



ENGINEERING OPTIONS AS TOOLS FOR SALINITY MANAGEMENT IN THE SPENCER GULLY CATCHMENT



**Water and Rivers
Commission**

ENGINEERING OPTIONS AS TOOLS FOR SALINITY MANAGEMENT IN THE SPENCER GULLY CATCHMENT

By

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Modified drainage line in Spencer Gully by

Tim Sparks

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Executive Summary

Groundwater pumping and/or deep drainage were modelled and showed a significant reduction in salt-affected land.

The increased recharge through shallow rooted plants (up to one order of magnitude) has resulted in hydrological imbalance and enhanced groundwater flow which has increased groundwater pressure of deep semi-confined aquifers and resulted in water level rise in shallow near-surface aquifers. The seepage of saline groundwater from deep aquifers into the natural drainage lines has increased saline base flow and resulted in increased salinity in the river systems.

The adverse impact of river salinisation on water resources is exemplified in the Collie catchment—in the largest water supply catchment in southwest of Western Australia. The mean annual salinity of the Wellington Reservoir (fed by the Collie river) currently is ~ 885 mg/L—a four-fold increase compared with salinity prior to clearing (Public Works Department, 1979).

The Collie River and, consequently, the Wellington Reservoir receive a disproportionately high salt load (50% of the total salt and 25% of the flow) from the extensively cleared East Collie subcatchment. The saline (~ 15 000 mg/L) groundwater seepage into the river is the main cause of the high salinity in the reservoir. Reducing the salt contribution from this subcatchment is, therefore, an important step in reducing the salinity in the Wellington Reservoir to a potable level. The groundwater balance estimation and the effects of various salinity intervention scenarios on catchment water balance can be predicted using numerical models.

Engineering works, such as groundwater pumping and deep open drains, to lower the watertable and decrease saline seepage into the Collie River were the salinity management options numerically modelled in this study. The aim was to predict the impact of engineering options in a small catchment like the Spencer Gully catchment. The results indicate that MODFLOW is a powerful tool to delineate and map areas underlain by a shallow watertable (the salinity risk area). The accuracy of the predicted models depends on the datasets used and the assumptions made in the conceptualisation of the catchment and must only be used in relative terms.

The impact of dykes and faults on the distribution of shallow groundwater is limited. This is primarily due to the orientation of the dykes and faults with respect to the direction of groundwater flow. The limited effect of geological structures appears to be due to the apparent lack of lateral continuity in many of the dykes. This may be the result of masking effects of magnetite destruction.

The modeled two-metre deep drains and abstraction bores have a significant impact on the distribution of groundwater. The modeled drains lower the watertable in the adjacent cells of the model by up to one metre. The modeled abstraction bores also lower groundwater in up to four cells adjacent to the bores. Such a watertable lowering would be beneficial in solving waterlogging problems on the low-lying areas. The relief bores have an insignificant impact at the scale simulated in this investigation. They only lower groundwater head to the tops of the bores so the groundwater head will still be at the surface in the surrounding areas.

Groundwater-discharge intervention schemes (engineering options) increase the discharge rate and so drive the catchment to equilibrium faster. Therefore, it is essential, particularly for larger-scale catchments, to calculate the time required for the catchment to reach equilibrium. If the priority is to gain time by implementing recharge intervention scenarios, discharge intervention scenarios should be omitted.

Keywords: Collie River, Wellington Reservoir, reforestation, groundwater, surface water, salinity, engineering options, drain, groundwater pumping.

1 Introduction

1.1 Background and objectives

The Collie River Recovery Catchment covers an area of approximately 2830 km² and is drained by the Bingham, East Collie, and Southern Collie rivers. The Collie River is one of the major water resources of the southwest region of Western Australia. The Wellington Reservoir is located downstream on the Collie River ~ 30 km inland and has a capacity of 185 x10⁶ m³ which represents approximately 10% of the fresh water supply of the southwest region.

The increased salinity of the Collie River and the water in the Wellington Reservoir is a major environmental and economic problem facing the southwest region of Western Australia (Schofield, 1988; Schofield and Ruprecht, 1989). The clearing of deep-rooted native vegetation and its replacement with shallow-rooted annual agricultural crops and pasture has resulted in an increased groundwater recharge rate over two orders of magnitude (Allison and Hughes, 1978; Peck and Williamson 1987; Nulsen, 1998). The increased recharge rate and subsequent groundwater level rise caused mobilisation of salt previously stored in the unsaturated zone (Peck, 1983a). The discharge of this saline groundwater through seepage in the low-lying areas has increased the salinity in the Collie River tributaries and ultimately in the Wellington Reservoir.

The mean annual salinity of the Wellington Reservoir currently is ~ 885 mg/L—a four-fold increase over salinity prior to clearing (Public Works Department, 1979). Although the salinity trends associated with past clearing of the catchment have been masked by other factors such as annual variation of rainfall and the delay between clearing and the response of the rivers, the effect of clearing on the increase of the river salinity is well documented (Peck et al., 1973; Ruprecht and Schofield, 1989).

Experiments into partial reforestation of the already cleared land were established in 1970s and a number of sites were selected for various reforestation strategies embracing different layouts and densities (Ruprecht and Schofield, 1991a, b). These investigations demonstrated the effectiveness of the reforestation in lowering the groundwater level and, in turn, reducing the flux of saline groundwater discharged into the rivers. Currently ~ 78% of the Collie catchment is covered by native bushland, 5% is reforested and the remaining 23% of the catchment is farmed with shallow-rooted cereals and pasture.

As a part of the Western Australia State Salinity Strategy, the Water and Rivers Commission has undertaken to restore the salinity of the Wellington Reservoir to potable levels by 2015. Preliminary analysis suggests that, in the East Collie River branch, a reduction of approximately 50% in the surface water salt load is required to achieve this target (Mauger et al., 2001).

