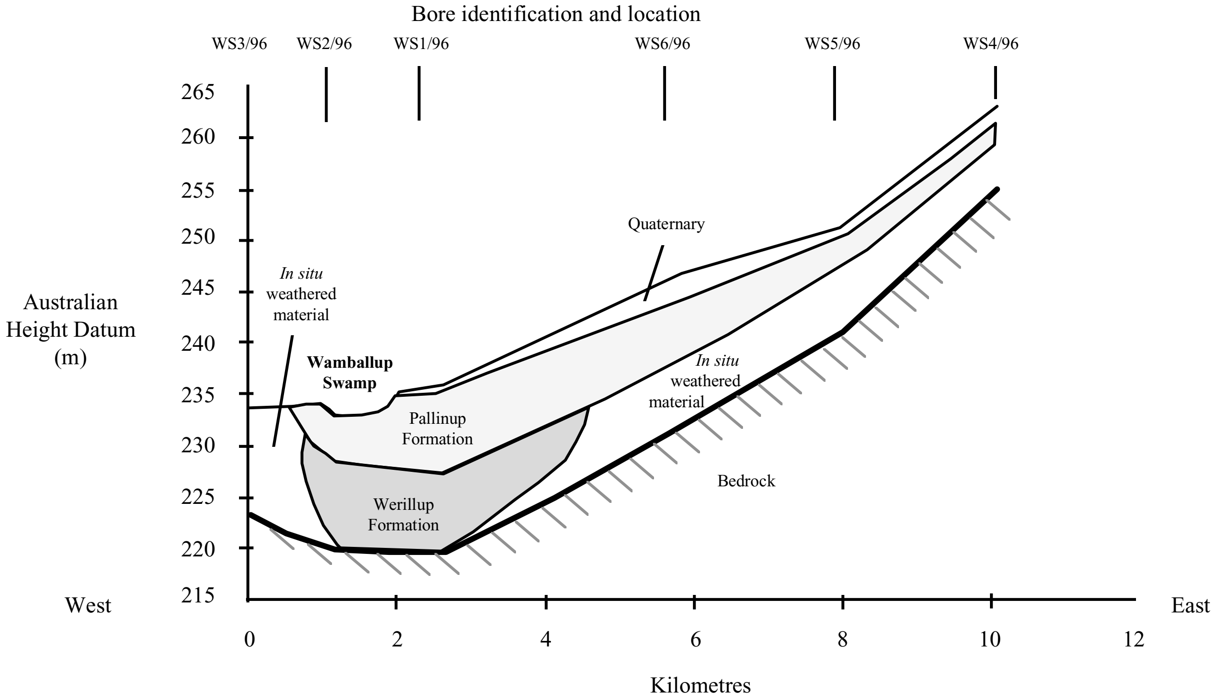


Figure 5: East-west cross-section of the study area showing variation in depth of sediments and in situ material. It also shows that at the outlet of the area (west), the bedrock is higher than under the Wamballup Swamp.

5.2.4. Ancient drainage valleys (ADV)

This HS covers *Tertiary Floodplains* and *Flat-bottomed valleys with lake systems*. These areas have a full Tertiary Profile of Pallinup silts (between 7 to 10 m depth) over Werillup lignite (< 1 m thick) over Werillup coarse sand. The coarse layer has a very high hydraulic conductivity and the holes yielded more than 1L of water per second. We expect that the soil profile in this zone is very deep (>25m). Bore numbers WS1/96 and WS2/96 are typical of this zone. The *Flat-bottomed valleys with lake systems* not only cover the south-western part of the study area but they continue further south covering Kwornicup Lake. We expect that the full Tertiary sediments continue under this LFP. Thus the aquifer which is in the study area extends far beyond the physical boundary of the catchment and reaches Kwornicup Lake

6. Salt storage

Salt storage varies from one HS to another. In the *Catchment divides* that have moderately shallow profiles, salt storages are generally low (<500 t/ha).

Most areas of the *Plains with swampy floors* have moderately low salt storages (500 to 1000 t/ha) but in some areas the soil profile is moderately deep and salt storage can reach 1500 t/ha.

Swampy terrains that have deep clayey profiles have high salt storages that can exceed 3000 t/ha.

Ancient drainage valleys and *Lakes*, despite having deep profiles, have only moderately high salt storages (1000 to 2000 t/ha). This is because the deep, coarse Werillup sands do not store much salt.

7. Groundwater salinity and hydrology

7.1. Groundwater salinities

Groundwater salinities varied between 520 mS/m and 2500 mS/m. The Werillup coarse sands (under the Wamballup Swamp) had the lowest groundwater salinities. This is probably because the high hydraulic conductivity of the aquifer allows the salt to be flushed out of the soil profile. The flushing has probably reduced salt storage and groundwater salinity further downstream.

In other areas, groundwater salinity varied between 850 and 2500 mS/m. The extreme salinities were in bores that had small salt storage, coarse sand and were near catchment divides (bore WS8/96 and WS9/96). This may be due to two factors:

- These areas did not have a permanent aquifer before clearing to flush the salt.
- The coarse layer can easily release the stored salt into the aquifer, which developed after clearing.

7.2. Groundwater levels

Groundwater levels were measured in early June 1996, which until then, had been a very dry season. Because of little rain and no recharge the groundwater had dropped to low levels. Thus the groundwater levels would have been higher than these levels if the rainfall had been normal.

We estimated pre-clearing groundwater levels by interpreting the salt storage profile. In the Upper Denmark Catchment (south-west of the study area), Ferdowsian and Greenham (1992) found that profiles less than 8 m deep had no permanent groundwater before clearing. The salt storage in the lower part of these profiles gradually increases down to the bedrock. However, in profiles deeper than 8 m, salt storage decreases just over the bedrock, where groundwater had existed before clearing.

Salt storage in profiles WS4/96 and WS8/96 in the study area increase gradually down to the bedrock. We assume that these two sites had no permanent groundwater before clearing. These two bores are 8 m and 7 m deep. Their present groundwater levels are at 2.15 and 2.10 m below ground level respectively. Thus both of these bores have developed a permanent aquifer since clearing and their groundwater levels have risen by 5 to 6 m during this period (about 35 years). We estimated that groundwater levels in the other areas have risen by between 1.4 and 6.0 m (Table 5). Bores with the smallest rise are near discharge sites.

Table 5: Pre-clearing and present groundwater levels in the study area and estimated rises

Bore number	Hydrological systems	Present groundwater levels (m)	Estimated pre-clearing groundwater levels (m)	Rise of groundwater levels since clearing (m)
WS1/96	ADV	1.13	4	2.90
WS2/96	ADV	1.39	3	1.60
WS3/96	PSF	1.68	8	6.30
WS4/96	PSF	2.15	>8	>6.00
WS5/96	ST	2.15	5	2.85
WS6/96	ST	3.40	6	2.60
WS7/96	ST	1.60	3	1.40
WS8/96	ST	2.10	>7	>5.00
WS9/96	ST	3.10	10	6.90
WS10/96	ST	0.08	5	4.90

Note: ADV = Ancient Drainage valleys; PSF = Plains with swampy floors; ST = Swampy terrains.

The present rate of groundwater rise depends on how far the bore is from a discharge site. In the lower part of the catchment, groundwater levels are close to the soil surface and are discharging through root zones and capillary voids. The rise in these areas is slow but groundwater levels show strong seasonal fluctuation (Figure 6A; 16 km west of the study area). In the **Catchment divides** and **Plains with swampy floors** (section 4 and 5.2) the rate of rise may be about 0.20 m/annum (Figure 6B; 15 km west of the study area).

7.3. Type and attributes of aquifers in the study area

The ***Catchment Divides*** have local aquifers (Appendix 3) that are separated by the granite highs (near catchment and subcatchment divides). However, aquifers in the ***Swampy terrains, Ancient drainage valleys,*** and the **Lakes** are regiona*l*. 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 presently in ***Plains with swampy floors*** will become regional.

In areas where the aquifer is a local one, the salinity and rising groundwater is an on-site issue. Therefore managing land outside the local aquifer will have little or no effect on that aquifer. However, the management of land with a local aquifer will affect others downstream. In contrast, salinity in areas with regional groundwater is affected by on-site as well as off-site management. Thus they are affected by farming practices on higher parts of the catchment.

7.4. Hydrology of the Wamballup Swamp and its relation to the regional aquifer

Groundwater salinity under Wamballup Swamp (bore WS2/96) was 520 mS/m which was the freshest groundwater in the study area. Groundwater salinity in bore WS1/96 (just east of the reserve), was 1140 mS/m. Hydraulic gradients show that the aquifer has a westerly flow direction. Thus the relatively fresh groundwater which is under the lake will eventually be replaced by more saline groundwater.

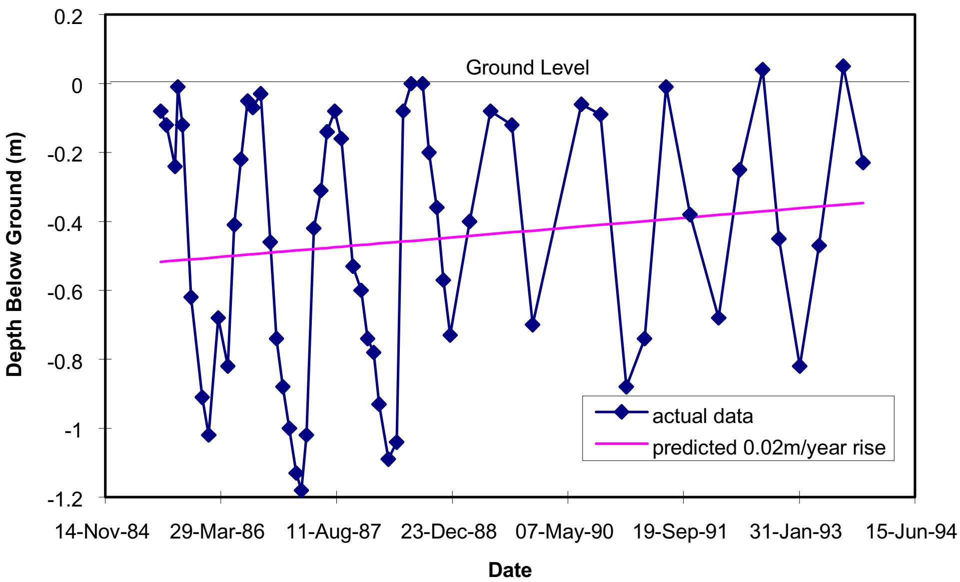
Based on interpolation between groundwater levels in bores to the east and west of the reserve, it was estimated that the groundwater level under the lake is between 233.30 m and 233.80 m (AHD). The one metre contour lines of the study area, and surface area of water in the lake as seen on the aerial photographs show that the water level in the lake is about 235.0 m (AHD; as at June 1996). Thus lake water is perching about 1 m above the present groundwater levels. This situation will change in future if groundwater levels rise above the present levels.

The salinity of water in the lake has been measured occasionally by the Water Authority of WA (WAWA) since 1981. The sampling site is the outflow of the lake which is 100 m north of bore WS2/96 (Figure 1). These measurements show that immediately after runoff, the lake is less saline but later, due to evaporation and salt concentration, salinity increases. Based on these measurements, the salinity of the lake has fluctuated between 280 mS/m and 1200 mS/m (Figure 7). Salinity of nine water samples out of thirteen were between 400 and 800 mS/m. Although these salinity levels are similar to groundwater salinities, they are the result of salt in surface runoff and not salt in the groundwater. The main source of salt in the lake is the salty baseflow generated from the areas immediately to the east of the reserve.

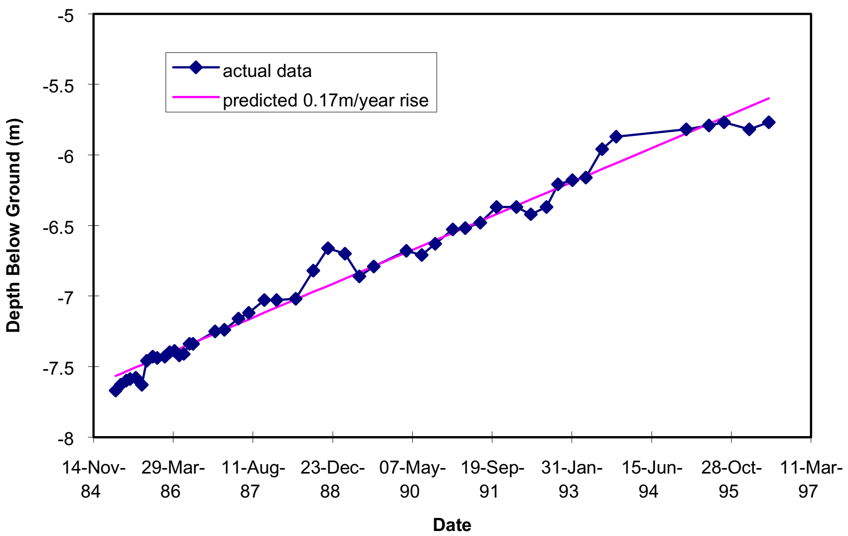
8. Recharge in the study area

Recharge is that component of annual rainfall that bypasses the root zone of crops 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:



A: Groundwater levels in or near discharge areas have risen to the soil surface. They have little or no rise but have seasonal fluctuations.



B: Groundwater levels in undulating areas are rising. The rate of rise in these parts may be as high as 0.3m/year.

Figure 6: Groundwater trends in the Kent River Catchment

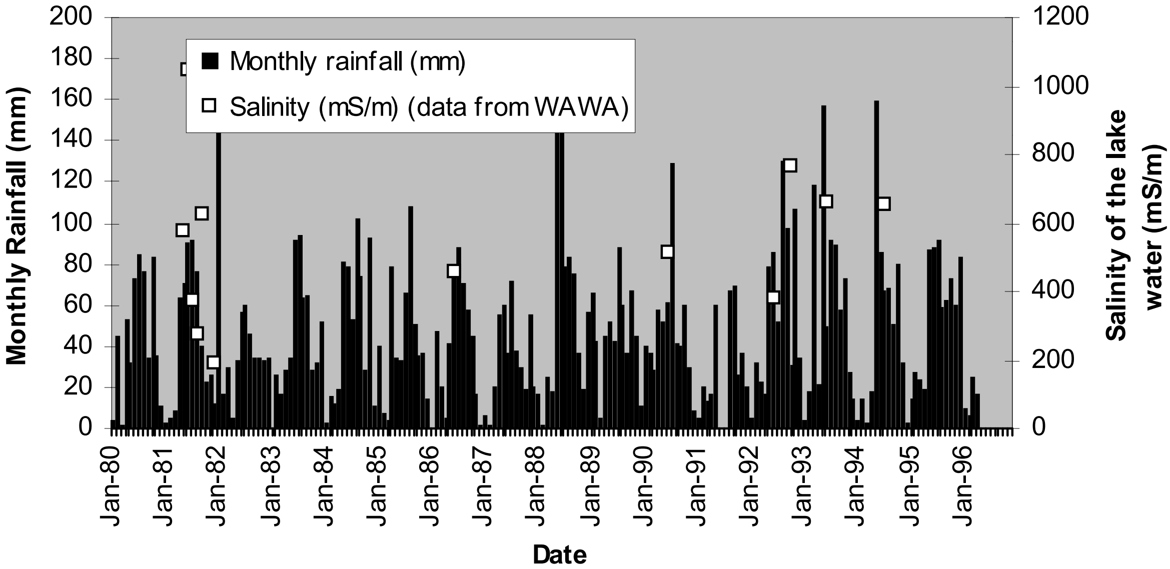


Figure 7: Monthly rainfall and salinity of water in the Wamballup Swamp.

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

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 that is stored in the root zone of crops and can be used by plants when monthly **ET_a** exceeds the monthly rainfall. **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 dS and dD can be ignored and the equation becomes:

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

We have calculated the rate of annual recharge for the study area for a rainfall level that will occur during the wettest 20% of years, an average rainfall year, as well as for the two driest years in ten. We have assumed that PAWC in the root zone of crops and pastures is about 50 mm. The process is as described by Ferdowsian and Greenham (1992). The results are as follows:

- In the wettest 20% of years (decile 8 precipitation; 2 wettest years out of every 10), between April and August, rainfall will exceed the sum of plant water use and runoff. Rainfall in these months will be 405 mm, plant water use 240 mm, runoff (without interceptor drains) about 55 mm and recharge about 110 mm.
- In a year with average rainfall (560 mm), between May and August, rainfall will exceed the sum of plant water use and runoff. Rainfall in these months will be 300 mm, plant water use 205 mm, runoff (without interceptor drains) about 30 mm and recharge about 65 mm.
- In exceptionally dry years (2 driest years out of ten), between May and August, rainfall will exceed the sum of plant water use and runoff. Rainfall in these months will be 255 mm, plant water use 200 mm, runoff (without interceptor drains) about 10 mm and recharge about 45 mm.

9. Potential salinity of the study area

The extent of soil salinity may be related to the hydrological systems and landform patterns of the study area. Future soil salinities in relation to the hydrological systems are as follows:

- In the ***Catchment Divides*** groundwater levels are > 3 m from the soil surface. The hydraulic conductivity in this HS is high as indicated by the yield of the bores and their fast recovery time. The groundwater levels are probably still rising but because of the high hydraulic conductivity the groundwater would flow into the lower HSs when the hydraulic gradients increase. *Catchment divides* probably have less runoff and waterlogging but a higher rate of recharge than the other areas. There appears to be very little or no risk of soil salinity in this HS.
- The hydraulic conductivity of aquifers in the ***Plains with swampy floors*** and ***Swampy terrains*** is very low. An indication of the low hydraulic conductivity was the long time (several days) it took before water in bores came to the rest level. This low conductivity together with the low hydraulic 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 stop the groundwater levels rising. As a result, salt-affected areas will continue to grow.
- Groundwater levels in the depressions and flats of the ***Ancient drainage valleys*** are at the soil surface and most are discharging (only the elevated areas are not discharging). In these areas, because of the topography and high hydraulic conductivity of the aquifer, the extent of soil salinity will not change very much. The lakes and low lands that are in this HS will continue to discharge saline groundwater and stay saline. It is, however, technically possible to reverse the salinity trend of the Wamballup Swamp if its environmental value warrants it. If nothing is changed, only the flushing of the swamps by flood water will periodically reduce their salinity levels.

The extent of potential salinity has been mapped (Figure 4) based on interpretations of aerial photographs, one meter contour maps and the results of drilling. Comparisons of potential saline areas within the LFPs of the study area show that >40% of agricultural areas in some of the LFPs may eventually become salt-affected while others, like *Broad crests, are much less likely to become* saline (Table 6).

10. Waterlogging

Between May and mid-August the rainfall in the study area exceeds the potential evaporation and widespread waterlogging occurs. Approximately 73% of the catchment is affected by waterlogging in an average year. The extent of waterlogging varies from one LFP to another (Table 7). These figures do not include the slightly waterlogged areas of the Wamballup Catchment.

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

11. General management options to reduce recharge and the extent of salinity

Degradation problems in the Wamballup Swamp area are catchment issues. The best results will be achieved if the following management options are applied throughout the area. Small scale 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:

Table 6: Potential salinity in the study area varies with the type of landform patterns

Landform patterns and Hydrological systems * (LFP)	(HS)	Total area (ha)	Potential salinity in landform patterns (ha)	(%)
Broad crests	CD	829	16	2
Gently undulating plains	CD	452	26	6
Gently undulating plains with saline depressions	PSF	243	98	40
Very gently undulating plains	PSF	2546	358	14
Flat-bottomed valleys with lake systems	ADV	410	101	25
Flats with well defined drainage	ST	405	168	42
Stagnant flats	ST	1540	740	48
Tertiary Floodplains	ADV	263	180	69
Lakes	Lakes	105	105	100
Total		**6793**	**1792**	**27.4**

* See section 4.