The interaction between saline groundwater and surface water is a complex and dynamic process and not well understood. This is particularly true in catchments that have reached the groundwater hydraulic equilibrium (when groundwater reaches steady state and the watertable level remains constant with only minor seasonal variations). The hydraulic equilibrium does not necessarily mean that the catchment has reached equilibrium in terms of salt balance.

Managing groundwater discharge areas may or may not contribute to the salt balance of a catchment. By increasing the groundwater discharge rates as a salinity management strategy, the watertable may be lowered (increasing the productivity of the previously saline land) but the surface water salinity will increase as a higher salt load is exported from the catchment.

Because increasing groundwater discharge will affect the output component of the water balance of a catchment, numerical models may prove useful tools to examine, quantitatively, the impacts of various groundwater discharge schemes (engineering options) on the reduction of surface water salinity.

The Water and Rivers Commission selected the Spencer Gully subcatchment in the Collie River catchment as a demonstration site to identify and understand the extent of saline land and its impact on surface water salinity. This study attempts to ascertain the appropriate level of site investigation required for implementing salinity management strategies to reduce stream salinity. This process included defining salinity risk, carrying out a hydrogeological investigation to understand groundwater flow characteristics and refining the operational use of the groundwater models such as MODFLOW (Michael et al., 1988), and MAGIC (Mauger and Aust., 1996).

The numerical models MODFLOW and MAGIC used in this investigation are groundwater flow models that deal only with the volumetric balance of groundwater. However, understanding the development and evolution of dryland salinity and its effect on surface water salinity requires estimation of catchment salt balance. Therefore, the average concentrations of groundwater salinity for various components of the water budget (groundwater, surface water, and rainfall) from the limited datasets were estimated and then used, in conjunction with the water budget components, to estimate the salt balance of the catchment.

Previous investigations on the 'Harringtons' property, to the south-east and adjoining the Spencer Gully catchment, were carried out to determine whether contour belts of trees could reduce salinity and groundwater levels. Data from this study were also used to further develop the MODFLOW and MAGIC models and will be included in the analysis of the current study.

The main objectives of this study were to (i) map the potential distribution of saline areas at steady state (where the watertable is less than 2 metres below the natural surface); (ii) present a conceptual model for the groundwater flow and hydrogeology of the catchment; (iii) test the usefulness of various datasets (i.e. desk top analysis; hydrogeological investigations which included drilling; airborne geophysical survey; field work and groundwater modelling) in identifying the spatial and temporal distribution of the saline areas; (iv) compare the results of the MODFLOW and MAGIC models in terms of salinity distribution; and (v) test recommended management options such as drains, groundwater pumping and relief bores (i.e. flowing bores) and finally (vi) develop a groundwater model to use for salinity management strategies.

1.2 Salinity risk assessment

The use of various biophysical datasets to measure current saline-affected land in Western Australia has been well documented (George and Dogramaci, 2000; Short and McConnell 2001). These datasets are characterised by various degrees of accuracy, depending on the method and scale at which they were acquired. Regional-scale geological and hydrogeological maps are accurate when used in regional-scale studies, but their accuracy diminishes proportionally when they are used as the main datasets at smaller scales, such as small subcatchment or farm scale.

The objective of early salinity investigations was to determine the extent of dryland salinity at regional scales using information from geological, soil, topographic and airborne geophysical survey maps (Short and McConnell, 2001; George and Dogramaci, 2000; Ferdowsian et al., 1996). The accepted error margin in mapping the extent of dryland salinity at regional scales is commonly greater than that acceptable at farm scale where salinity risk areas must be more accurately delineated. In addition, smaller scale investigations concentrated on the impact of salinity management strategies related to economically or ecologically high value assets such as infrastructure in rural towns (Matta, 2000) and wetlands (George and Dogramaci, 2000). Therefore, a combination of regional and local scale datasets is required to increase the predictive accuracy of the current and potential extent of dryland salinity and assess as accurately as possible the effects of management options on controlling its spread.

Previous investigations into dryland salinity in the Water Resources Recovery Catchments used various definitions for 'salinity risk assessment' (Land Assessment 1999; Hundi and Mauger, 2001; De Silva et al., 2001). Some assumed that the groundwater discharge area at equilibrium was the area at risk from salinisation. The groundwater discharge may occur in areas characterised by steep surface gradients underlain by relatively fresh groundwater where watertable rises and the eventual discharge of groundwater is likely to contribute little salt but relatively large volumes of fresh groundwater to the surface runoff. On the other hand, fresh groundwater discharge in areas where surface gradients are relatively low may result in groundwater remaining on the surface for a prolonged period allowing evaporation and the development of saline soils.

The Land Assessment (1999) investigation of the Spencer Gully catchment used soil salinity as a definition for 'salinity risk assessment'. The current extent of the saline land referred to as 'surface soil salinity' was mapped using soil-type data, aerial photographs and a field survey where the area was gridded and 61 surface soil salinity measurements obtained. The study concluded that saline areas currently make up ~ 5% of the catchment and are located mostly along the main drainage line. The study predicted that over 17% of the catchment is at risk of salinisation from rising groundwater levels as the catchment reaches hydraulic equilibrium. Importantly, this method may underestimate the extent of salinity when defining a 'salinity risk area' as it does not take into account likely saline areas developed due to groundwater evaporation through capillary action. Capillary action occurs at depths < 2 m below the land surface where groundwater moves upward in the unsaturated zone (Freeze and Cherry, 1979). This results in further evaporation of groundwater and the concentration of salts in soils, at or near the land surface. The time for enough salt to accumulate that it has an adverse effect on the vegetation may be lengthy, which means that increases in salts stored in this zone are not readily detected and accounted for when mapping potential saline risk areas.

This study builds on previous work that used biophysical datasets to investigate the spatial distribution of existing and potential saline areas at hydraulic equilibrium. In this report, *the salinity risk area is defined as areas where, at steady state condition, the minimum depth to watertable is less than 2 metres below the natural surface*. At this depth, the combined effects of direct evaporation of groundwater, together with evaporation of groundwater due to capillary action, exacerbate the effects of salinisation at the land surface.