- increasing surface and sub-surface runoff (surface drains);
- increasing the area under perennial pastures;
- introducing phase cropping (Section 11. 3);
- 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 discharging it into the creeks.

In the following discussions, these issues have been related to the HSs and LFPs of the study area.

Table 7: Extent of waterlogging in the study area varies with type of landform pattern

Landform Patterns and Hydrological systems @ (LFP)	(HS)	Total area (ha)	Severely to very severely waterlogged %	(ha)	Moderately waterlogged areas (%)	(ha)
Broad crests	CD	829	20	(165)	30	(250)
Gently undulating plains*	CD	452	15	(80)	30	(135)
Gently undulating plains with saline depressions*	PSF	243	35	(85)	30	(75)
Very gently undulating plains*	PSF	2546	40	(1020)	35	(890)
Flat-bottomed valleys with lake systems	ADV	410	30	(125)	30	(120)
Flats with well defined drainage*	ST	405	40	(160)	3 0	(120)
Stagnant flats*	ST	1540	65	(1000)	20	(310)
Tertiary Floodplains	ADV	263	70	(185)	20	(50)
Lakes	Lakes	105	100	(105)	00	(00)
Total		6790	43	(2925)	30	(20455)

@ See section 4.

∗ Here the extent of waterlogging is based on the extent of waterlogging of similar LFPs in the Upper Denmark Catchment (Ferdowsian and Greenham, 1992). Waterlogging in the Upper Denmark Catchment was documented after an intensive soil survey of 10,000 ha.

11.1. Reducing recharge and increasing surface and sub-surface runoff by drainage

Waterlogging reduces crop and pasture yields but this is often unnoticed. People may notice waterlogging when it has affected crops or pastures badly. Many farmers think that their land is waterlogged only when they can see free water on the soil surface. However, waterlogging occurs when free water is found within the top 0.30 m of the soil profile. When water fills the soil profile and appears on the soil surface, it is called inundation or surface ponding. Waterlogging may be slight, moderate or severe to very severe.

Between May and mid-September, rainfall exceeds the sum of plant water use and runoff. Most of the excess water stays in the root zone of crops and pastures causing waterlogging. In an average year, 43% of the study area can be severely to very severely waterlogged between May and August. Half of these areas may be inundated for more than two to three weeks. A further 30% of the area is moderately waterlogged (Table 7). In the study area, crops and pastures do actually better during years when the rainfall is less than average in June, July and August.

Surface drains help to reduce waterlogging and inundation and improve the cropping capability of the area.

The following studies were done at the Mt. Barker Research Station and in the Denbarker areas both of which have a similar rainfall to that of the Wamballup Swamp Catchment.

Effect of drains on production

Cox (1988) studied the effect of interceptor drains on waterlogging and crop yield and found that at the Mount Barker Research Station (10 km south of the study area):

- Waterlogging was reduced 24 m downslope and 7 m upslope of drains in wet years, provided drain channels were cut into the clay subsoil;
- The drains removed between 22 and 39% of the growing season's rainfall (16 to 29% of the annual rainfall);
- The drains became increasingly effective as rainfall increased;
- The optimum drain spacing, based on maximum net present value over 20 years, for Mount Barker was 40, 60, 80, and 100 m for areas with 90, 70, 50, and 30% waterlogging probability respectively (for a crop-crop-pasture rotation);
- There was a positive return on the investment in drains, even when future benefits were discounted and inflation was taken into account. Benefits were highest when the area was cropped frequently and the probability of waterlogging was high.

Economics of interceptor drains

Bathgate and Evans (1990) evaluated the economics of interceptor drains to reduce waterlogging of pastures on a farm in the Denbarker region. They concluded that:

- Interceptor drains were likely to increase substantially the net return per hectare;

- Only a 4% increase in stocking rate was needed to cover the cost of the drains (including the loss of land occupied by the drains);
- The ability to crop paddocks which had previously been too waterlogged further increased the profitability of the drains because the farmer had more flexibility in managing his land.

Type of drains for the study area

In the low lying areas of the ***Plains with swampy floors***, ***Swampy terrains*** and ***Ancient drainage valleys***, the soil profile was dominated by very heavy clays. Thus the hydraulic conductivity of near surface material (subsoil only) was very low and any deep drains (>0.6 m deep; open or sub-surface) may not be effective or economic. All subsequent references to drains refer to well-designed surface drains that are usually grader, and occasionally scraper, built open drains. Selection of drains should be based on the attributes of the LFPs and HSs. In the deep gravely sands with a clayey subsoil more than 0.60 m deep, found within the *Catchment divides*, it is not feasible to construct surface drains. Waterlogging of these soils is not common enough to warrant the expense. Drain spacing is related to type of the drains and attributes of the area. In Table 8, recommendations on the type and spacing of drains in relation to the landform patterns of the study area are given.

11.2. Reducing recharge by growing perennial pastures

Various workers (Nulsen and Baxter 1982; Carbon *et al*. 1982; Nulsen 1984; and Joffre *et al*. 1988), have found that perennial pastures use more water than annual pastures. Their ability to use more water is attributed to their deeper root zone, denser root system and their ability to use the summer rainfall provided they were not summer dormant. However, some perennial pastures, such as perennial ryegrass (*Lolium perenne*) and cocksfoot (*Dactylis glomerata*) may not use more water than annual pastures because of their shallow root system (Ferdowsian and Greenham, 1992). 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 (kikuyu). Thus it is recommended to grow a mixture of annual and perennial pastures to reduce recharge. Management changes may be necessary if pastures are used for wool production.

Table 9 shows which perennial pastures are recommended for different Land Management Units (LMUs) in the study area.

11.3. Reducing recharge by phase cropping

In areas that have a low rainfall and low rates of recharge (<40 mm), farmers have managed to control the extent of soil salinity by phase cropping (N-E of Ongerup; personal observation). 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 again. The rotational phases may be three years in areas of moderate to high rainfall or 4 to 5 years in areas that have a low rainfall. During the cropping phase, recharge will fill the soil profile. This storage will be used by lucerne in the following phase. Lucerne is very suitable for phase cropping and most the success stories are related to growing a mixture of lucerne with other perennial pastures such as phalaris, tall wheatgrass and annuals.

The study area has more recharge than lucerne can use on its own. Thus phase cropping should be considered as one of the options and not the whole solution. ***Catchment divides*** and ***Plains* with swampy floors** and upper parts of the ***swampy terrains*** are suitable for phase cropping because there is enough unsaturated soil above the groundwater for the lucerne roots to explore. Lucerne does not tolerate severe waterlogging and will not do well in acidic soils. Thus only 57% of the area (Table 7) is suitable for phase cropping. Lucerne is slightly salt tolerant and has very deep roots that can penetrate sodic subsoils and use the moisture stored at depth. Inoculating seed before planting will improve the performance of lucerne. The economic life of lucerne is between 4 and 6 years. Following 3 to 4 years of lucerne, the land may be used for the cropping phase. During this period the recharge that occurs under crops will fill the soil profile.

Table 8: Types, spacing and cost of drains in relation to the landform patterns of the study area

Landform patterns and hydrological systems (LFP) (HS)		Functional drains	Spacing (m)	Costs * $/km	$/ha
Broad crests	CD	V-shaped conventional interceptor drains	80	500	63
Gently undulating plains	CD	V-shaped conventional interceptor drains on upper slopes	60 to 80	500	65 to 85
		Flat bottomed interceptor drains on lower slopes	80	700	88
Gently undulating plains with saline depressions	PSF	V-shaped conventional interceptor drains on upper slopes	60 to 80	500	65 to 85
		Flat bottomed interceptor drains on lower slopes	80	700	88
		No drains in depressions			
Very gently undulating plains	PSF	Flat bottomed interceptor drains on lower slopes	80	700	88
		Grass or tree covered waterways**	1000	1000	10
Undulating areas of Flat-bottomed	ADV	V-shaped conventional interceptor drains on upper slopes	60 to 80	500	65 to 85

valleys with lake systems		Flat bottomed interceptor drains on lower slopes	80	700	88
Stagnant parts of Flat-bottomed valleys with lake systems	ADV	Spoon drains W drains	50 600	750 1500	150 25
Flats with well defined drainage	ST	Flat bottomed interceptor drains No drains in depressions	60	700	117
Stagnant flats	ST	Spoon drains W drains Grass or tree covered waterways	50 600 1000	750 1500 1000	150 25 10
Tertiary Floodplains	ADV	Spoon drains W drain Grass or tree covered waterways**	50 600 1000	750 1500 1000	150 25 10

* These costs are when graders are used to build the drains. The most expensive drains ($/ha) are spoon drains followed by flat-bottomed interceptor drains, because soil must be transported away from the cutting point. To construct these drains, scrapers may be cheaper if the volume of work is large. For small sections or a few drains, graders may be the most economic choice.

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

Table 9 : The perennial pastures recommended for different LMUs of the study area. Numbers (between 1 and 5) are in order of decreasing preference

Land Management Units	Recommended perennials	
Deep well-drained white sand (>0.50m)	Tagasaste (1) , Kikuyu (2)	Perennial veldt grass (2), Lucerne (3)
Deep well-drained yellow or brown sand (>0.50m)	Tagasaste (1), Lucerne (2)	Kikuyu (1), Perennial veldt grass (2)
0.50 to 0.60 m gravelly sand over clay	Perennial veldt grass (1) Rhodes grass (2),	Cocksfoot (1), Lucerne (3), Tall fescue (3)

	Tagasaste (3)	
0.30 to 0.50 m gravelly sand over clay	Lucerne (1), Kikuyu (2) ,Cocksfoot (2), Tall fescue (3)	Rhodes grass (1), Phalaris (2), Perennial ryegrass (2), Perennial veldt grass (3)
Well-drained loamy sand or clay close to soil surface	Phalaris (1) Lucerne (2) Tall fescue (2)	Perennial ryegrass (1), Tall wheatgrass (2), Cocksfoot (2)
Deep waterlogged sand (>0.50m)	Kikuyu (1), Tall wheatgrass (2), Rhodes grass (2)	Yorkshire fog (1), Tall fescue (2), Phalaris (3)
Waterlogged loamy soil	Kikuyu (1), Strawberry clover (1), Tall wheatgrass (2)	Yorkshire fog (1), Phalaris (1), Tall fescue (2)
Waterlogged clayey soil	Phalaris (1), Strawberry clover (1), Tall wheatgrass (1)	Kikuyu (1), Yorkshire fog (1), Tall fescue (1)
Slightly to moderately salt-affected soil	Tall wheatgrass (1), Strawberry clover (1), Kikuyu (2)	Tall fescue (1), *Acacia saligna* (2), Phalaris (2)
Moderately to strongly salt-affected soils	Puccinellia (1), *Acacia saligna* (2)	Tall wheatgrass (2), Saltwater couch (2)
Active discharge sites	Saltwater couch (1), Tall wheatgrass (3)	Puccinellia (2)

For more information on perennial pastures refer to “Perennial pastures for areas receiving less than 800 mm annual rainfall (1994), by R.A. Sudmeyer, C. Saunders, I. Maling and T. Clark. Bulletin No. 4253.