1.3 Location and climate

The Spencer Gully catchment is located in the upper reaches of the Collie River catchment, within the East Collie River subcatchment (James Crossing), ~ 8 km west of Darkan (Fig. 1). The area is about 5.4 km². The land is predominantly cleared and used for sheep grazing with minor areas used for cropping.

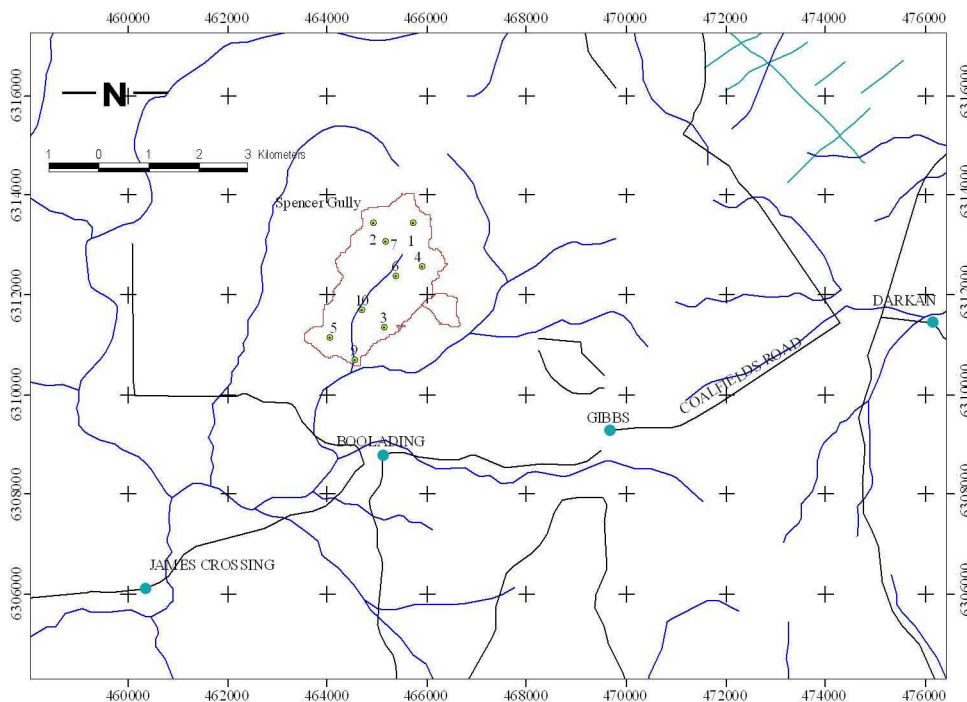


Figure 1. The Spencer Gully catchment and drainage system

The climate is Mediterranean with warm, dry summers and cold, wet winters. Mean annual rainfall near Darkan is 610 mm and the mean maximum and minimum temperatures in January and August for Darkan are 31 °C, 16 °C and 14 °C, 4 °C respectively.

1.4 Topography and drainage

The land surface of the Spencer Gully catchment displays a variation in relief that may closely resemble the underlying bedrock topography. Undulating areas of granitic and gneissic outcrops with northerly-trending ridges characterise the catchment. The topography gradually increases in elevation from ~ 270 m above Australian Height Datum (AHD) in the southern part of the catchment to ~ 370 m AHD in the northern and north-western catchment boundary (Fig. 2).

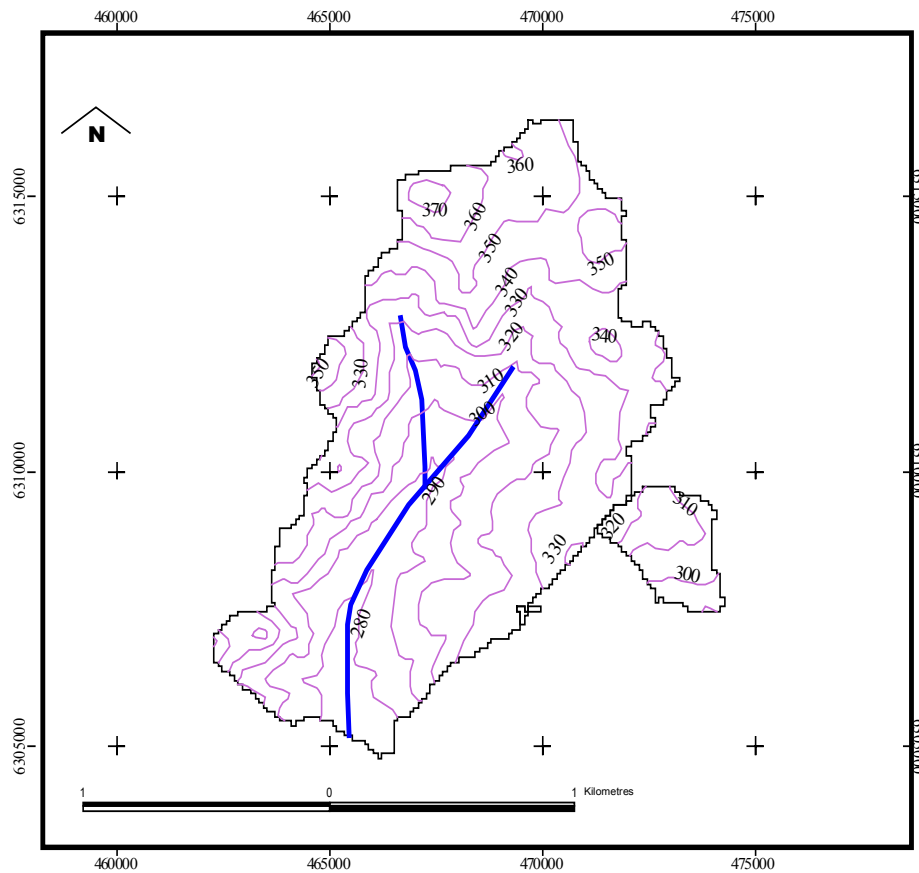


Figure 2. Catchment topography and main drainage

The drainage system of the catchment comprises the main Spencer Gully creek and a series of tributaries draining the eastern and western flanks of the catchment. The drainage system has a relatively steep gradient of ~ 5%.