11.4. Reducing recharge by adopting better management practices

Any management strategy that increases pasture and crop growth can also increase transpiration. These options include: growing high yielding crops; any measures that can defer grazing the annual pastures in autumn; maintaining optimum pasture mass; applying nitrogen to grassy pastures; and strip grazing. These management options are only likely to benefit farmers who run high stocking rates and experience feed gaps early in the growing season.

11.5. Increasing groundwater use by revegetating selected areas and the limitations due to groundwater salinity

Tree planting is the most profitable treatment to tackle the excess water associated with salinity in this region. Ferdowsian and Greenham (1992) found that returns from tree plantations were greater than returns from growing wool, beef or crops. They recommended a range of trees for different conditions of soil salinity and waterlogging. Trees that can grow in salt-affected areas have little commercial value. Their merit is in reclaiming land and helping reduce the extent of salinity in the other parts of a catchment.

Ferdowsian and Greenham (1992) also calculated the water use of trees in the Upper Denmark Catchment and found that trees may use as much as 2,200 mm per annum if good quality water is available. They recommended that trees planted strategically on 25% of the farming land was one of the necessary treatments to tackle the salinity problem. Their findings and recommendations could also be applied to the Wamballup Swamp Catchment.

Soil salinity can be reversed by growing trees, crops and pastures in a balanced combination. Wood production, in whole-farm plantations, will be limited by rainfall and not by the potential of soil and available sunshine. Lack of water may kill trees or reduced their growth rate. In the study area, there is not enough rainfall to satisfy trees that cover whole paddocks. If trees are planted in strips, they may access extra water that passes below the root zone of the nearby pasture.

The salinity of groundwater is too high in most of the study area for trees. Trees will only use the fresh water that is stored within the soil profile and to a lesser extent the relatively fresher water that may be on top of the aquifer.

Layout of trees

The layout of trees should optimise wood and pasture production and provide protection from the wind. Placement of trees in the landscape will be limited by available water (low annual rainfall) and high groundwater salinities. There are several points to remember when designing the layout of trees:

- Do not expect groundwater levels and the extent of salinity to fall when large plantations are planted in one part of the catchment and nothing is done to the rest.
- Trees that are required for using excess water should be scattered throughout the area, as widely as possible.
- Because isolated trees are difficult to protect, strip plantations are the best option.
- If the strip plantations are to be self-supporting and self-pruning they need to have at least six rows; the six rows will make it possible to have partial harvesting of the tree belts without disrupting their function.
- The trees should be spaced as close as possible to encourage deep rooting and good forms (shape).
- Creek lines, swamps, lakes and salt-affected areas and their fringes should be fenced off and revegetated. A Geonics EM38 should be used (before fencing) to mark the areas that are in immediate danger of salinity.
- We discourage whole-farm plantations, although this method is the quickest way to prevent excess recharge and associated salinity.
- Where drains are constructed in association with the tree belts, their best position is along the upslope side of the tree belts.

- The best option for the study area is to have trees on 25% of the catchment so the strips of pasture or crops should be approximately 100 m wide. If strips of pasture or crops are within boxes, tree strips can be 150 m wide by 350 m long or 125 m wide by 600 m long or any other combination that secures 25% under tree plantation.

(Further information on Agroforestry and Alley Farming: Journal of Agriculture No 4 1994 and No 3 1994 Dept. of Agriculture).

11.6. State of the existing native vegetation in the study area

The small patches of on-farm native vegetation in the study area are in various stages of deterioration. Some blocks are completely dead. On-farm native vegetation that has deteriorated will probably use very little water and thus have very little impact on preventing salinity. The badly deteriorated native vegetation may exacerbate salinity by recharging the aquifer. The form and causes of deterioration depend on location in the landscape:

- The factors that contribute to the deterioration of isolated remnant vegetation on hillcrests and hillslopes (*Catchment divides*) are likely to be: grazing pressure; exposure to wind, cold, 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 by stock 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 courses (PSF, ST, and ADV), is primarily caused by rising groundwater, but grazing pressure, exposure, disease, and isolation also contribute.
- Death of the natural vegetation that surrounds the wetlands, swamps and playas is mainly due to the rising saline groundwater, which drowns their roots. Short periods of inundation and grazing pressure may exacerbate the problem but in most cases, are not the main cause of it.

It is suggested that the gaps in badly deteriorated and isolated native vegetation should be replanted with trees that use more water. Remnant vegetation that is in reasonable condition should be fenced and protected. Regeneration of these areas will improve their water use and can be expected to have an impact on reducing salinity.

(Further reading on managing remnant bush: Journal of Agriculture No 3 1994 Dept. of Agriculture).

11.7. Pumping saline groundwater and discharging it into creeks

Pumping is an engineering solution that does not address 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 will be limited to the ***Ancient drainage*** hydrological system.

Pumping will lower groundwater levels in the areas that immediately surround the pumping bores. Pumping saline groundwater presents three problems:

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

12. Specific management options

Specific management options that reduce recharge and the extent of salinity are related to each hydrological system.

12.1. Specific management options for the Catchment Divides

Some areas in this HS have deep (>0.60m) gravelly sand (A horizon) over a clayey B horizon (subsoil). The water holding capacity of the sandy layer is low (25 mm), while the water holding capacity to similar depth in loamy soils may be >80 mm. Thus the deep sandy areas will cause between 20 and 40 mm more recharge than those that have a shallower A horizon and loamy soils. This recharge will increase the salinity problem of the lower HSs. It is expensive (and not recommended) to construct surface drains in the deep gravelly sands. The main options to reduce recharge in these areas are better management, perennials, phase cropping and strip planting of trees.

Shear zones in this HS (Figure 4) facilitate groundwater movement. The potential salinity in these areas is limited and confined to depressions that are associated with the shear zones. It is recommended that these shear zones be planted with trees and fenced off as part of the revegetation of selected areas. Faults, on the other hand, are unlikely to have high hydraulic conductivity and are very wide zones. Faults should be dealt with as other parts of the landscape.

12.2. 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 lower parts of this HS have very few, well-defined depressions to contain runoff and large areas may become flooded. Waterways are recommended to limit water to defined areas. Because there is sufficient slope, there is no need to construct W drains in the middle of these waterways. The interceptor drains should discharge their water into these waterways and on to natural drainage lines.

12.3. Specific management options for the Swampy terrains

There are two landform patterns in this HS: Flats with well-defined drainage and Stagnant flats.

The Flats with well-defined drainage have a natural water course that is either salt-affected already 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 a Geonics EM38 instrument (an instrument that can indicate salinity in the top one metre of a soil profile). EM38 readings on slightly salt-affected areas will be between 60 and 80 mS/m (Ferdowsian and Greenham, 1992). We recommend that areas with Em38 conductivity readings above 50 mS/m be planted with trees. Trees should be planting in the depression in conjunction with treatments on the other parts of the landscape. If the other parts of the catchment are not treated, groundwater will continue discharging into these depressions. Eventually, salt may accumulate in the root zone of the trees and kill them.

The ***Stagnant flats*** need spoon and W drains. These drains are relatively expensive (Table 8). 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 fenced off and planted with trees. W drains and waterways should be positioned in the salinity prone areas. Waterlogging-tolerant trees should be selected. Ripped 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. Kikuyu which can tolerate severe waterlogging and inundation in winter months, is recommended for these areas.

12.4. Specific management options for the Ancient drainage valleys

The undulating areas of this HS should be dealt with like the ***Plains with swampy floors***. The stagnant parts of this HS have many similarities with the *Stagnant flats*. The main difference is that these areas have become permanent discharge sites and their salinity is almost wholly due to off-site problems. They have very little recharge to flush salt from the root zone of the trees. This means that the trees will be struggling to survive in an increasingly saline environment. Drains can improve the condition as a first step. Other treatments should be deferred until the rest of the catchment has been treated and the overall salinity conditions in the catchment have improved.

12.5. Specific management options for the lakes in Ancient drainage valleys

The death of the natural vegetation surrounding the wetlands, swamps and playas is mainly due to the rising saline groundwater. Before clearing, lakes had reached a hydrological and salt balance. The reasonably fresh water recharged the aquifer below the lake floor, reducing the salt load and maintaining low groundwater salinities (as indicated by low groundwater salinities in the Werillup Formation; drilling site WS2/96). After clearing, as the groundwater levels rise, the wetlands became permanent discharge sites, and their salinities increased. They may have also received saline baseflow from salt-affected areas which increased their salt concentration. The management options that can have a positive impact on these lakes and swamps are:

- Fencing off areas well away from the present high water mark, keeping stock away from lakes and swamps and actively or passively revegetating inside the fence to create new fringe vegetation.
- Avoid discharging surface runoff into lakes if it can be discharged into creeks and rivers. However, in the absence of creeks and rivers, lakes may be the only possible places to discharge runoff and shallow seepage.
- Where lakes contain fresh water, it could be used for irrigating perennial pastures, to reduce recharge into the aquifer below lake. The problem with pumping water

out of the lakes is that as soon as their water levels drop below the groundwater levels, saline groundwater will start filling the lake. To avoid that, drill a bore near the lake, measure the groundwater level in the bore, and make sure that the water level in the lake does not drop below the groundwater level.

- Areas that become inundated every few years should be drained and revegetated.

12.6. Specific management options for Wamballup Swamp

There are some management options that will help protect the Wamballup Swamp from becoming more salty:

- The salty baseflow can be diverted away from the lake, letting only the relatively fresh flood water pass through the lake. This may be achieved by control gates and a bypass channel that can divert saline flow.
- The outflow from the lake can be controlled to keep the lake’s water level above that of the saline groundwater.
- The Werillup Formation that extends under the lake has a high hydraulic conductivity. It may be possible to pump groundwater and drop the aquifer levels below the lake floor.

Since the Werillup Formation extends further south, to Kwornicup Lake, it may be possible to treat the whole area as one unit. In that case it may be possible to discharge pumped water into the head waters of either the Kent or the Hay Rivers. Pumping groundwater may have some environmental consequences, however. Further drilling and pump tests are needed to test the feasibility and environmental impacts of this option.

At present, the salinity of groundwater under the lake is about 520 mS/m. This level of salinity is 60% of the baseflow salinity in the same catchment (7 km downstream where the creek crosses the Mallawillup Road) and 52% of the Kent River’s baseflow salinity where it crosses the same road. It is possible that as groundwater is pumped out it may be replaced by saltier groundwater. This is a real threat and will eventually happen with or without pumping. An indication of this is the relatively high groundwater salinity in bore WS1/96 (east of the reserve; 1140 mS/m).

13. Future monitoring

It is essential to monitor the salinity situation in the Wamballup Swamp Catchment. Landholders should monitor the situation and send the data to Agriculture WA in Albany for interpretation. Monitoring needs to be coordinated to ensure that it is done effectively. The following monitoring is necessary:

- Groundwater levels should be measured once a month during the first year and three monthly thereafter.
- Groundwater salinities should be measured once every second year, preferably in April. Samples should be collected only after flushing the holes.
- Weekly water samples should be collected from surface runoff during October each year (after the major rains have ceased) and sent to Agriculture WA in Albany. Three sites are recommended for sampling: at Boyup Road crossing, at the outlet of Plantagenet Location 10 and at Mallawillup Road crossing.
- We currently have two Data Loggers that measure the depth of water that enters the Wamballup Swamp Reserve. We hope to monitor the runoff that enters the Reserve.

14. References

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Appendix 1: Drill Logs

The following pages show the drill logs of 10 bores that were drilled in the study area in April 1996. The location of these bores is marked on Figure 1. The drill logs contain the following information:

- Eastings and northings (Australian Map Grid) of sites;
- Salt concentration profile (kg/m^3), which ranges from 1 to 30;
- Total salt stored (t/ha) in the whole profile, which ranges from 293 to 3427;
- Groundwater salinity (mS/m), which ranges from 520 to 2210;
- Water level (m), which ranges from -0.08 to -3.4;
- Which landform pattern it is drilled in;
- Interpreted geology;
- A full description of the soil profile (lithology).

Drilling Log Wamballup Swamp 1996

WS1/96

Easting: 542091 **Northing:** 6180698 **Salt Storage (TSS t/ha):** 1802
Groundwater salinity (mS/m): 1140 **Water level below ground (m):** -1.31
Landform Pattern: Flood plains. **Hydrological System:** Ancient drainage valleys.
Interpreted Geology: 0-8 m Pallinup, 8-14 m Werillup, >14 m Tertiary sediments.

Drilling log

0-1 m silty clay 10YR 3/1 (very dark grey)

1-3 m heavy clay 10YR 7/2 (white)

3-4 m fine silty clay loam 10YR 7/1 (white) with mottles 7.5YR (reddish yellow)

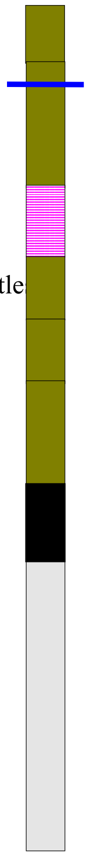
4-5 m heavy clay 10YR 7/1 (white) with red mottle 5YR (reddish and greenish yellow)

5-6 m same as 4-5m but saturated

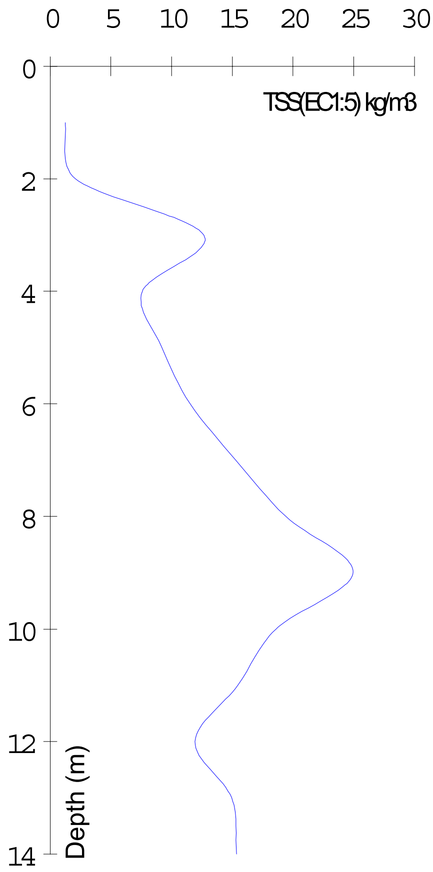
6-8 m heavy clay 10YR 7/1 (white)

8-9 m lignite (with coal)

9-14 m coarse sandy loam



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 Wamballup Swamp 1996

WS2/96

Easting: 540554 **Northing:** 6180509 **Salt Storage (TSS t/ha):** 590
Groundwater salinity (mS/m): 520 **Water level below ground (m):** -1.39
Landform Pattern: Flat-bottomed valleys with lake systems (less than 10 m relief).
Hydrological System: Ancient drainage valleys. **Interpreted Geology:** 0-6 m Pallinup, 6-14 m Werillup, >14 m Tertiary sediments.

Drilling log

0-1 m light clay 10YR 4/1 (dark grey)

1-2 m silty clay 10YR 7/4 (very pale brown)

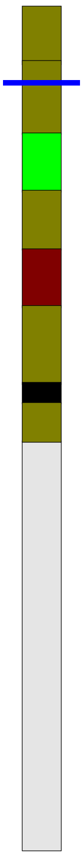
2-3 m hard pan cemented 5YR (reddish brown)

3-4 m clay 10YR 8/1 (white)

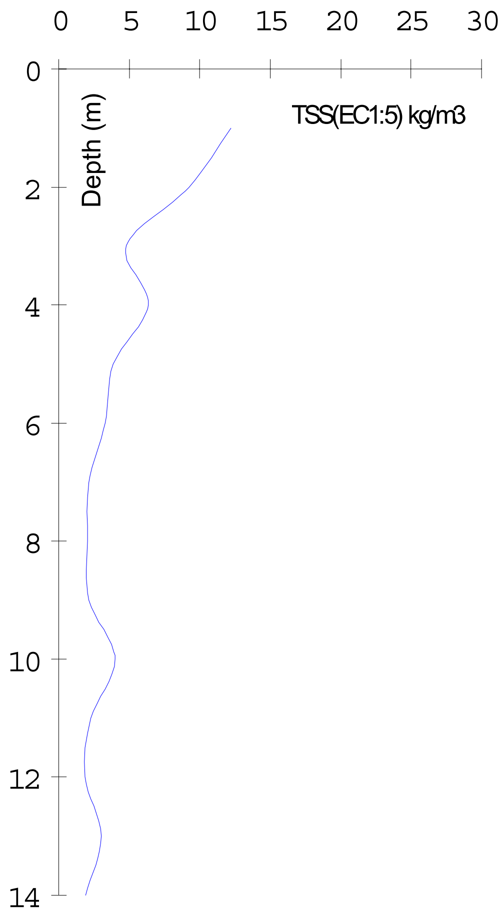
4-5 m sandy clay 10YR 8/1 (white) very moist

5-6 m clay 10YR 8/1 (white)
6-6.3 m lignite
6.3-7 m silty clay 10YR 3/1 (very dark grey)

7-14 m coarse sand (developed water at 7 m)



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 Wamballup Swamp 1996

WS3/96

Easting: 539462 **Northing:** 6180745 **Salt Storage (TSS t/ha):** 523
Groundwater salinity (mS/m): 1438 **Water level below ground (m):** -1.58
Landform Pattern: Very gently undulating plains (less than 10 m relief).
Hydrological System: Plains with swampy floors.
Interpreted Geology: Weathered bedrock. A quartz dyke. Bedrock at 11 m.