1.5 Geological setting

The principal lithology mapped in the Spencer Gully catchment is migmatite of Archaean age which is described by Wilde and Walker (1982) as a strongly contorted, nebulitic and banded metamorphic rock (Fig. 3). This ‘mixed rock’ formed during the comagmatic intrusion of Archaean granitoids; granite, adamellite and quartz monzonite (Wilde and Walker 1982). In terms of fabric, outcrop and drilling observations reveal both characteristic metamorphic mineralogical ‘banding’ and granitic textures within the migmatite (Wilde and Walker, 1982).

Similarities in the migmatite’s mineralogical and fabric character, with respect to the adjacent igneous rocks (its precursors), are supported by a general lack of magnetic variability observed in the aeromagnetic dataset. Conversely, demagnetized fault zones, along with the strong magnetic character of Proterozoic gabbroic and doleritic dykes are clearly delineated in the magnetic data. However, in the case

of mafic dykes, although there is sporadic outcrop within the catchment, the outcrop is too small to be geologically mapped at the scale of 1:250 000 shown in Figure 3. The magnetic characteristics are interpreted from aeromagnetic survey and described below.

1.6 Aeromagnetic surveys

Aeromagnetic surveys map the variations in the intensity of the Earth's magnetic field due to magnetic susceptibility variations and/or remnant magnetic variations in the near surface. Rocks regarded as non-magnetic (0.2 to 0.5% magnetite) in hand specimen may produce a substantial aeromagnetic response when they occur in large volume. Conversely, a muted response from lithologies known to contain magnetic material provides information on magnetite destruction and the possible pathways of alteration fluids through weaknesses in the bedrock.

The aeromagnetic data are particularly useful in areas of limited bedrock exposure, such as in the Collie River catchment, where deductions can be made on the lateral continuity of variably magnetic lithologies and structures. In Spencer Gully catchment, the magnetic variability of the Archaean granitoid and migmatitic basement rocks is minimal apart from a decrease in the magnetic response in the central and south-western sections of the catchment. This transition is attributed to a slight compositional change and/or magnetite destruction due to the passage of alteration fluids through nearby faults. There are a number of suites of Proterozoic dolerite dykes interpreted from the data and characterised by moderate to strong magnetic responses, with the variation likely to correspond to a change in mineralogy (Fig. 3). The dominant trends of these dykes are regional east-west, with a strong east-southeast and a dominant northwest phase corresponding to the regional mineral foliation (Wilde and Walker, 1982). This foliation is responsible for curvilinear trends frequently observed in the dykes and is associated with metamorphism prior to their emplacement (Wilde et al., 1996). The northwest-trending dolerite dykes are commonly thinner and more laterally extensive than their counterparts, and are particularly pervasive in the northern section of Spencer Gully where they cut and displace dykes with east-west orientations.

The faults show similar trends to the dolerite dykes, with three major, regional northwest-trending demagnetised zones representing major faults with intense magnetite destruction. Faults, along with dolerite dykes, locally control the position of modern drainage lines. However, frequently, the development of a superimposed drainage system simply reflects the contemporary land surface.

The local trends in the Spencer Gully catchment generally mimic the regional observations. East-west-trending dolerite dykes occur to the north and south of the drilling area are cut and displaced by laterally continuous northwest-trending dykes. The disruption of the lateral continuity of many of the dolerite dykes is possibly due to factors including: 'pinching and swelling' during intrusion; magnetite destruction associated with geological events including emplacement; cooling; and the passage of alteration fluids during episodes of metamorphism and faulting. To the south of the area, northwest-trending dykes are displaced by north-east-trending faults. These faults are dominant and are observed, at this scale, to constrain sections of the main drainage lines. North-west faults are less obvious, with one north-west fault to the south influencing a drainage confluence, and others, not annotated due to the scale of the interpretation, likely to coincide with the positions of the laterally continuous north-west dykes.

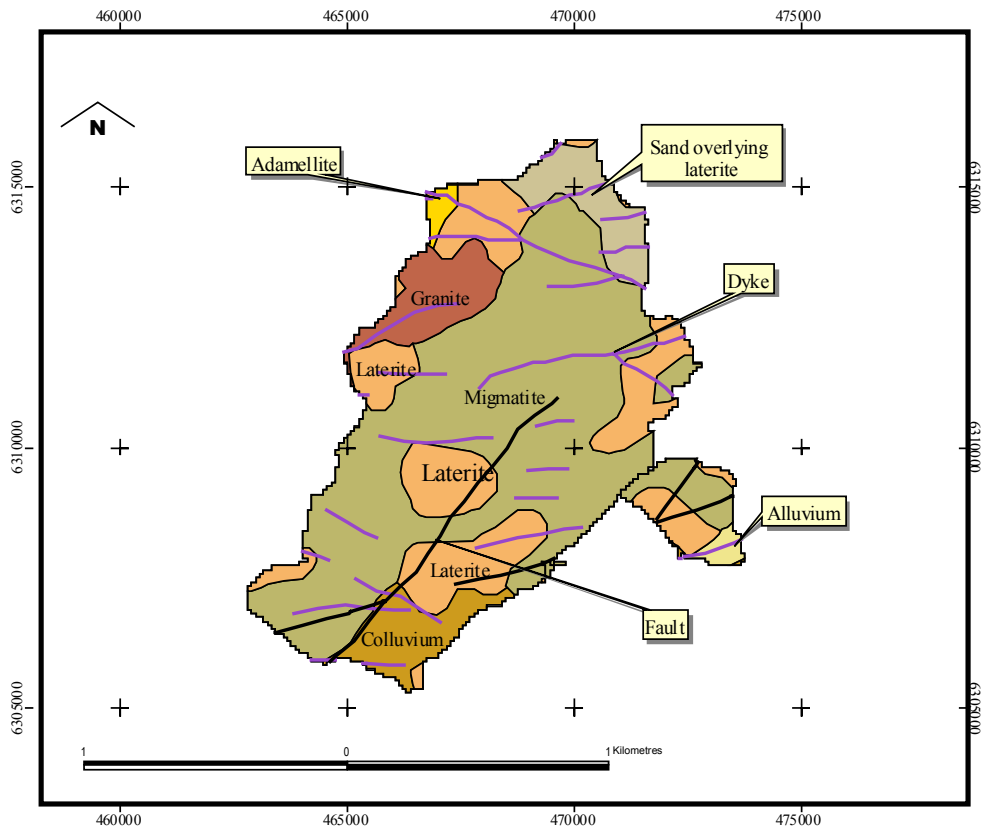


Figure 3. Geological map (after Wilde and Walker, 1982)

The interpreted faults and dykes are based on the aeromagnetic survey.

2 Desktop study and prediction of potential salinisation

Investigation of the potential land salinisation at hydraulic equilibrium (steady state) for the Spencer Gully catchment started after a field visit to discuss the results of the preliminary soil-landscape-based mapping of saline areas by Land Assessment (1999). The definition of ‘salinity risk’ used for this analysis was *‘the likely incidence of a shallow watertable under steady state conditions where sufficient groundwater discharge is likely to result in the reduction of yield of traditional crops and pastures or the reduction in health of native vegetation’* (Fig. 4). The desktop study relied on the following data sets and information.

- Stereophotographs (slope, terrain attributes)
- Land type (soils, geology and landforms as a surrogate for regolith)
- Land use (cover, area)
- Date of clearing (mapping)
- Existing salinity (field inspection)
- Local hydrogeology / drilling (Harrington’s; proximal SE)
- Experience from related studies nearby and within the region.
- Discussion of the history of development with land holders.

2.1 Criteria for mapping salinity risk area

The interpretation of the above datasets and the field investigation allowed areas at risk of dryland salinity to be mapped according to the following criteria:

- Topography: On steep (convex) slopes, saline areas will be closer to the drainage line, while for concave slopes, the salinity expands to the shape of the contour lines, with the saline area restricted below the ‘break of slope’.
- Regolith thickness, geology and soil maps: Salinity will be more extensive on topographically flat areas, below deep soils towards the lower slopes, near outcrop in drainage lines, and proximal to geological structures such as faults and recognised geological ‘barriers’ (for example, dykes). Greatest risk will be below areas of gravels and sands that were cleared recently.
- Land use: There is limited risk of salinisation at the large areas of intact remnant vegetation.
- Date of clearing: While salinity develops within 20–30 years of clearing on deep soils, it develops at a slower rate in deep, *in situ* regolith, and is stationary in shallow areas soon after clearing (assuming shallow regolith equates to a ‘low’ and therefore ‘quickly’ flushed, or non-existent salt store).
- Existing salinity: Salinity will expand from existing saline areas, or will develop at the confluence of slopes (convergence zones). The risk is based on nearest incidence of salinity or outcrop in zone of convergence.

- Local hydrogeology—local flow systems: The rise of salinity in up-slope monitored bores may indicate the development of salinity, and, in currently saline areas, increased discharge rates and the expansion of existing salinity.
- Experience was used to define similar incidences of salinity development in similar terrains, through integrating hydrogeological results from drilling with landform attributes.
- An account of the history of the farm was required to set the temporal aspects (especially clearing) in the context of the physical attributes.

2.2 Salinity risk map

The salinity risk map at steady state is based on the average rainfall of 610 mm/year. The saline risk area (Fig. 4) is likely to have a minimum watertable depth of 2 m in early summer when the groundwater systems have attained a new equilibrium (within 10–20 years). About 24% of the catchment is potentially saline.

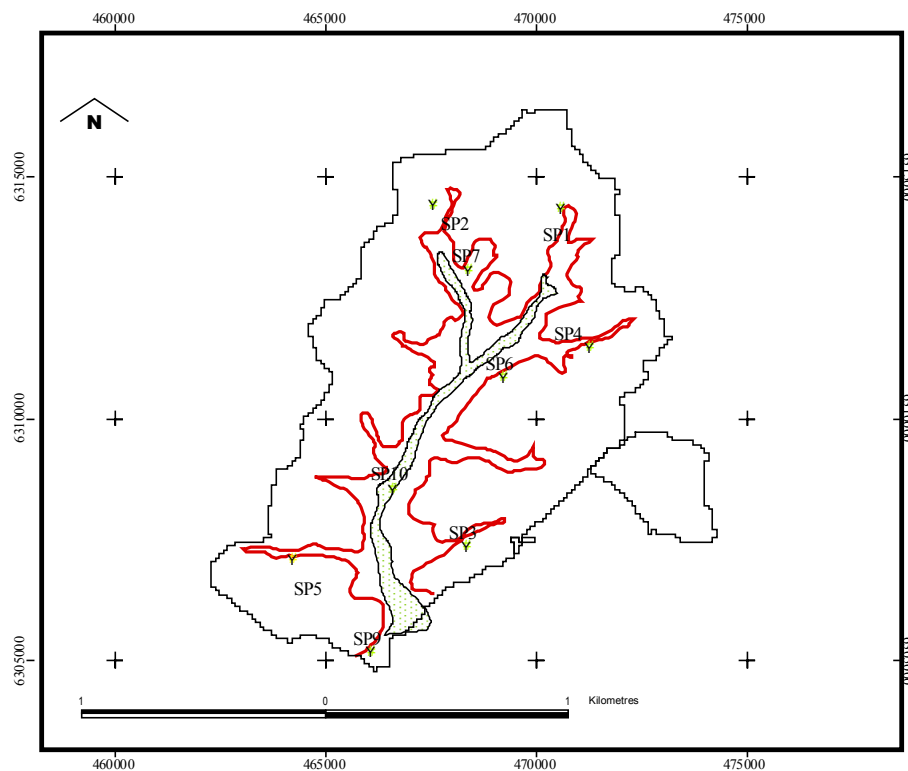


Figure 4. The potential extent of saline area at steady state —approximately 24% of the catchment

Based on desktop analysis (see section 2). The existing saline area (7% of the catchment) mapped by Land Assessment (1999) is shown by the dotted area. SP 1-10 are bore locations.