Drilling log

0-0.5 m sandy loam (some gravel)
0.5-1 m sandy heavy clay 7.5YR 6/4 (light brown)
1-2 m sandy heavy clay 10YR 6/3 (pale brown)

2-4 m sandy heavy clay 10YR 6/3 (pale brown) and layer of greenish blue

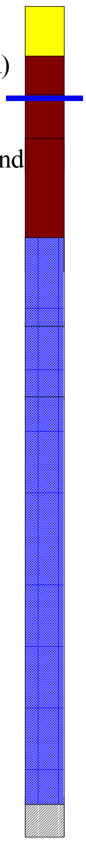
4-5 m moderately weathered bedrock

5-6 m weathered bedrock (feldspar and quartz)

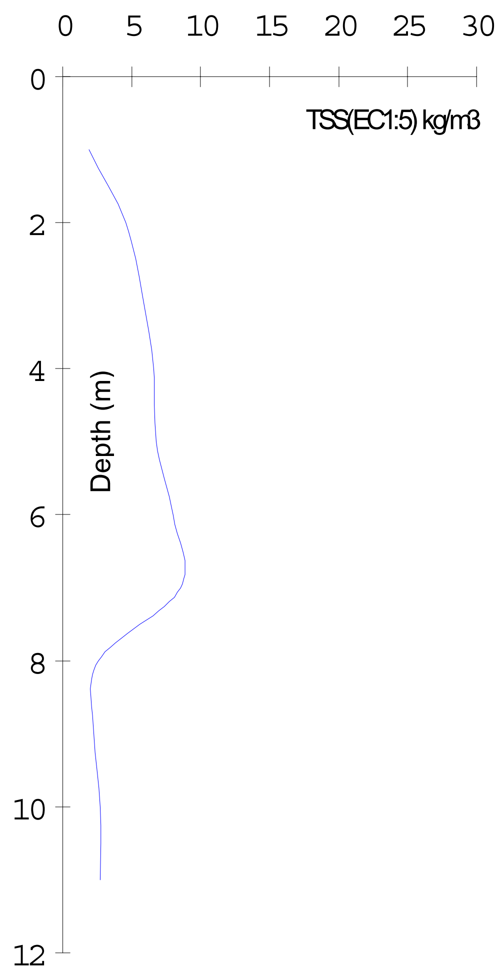
6-10 m chunks of bedrock (quartz and feldspar)

10-11 m less weathered (feldspar and quartz)

11 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 Wamballup Swamp 1996

WS4/96

Easting: 548812 **Northing:** 6178572 **Salt Storage (TSS t/ha):** 293
Groundwater salinity (mS/m): 1202 **Water level below ground (m):** -2.15
Landform Pattern: Gently undulating plains with saline depressions (0-30 m relief).
Hydrological System: Plains with swampy floors. **Interpreted Geology:** 0-2 m alluvium, 2-4 m sedimentary, 4-8.2 m granitic material, 8.2 m bedrock.

Drilling log

0-1 m gravelly sand 75% gravel

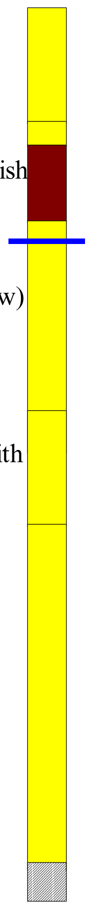
1-1.2 m gravelly sand
1.2-2 m sandy heavy clay 10YR 6/4 (light yellowish brown)

2-4 m fine loamy sand 10YR 6/6 (brownish yellow)

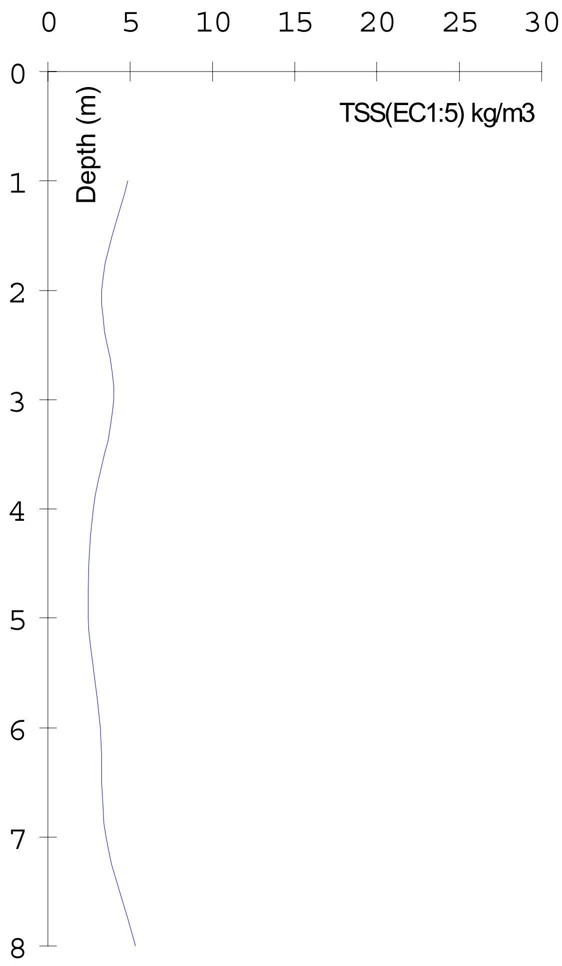
4-5 m greenish loamy sand 5Y 6/1 (light gray) with some coarse material

5-8.2 m loamy clay sand 7.5YR 5/4 (brown) (developed water at 5m)

8.2 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 Wamballup Swamp 1996

WS5/96

Easting: 547331 **Northing:** 6180227 **Salt Storage (TSS t/ha):** 584
Groundwater salinity (mS/m): 1374 **Water level below ground (m):** -2.24
Landform Pattern: Stagnant flats (less than 5 m relief).
Hydrological System: Swampy terrain. **Interpreted Geology:** 0-1 m alluvium, 1-3.2 m sediments, 3.2-10.3 m medium grained granitic material. 10.3 m bedrock.

Drilling log

0-1.2 m gravelly sand

1.2-2 m heavy clay 10YR 6/6 (brownish yellow)

2-3 m silty clay 2.5Y 8/1 (white)

3-3.2 m silty clay 10YR 6/6 (brownish yellow)

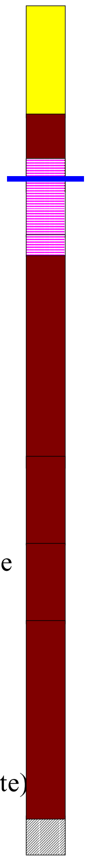
3.2-6 m silty sandy clay 2.5Y 8/1 (white)

6-7 m sandy clay 5Y 7/1 (light gray)

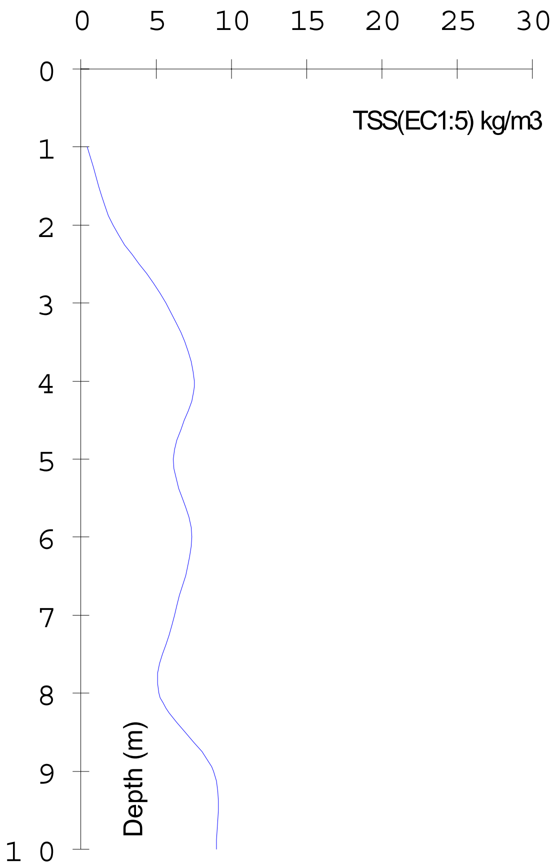
7-8 m sandy clay 5Y 8/2 (white) with some coarse sand

8-10 m sandy clay 5Y 8/2 (yellowish white)

10-10.3 m hard sandy clay 5Y 8/2 (yellowish white)
10.3 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 Wamballup Swamp 1996

WS6/96

Easting: 545235 **Northing:** 6180166 **Salt Storage (TSS t/ha):** 508
Groundwater salinity (mS/m): 1990 **Water level below ground (m):** -3.4
Landform Pattern: Stagnant flats (less than 5 m relief).
Hydrological System: Swampy terrain. **Interpreted Geology:** 0-2.5 m alluvium, 2.5-8 m Pallinup, 8-14 m *in situ* weathered granite, 14 m bedrock.

Drilling log *Salt Storage Profile*

0-1 m gravelly silty loamy sand

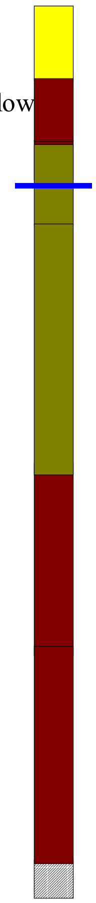
1-2 m sandy heavy clay 10YR 6/6 (brownish yellow
2-2.5 m sandy heavy clay moist
2.5-3.5 m heavy clay 10YR 8/1 (white)
3.5-4 m heavy silty clay 10YR 8/1 (white) with mottles 2.5YR 3/4 (dark reddish brown)

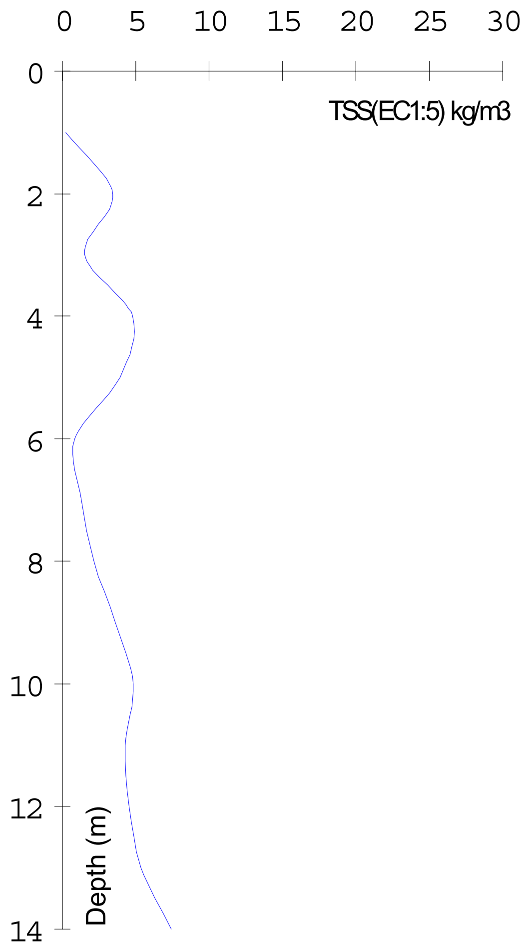
4-8 m silty heavy clay 10YR 8/1 (white)