3 Hydrogeology and groundwater flow

In order to understand groundwater dynamics and salinity distribution across the Spencer Gully catchment, a drilling program was initiated and nine sites were selected based on the interpretation of the airborne magnetic dataset and aerial photographs (Fig. 4). Drill sites were then selected based on the following criteria:

- Recharge potential (causing the rise of the watertable)
- Evaluation of the conceptual model (hydrogeology)
- Impact of time of clearing (the response of stream salinisation to clearing)
- Salinity Risk (areas underlain by shallow groundwater).

All nine sites were drilled to the 'basement' (defined at Spencer Gully as drill refusal) with the Rotary Air Blast Rig. It was apparent that, in the majority of sites, groundwater infiltration into joints and fractures had slightly weathered some of the mineral grains promoting dissolution along grain boundaries. The majority of bores drilled in the catchment penetrated migmatite-derived regolith that was typically composed of biotite-rich melanosomes and leucosomes of coarse-grained quartz and feldspar-rich material. Metamorphic fabric was absent from granitoid regolith in bores, SP1 and SP2, in which the dominant constituents were clays and fine-to coarse-grained quartz sand.

The stratigraphy of the regolith shows vertical continuity between the drill holes and can be described according to three main horizons.

- A lower horizon develops above the basement at the weathering front, which has a mean vertical thickness of 4 m, and is characterised by the formation of saprock. Saprock develops in response to the fragmental disintegration of basement rocks rich in quartz and feldspar and is typically 'gritty' due to this process promoting the separation of individual mineral grains within the rock.
- Above the lower horizon, primary mineralogy becomes less important as most primary minerals weather to clay, promoting the development of a saprolitic sandy-clay horizon. At Spencer Gully, the mean vertical thickness of the saprolite is 13 m.
- Surficial deposits comprising medium-to coarse-grained quartz sands and clays, with a maximum thickness of 1.9 m, overlie the saprolite.

Groundwater occurs within faults, fractures and joints, along with pore spaces in the weathered profile. Where saprock develops, the horizon is characterised by a relatively higher hydraulic conductivity, and is likely to represent the horizon where the majority of the lateral flow takes place (Fig. 5). The estimated yields from airlifting the boreholes during drilling were typically 0.2–0.5 L/s (SP 1,4,9,10). Two bores were only damp and did not produce sufficient water by the completion of drilling (bore SP 6 developed a thin groundwater system subsequently) and two (bores SP 2 and SP 5) made no continuous supply of water when airlifted (Table 1).

Table 1. Borehole construction, watertable levels and salinity

Bore	Depth to basement (m)	Depth cased (m)	Casing above ground (m)	Saprock thickness (m)	Conductivity (after bailing) (mS/m)	Estimated yield (airlift) (kL/day)
SP1	21.9	22.4	0.6	1.3	580	> 0.5
SP2	26.25	26.7	0.6	8.25	268	Minor
SP3	9.4	9.38	0.4	0.9	Dry	Nil
SP4	17.8	17.8	0.5	2.3	1540	< 0.5
SP5	20.4	20.32	0.5	5	1035	Nil
SP6	6.9	6.92	0.4	2.1	2340	Nil
SP7	11.4	11.41	0.5	10	1300	0.2
SP9	23	19.4	0.9	2.8	2060	< 0.5
SP10	10	10	0.5	2	2400	>0.5

The greatest yield was obtained from bore SP 1 (0.5 L/s) within the migmatite. The watertable is typically deep on the slopes (> 10 m), moderate in the mid-slopes (> 5 m) and shallow (< 2 m) within the valleys. Piezometric heads are between 1 and 2 m above ground surface within saline seeps. Based on these measurements, the watertable has a sufficient head difference to allow lateral groundwater flow in the catchment. The groundwater in the saprock aquifer is semi-confined by an overlying saprolite clay layer.

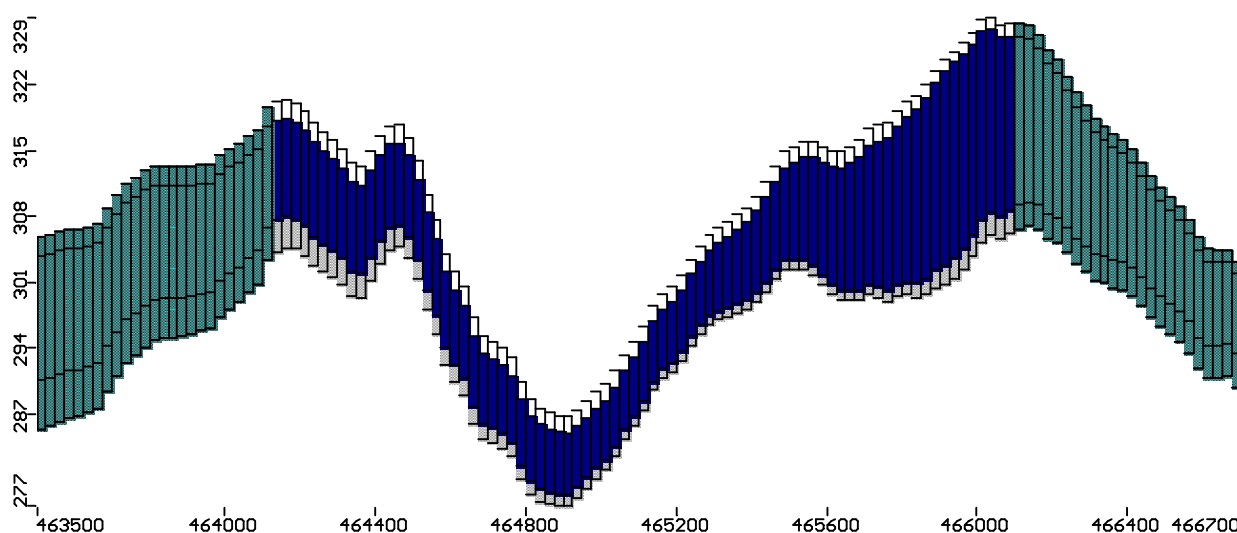


Figure 5. East-west cross section of the catchment showing the main hydrogeological units: saprock (grey), overlying weathered profile (blue) and surficial deposits (white). The saprock is the main water-bearing formation. The other cells are outside the model domain.