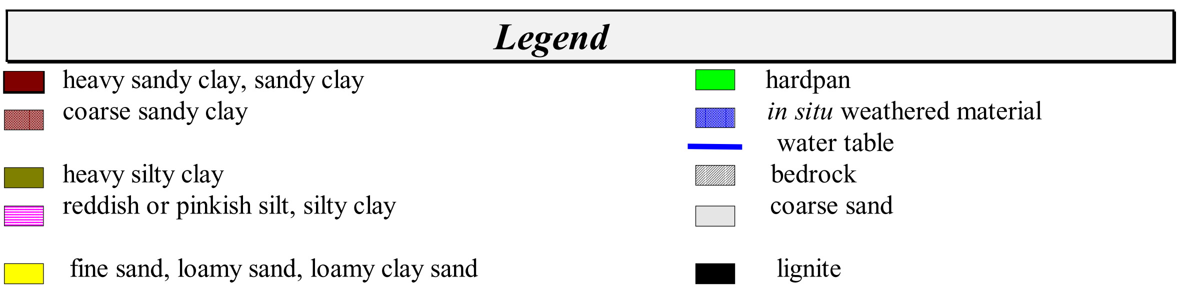
8-11 m sandy heavy clay 10YR 8/2 (white) (developed water at 8m)

11-14 m sandy heavy clay 10YR 8/2 (white)

14 m bedrock







Drilling Log Wamballup Swamp 1996

WS7/96

Easting: 545648 **Northing:** 6182631 **Salt Storage (TSS t/ha):** 3427
Groundwater salinity (mS/m): 830 **Water level below ground (m):** -1.82
Landform Pattern: Stagnant flats (less than 5 m relief).
Hydrological System: Swampy terrain.
Interpreted Geology: 0-6 m sediments, 6-32.5 m granitic material, 32.5 m bedrock.

Drilling log *Salt Storage Profile*

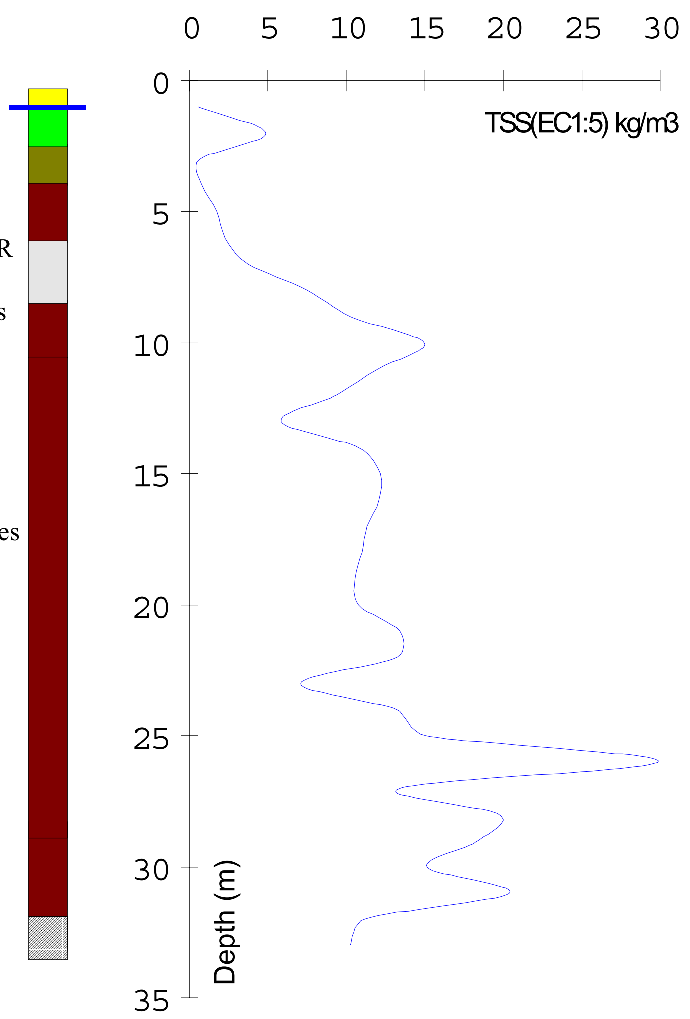
0-1 m gravelly loamy sand (podzolic layer)
1-2.4 m hardpan 2.5Y 3/4 (dark reddish brown)
2.4-4 m heavy clay 10YR 8/2 (white)

4-5.5 m sandy clay 2.5Y 7/0 (light gray)
5.5-7 m coarse sandy clay gritty sandy clay 7.5YR 7/8 (reddish yellow) water at 5.5m
7-10 m sandy clay 10YR 7/2 (white) with mottles 7.5YR 7/8 (reddish yellow)

10-28 m sandy clay 10YR 7/2 (white) with mottles 7.5YR 7/8 (reddish yellow)

28-32.5 m greenish sandy clay with coarse sand

32.5 m bedrock



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 Wamballup Swamp 1996

WS8/96

Easting: 547340 **Northing:** 6182011 **Salt Storage (TSS t/ha):** 454
Groundwater salinity (mS/m): 1711 **Water level below ground (m):** -2.23
Landform Pattern: Stagnant flats (less than 5 m relief).
Hydrological System: Swampy terrain.
Interpreted Geology: 0-1 m alluvium, 1-3.2 m Pallinup silt, 3.2-6.5 m *in situ* weathered granitic material, 6.5 m bedrock.

Drilling log

0-1 m gravelly loamy sand

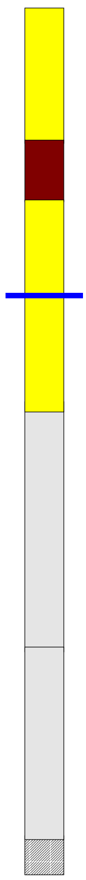
1-1.5 m sandy heavy clay 7.5YR 6/6 (reddish yellow) with mottles 10YR 7/2 (white)

1.5-3.2 m sandy clay loam 10YR 8/2 (white)

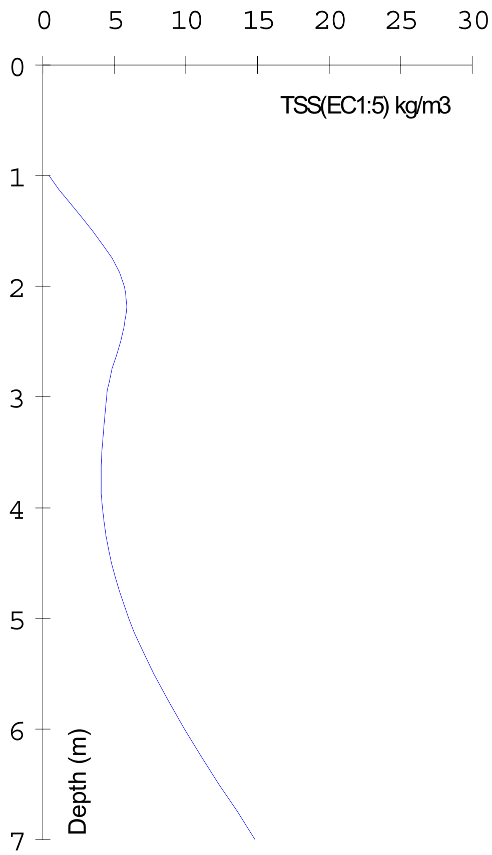
3.2-5 m coarse sandy clay 7.5YR 6/8 (reddish yellow)

5-6.5 m coarse sandy clay 7.5YR 6/8 (reddish yellow), developed water at 5.6 m

6.5 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 Wamballup Swamp 1996

WS9/96

Easting: 547324 **Northing:** 6181328 **Salt Storage (TSS t/ha):** 1445
Groundwater salinity (mS/m): 2210 **Water level below ground (m):** -3.17
Landform Pattern: Stagnant flats (less than 5m relief). **Hydrological System:** Swampy terrain. **Interpreted Geology:** 0-1.5 m alluvium, 1.5-3.5 m sediments Pallinup material, 3.5-13.5 m *in situ* weathered material, 13.5 m bedrock.

Drilling log

0-1 m loamy sand 80% gravel

1-1.5 m dry sandy clay 10YR 8/6 (yellow)

1.5-3.5 m silty clay 10YR 8/2 (white)

3.5-4.5 m sandy heavy clay 7.5YR 5/8 (strong brown)

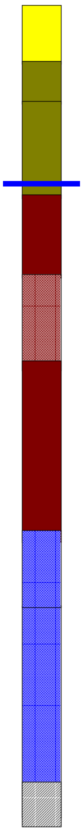
4.5-6 m coarse sandy clay 2.5Y 8/4 (pale yellow) quartz grains up to 5 mm

6-9 m sandy clay 10YR 6/8 (yellow) with mottles 10YR 8/2 (white)

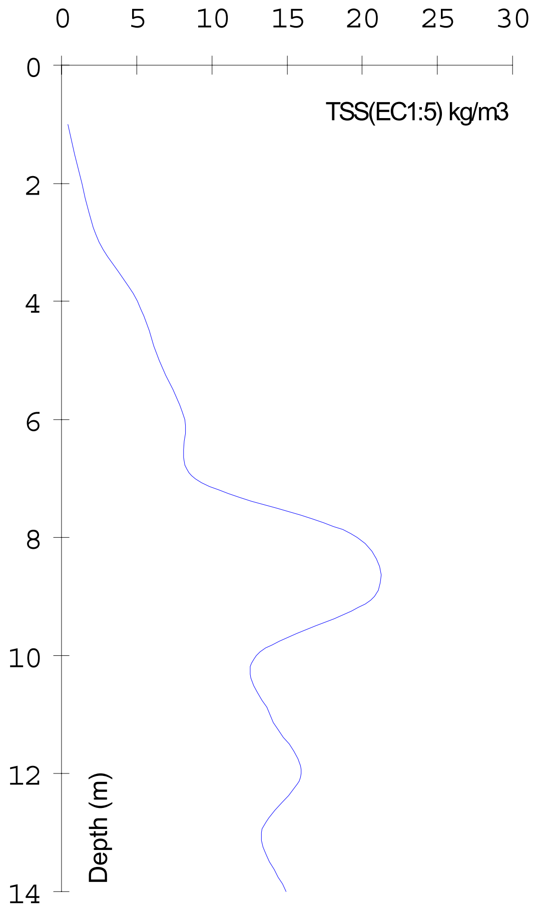
9-10 m highly weathered granite, some quartz

10-13.5 m highly weathered granite, some quartz

13.5 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 Wamballup Swamp 1996

WS10/96

Easting: 544638 **Northing:** 6182396 **Salt Storage (TSS t/ha):** >1422
Groundwater salinity (mS/m): 1990 **Water level below ground (m):** -0.08
Landform Pattern: Flats with well defined drainage. (less than 5 m relief)
Hydrological System: Swampy terrains **Interpreted Geology:** 0-8 m sediments, 8-20 m *in situ* weathered material, >20 m weathering continues, bedrock is >20m.

Drilling log

0-1 m gravelly sand with podzolic layer
1-2 m sandy clay loam 7.5YR 6/6 (reddish yellow) with mottles 7.5 YR 8/1 (white)
2-2.5 m sandy clay 2.5YR 5/6 (red)
2.5-3.5 m slity clay 7.5YR 8/1 (white)

3.5-8 m clay loamy sand 10YR 4/6 (dark yellowish brown) gradual change to sandy clay 2.5YR 6/6 (light red)

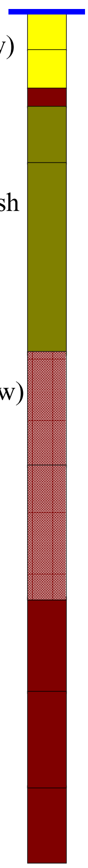
8-11 m coarse sandy clay 5YR 8/6 (reddish yellow) developed water at 9m

11-14 m coarse sandy clay 7.5YR 8/6 (reddish yellow)

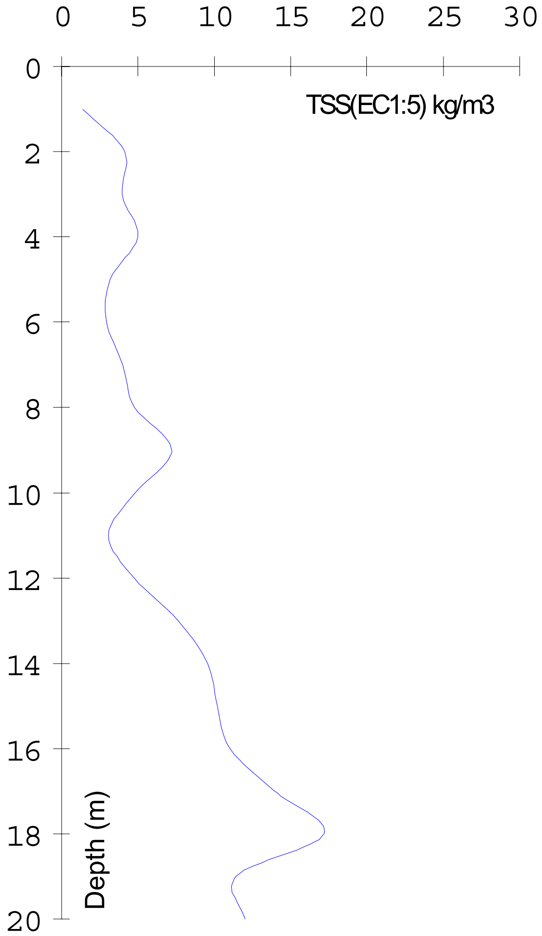
14-16 m sandy clay 7.5YR 8/4 (pink)

16-18 m sandy clay 10YR 8/4 (very pale brown) angular coarse quartz up to 10 mm

18-20 m sandy clay 10YR 8/3



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

Appendix 2: Bores that were Drilled by Three Land Holders in the Study Area, Water Levels and Groundwater Salinities (June 8-14 1996)

Owner	Bore NO	Location Number	Easting, Northing	Water Level (m)	Salinity (mS/m)	Depth Drilled (m)	Landform pattern and hydrological systems (LFP) (HS)*	
Jack Carr	1	5377	548257, 6177893	0.85	2000	3.6	Very gently undulating plains	CD
	2	5377	548445, 6177565	1.47	918	3.6	Very gently undulating plains	CD
	3	2801	548856, 6178437	dry	dry	3.6	Gently undulating plains with saline depressions	PSF
Ray Shepherd	1	755	548856, 6179593	dry	dry	3.6	Very gently undulating plains	CD
	2	755	548590, 6179807	dry	dry	3.6	Very gently undulating plains	CD
	3	755	548300, 6180005	0.8	2460	3.6	Very gently undulating plains	CD
Ken Frost	1	1211	545680, 6180952	0.47	2150	3.6	Stagnant flats	ST
	2	1211	545625, 6179296	0.98	832	3.6	Stagnant flats	ST

Note: CD = Catchment divides; PSF = Plains with swampy floors; ST = Swampy terrains

Appendix 3: Terminology and Abbreviations used in this Report

Terminology	Description
Aggradation	The process of building up surfaces by depositing sediments.
Alluvial or alluvium	Material that is deposited by water in low-lying areas and floodplains.
AMG	Australian Map Grid.
Aquifer	A water-bearing underground layer (stratum), that water can be extracted from.
Plant available water (PAWC)	Difference between water holding capacity and wilting point of a soil. Water which plants can obtain from unsaturated soil.
Baseflow	The extended, low flow in a creek after surface runoff has finished and when groundwater is the main contributor to the flow.
Basement rock	Or bedrock is hard rocks that are at the base of the soil profile
Bedrock	Unweathered hard rock that is at the base of a soil profile.
CALM	Department of Conservation and Land Management.
Capillarity	Rise of a liquid, which is in contact with a solid, due to surface tension.
Capillary	Fine spaces between soil particles which are interconnected.
Closed depression	A depression (basin) in the landscape that is lower than the surrounding areas and collects runoff.
Conductivity (electrical)	Ability of a rock to conduct an electrical current.
Degradation and degrade	Decline in the quality of natural resources commonly caused by human activities.
Depression	A low lying area.
Discharge	Volume of water flowing through a cross section in a unit time.
Discharging	Groundwater coming to the ground surface.
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 drilled and findings while drilling a bore.

Erosive velocity (m/second)	A velocity of water above which water may erode its channel. This velocity is 0.45m/s for sand, 0.60m/s for silty loam and about 1.0m/s for heavy, tight clay (all bare surfaces).
Fault	A long (sometimes many kilometres) fracture in rock that has displacement between the two sides of fracture.
Flash flood	Large volume of runoff that has short duration.
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.
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 grains are organised along 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.
HS	Hydrological system
Hydraulic conductivity	The rate of flow of water through soil per unit time.
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	Science of groundwater in relation to material through which it flows.

Hydrograph	Graphical representation of flow rate or water level during 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	Science of water movement in relation to land and the soil profile.
In situ; in situ weathered material	In place; Weathered material that has stayed in its weathering place.
Landform element (LFE)	Small part (20 to 30 m in radius) of 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.
LFP	Landform pattern
Leaching	The removal of some chemical components of a rock or soil by water.
Lignite	Low grade brown coal, silt with organic material
Lithology	Characteristics (composition and texture) of sedimentary material that may vary from one layer to another.
Local aquifer	An aquifer that has formed because of local recharge. Groundwater levels in a local aquifer usually form an open depression and flow lines are convergent.
Lunette	Elongated, convex, low sandy ridges that are built up by wind on east-south-east margins of playa lakes. 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 an unsaturated soil profiles, is attached to clay or is in a thin film of water that is tightly held around soil particles. As groundwater levels rise, some of this salt may enter the micropores and be moved by the flowing aquifer.

mg/L	Milligrams per litre.
Mottles	Mottles are spots, blotches or streaks in a soil profile which have different colours from the matrix colour of the soil.
mS/m	MilliSiemens per metre (a measure of electrical conductivity).
Off-site	Material or something that has originated elsewhere but has been transported or transferred to a site.
Open depression	A valley or depression that has an outlet through which water can flow out of that area.
Palaeochannels	Ancient drainage valleys 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.
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 general features of the land surface.
Piezometer	A tube inserted into an aquifer to measure the groundwater level.
Quartz dyke	A 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	A component of rainfall that drains below the root zone of vegetation and joins the groundwater.
Regional aquifer	An aquifer that is large, its flow lines are almost straight and parallel, and it is fed by on-site as well as off-site recharge.
Regolith	Weathered or sedimentary material that is over bedrock.

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 salt 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 is dependent on landform patterns and rainfall. In low hills that receive >1000 mm annual rain, salt storage may be less than 200 tonnes per hectare (< 1 kg TSS/m^3). Flats in low rainfall areas (< 350 mm per annum) may have more than 40,000 tonnes of salt per hectare (>100 kg TSS/m^3)
Shear zone	A fractured zone in the earth's crust that is caused by tectonic 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	Sink holes are steep-sided, closed depressions which occur in areas that have limestone or spongolite. A sinkholes 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, 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. 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 seas.
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	Total soluble salt, usually measured in milligrams per litre (mg/L)
Unsaturated soil profile	A zone in the soil profile where all 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.
Water holding capacity	Water that is held in the soil after gravitational water has drained away following soil saturation.
Waterlogging	The condition of a soil which is saturated and free water can be found in the root zone of plants (usually within the top 0.3 m). It affects plant growth adversely.
Water table	The upper surface of an unconfined aquifer.
Werillup Formation	Sequence of pebbles, sand and lignite that were deposited on low lying parts of the south coast of Western Australia prior to 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 soil moisture tension is 15 atmospheres. Because the suction force of plant roots can not overcome this tension, plants wilt.
WSC	Wamballup Swamp Catchment
Zone	A region, area or a portion of something that has specific or distinctive features or attributes.