The hydraulic conductivity of the material comprising the three hydrogeological units varies as a consequence of the rock mineralogy and location in the landscape. The pump test and slug test analyses to

calculate hydraulic conductivity of similar materials were carried out in various catchments of Western Australia (Martin 1984; Dogramaci, 1999; Clarke, et al., 2000).

The results showed differences in orders of magnitude in horizontal hydraulic conductivity between the surficial deposits (the top layer) and the saprock aquifer-associated material. As a generalisation, the hydraulic conductivity of the three hydrogeological units (namely the saprock, weathered sandy clay profile and overlying surficial deposits) range from 0.1 to 0.001 m/day, 0.01 to 0.005 m/day and 0.1 to 100 m/day respectively. Groundwater salinity expressed as electrical conductivity (EC) ranges from 268 mS/m to 2400 mS/m (salinity in mg/L = conductivity in EC x 5.5). The groundwater in bores SP1 and SP2 at northern catchment boundaries is relatively fresh (278 mS/m and 500mS/m respectively). Groundwater on the eastern and western slopes on the other hand is generally brackish to saline, with most groundwater samples having a salinity of between 1035 mS/m and 2340 mS/m.

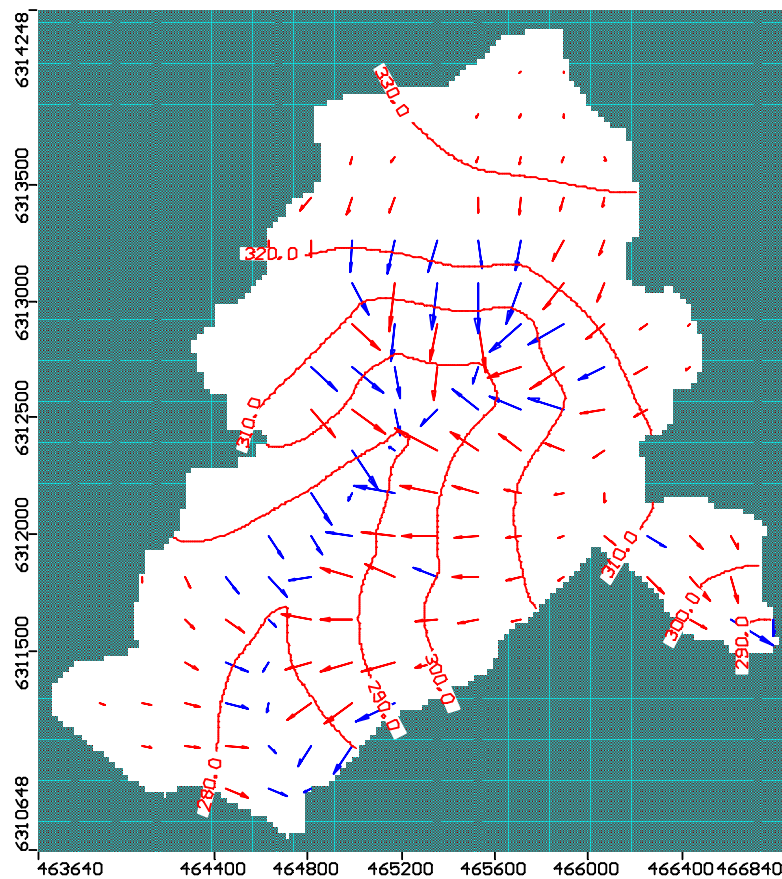


Figure 6. Arrows show the groundwater flow direction in the saprock aquifer. The contours represent watertable elevation in metres AHD.

4 Salinity of surface water and salt equilibrium

The electrical conductivity (EC a widely used surrogate for salinity) of the stream draining the Spencer Gully catchment was measured at 14 sites ranging from 1580 mS/m to 2560 mS/m (salinity ~8,500 to 14,000 mg/L). The EC upstream of the western branch (Fig. 2) is 1580 mS/m and steadily increases downstream to 1800 mS/m where it mixes with eastern branch. The EC upstream of the eastern branch is 1600 mS/m, and increases steadily down flow lines to 1800 mS/m. The EC of the main branch continues to increase and reaches a maximum value of 2560 mS/m where it mixes with the main Spencer Gully creek. The increase in the salinity levels along the natural drains is due to the mixing with shallow saline groundwater.

The flow rate of surface water discharging from the catchment is highly variable (Fig 7). The average daily flow starting from 20 April 2000 to 20 April 2001 is 1200 m³. These measurements only represent a first order estimate for stream flow at Spencer Gully and are consistent with measured discharge values of the similar sized cleared subcatchments within the Collie catchment (Williamson et al, 1987)

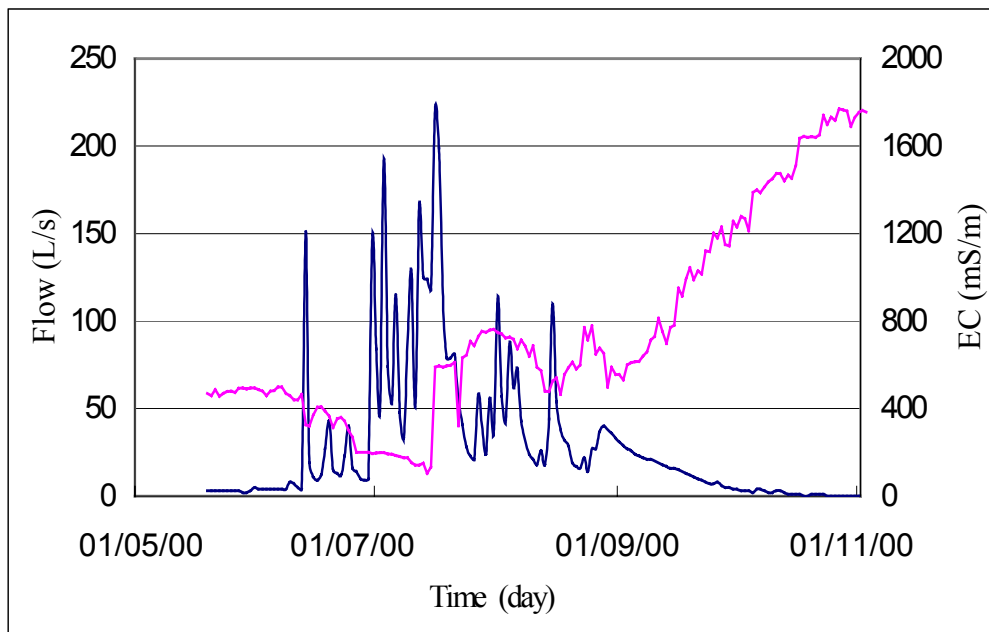


Figure 7. Flow rate and electrical conductivity of the surface water discharging from the catchment.

The average base flow was calculated by hydrograph separation using three different methods—Chapman (9.3 L/s), Boughton (6.9 L/s) and Lyne and Hollick (4.6 L/s). Assuming average base flow of 6.9 L/s and an average groundwater salinity in the valley floor of ~ 2200 mS/m (~12 000 mg/L) the salt flux discharged from the catchment is ~ 2600 tonnes. The catchment area is ~ 5,3 Km² and average rainfall is 610 mm, so assuming a concentration of Cl of 5 mg/L (Hingston and Gailitis, 1976), the average annual salt flux input via rainfall to the catchment is ~ 16 tonnes. The salt output/input ratio of ~ 160 suggests that the system is not in equilibrium in terms of the salt balance, and the flushing of salt continues from the catchment, most likely due to the mobilisation of salt (mainly) in the saprolite profile. The approximate turnover time of salt can be calculated by dividing the inventory of salt in groundwater by

the annual input (assuming there are no significant internal sources of chloride ion in the aquifer). The total amount of salt is ~ 400 000 tonnes for the Spencer Gully catchment, calculated assuming an average combined aquifer thickness of 18 m, a total porosity of 40% and salinity of 12 000 mg/L (Bari and Boyd, 1992). This yields a turnover time on the order of ~ 140 years, which is commensurate with the water residence time in this type of environment.

5 Numerical modelling (MODFLOW)

The drilling results and airborne magnetic data delineated the aquifers, geological structures and groundwater flow but, of course, only indicated the current distribution of groundwater levels in the catchment. Numerical modelling, on the other hand, can provide information on the temporal changes in watertable and flow dynamics in response to changes in the type of vegetation cover across the catchment. Salinity-susceptible areas then can be inferred from watertable maps obtained from numerical models.

The currently saline area extends over 7% of the Spencer Gully catchment (Land Assessment 1999) but the watertable measurements in the catchment and the adjacent 'Harrington' farm show that the watertable in some piezometers, particularly at the catchment boundary, is still rising. This may indicate that the catchment has not yet reached hydraulic equilibrium and more areas, particularly in the low-lying areas along the main Spencer Gully creek and along the smaller tributaries, may be affected by watertable rises in future. These areas represent saline and the potential salinity risk areas in the catchment. Numerical modelling such as MAGIC and MODFLOW will help to interpret and map the potential saline areas at hydraulic equilibrium.

The impacts of various intervention scenarios to control groundwater levels and prevent saline groundwater seepage were modelled. These groundwater modelling tools are useful in helping to plan projects in which objectives are set and met in a stepwise fashion. The numerical modelling, combined with the fieldwork, will assist decision making where various scenarios can be tested as a part of integral management options.

Comparing results from the two simulation models, MODFLOW and MAGIC, may be useful to illustrate the groundwater budget and the spatial distribution of saline-prone areas when the catchment reaches hydraulic equilibrium. The discrepancy of the results from the models may also highlight their usefulness and deficiencies for future catchment salinity investigations.

Conceptually, the hydrogeology of the Spencer Gully catchment is divided into three layers. The surficial deposits, a semi-confined sandy clay horizon and saprock. The surficial sediments are largely unconfined while the saprock can vary from confined to semi-confined by overlying weathered sandy clay material. This reflects the multi-layered nature of the aquifers within the catchment, with each hydrogeological units characterised by distinct hydraulic properties.

The inputs to the system are recharge, due to precipitation, and surface water inflow. The recharge rate was calculated using the estimated field saturation index of the top layer for the first 12-months. The average recharge into the catchment was calculated as ~ 55 mm/year. The top layer was treated as drainage where groundwater recharged the bottom layers and, when the watertable reached the land surface, overflowed downstream.

5.1 Steady State Model (MODFLOW)

The steady state model covers the Spencer Gully catchment and the 'Harrington Farm' on the east-side of the catchment. Ten additional bores on this farm are used in the model for calibration. The area of the

model, ~ 2.5 km by ~ 3 km, incorporates all the boreholes in the catchment and the adjacent farm. Each cell within the model represents 25 m² resulting in 144 rows and 128 columns, with 18 432 cells for the catchment area. The model consists of three hydrogeological layers and incorporates soil properties, topographical and climatic data.

The topographical data were taken from digital elevation maps of the catchment and then kriged to obtain a value for each node within the model area. The thickness of each hydrogeological layer was interpreted from the geological logs of the 19 bores in the study area. The effective porosity of the three layers (from the top) is 20%, 10% and 25%. Recharge for each individual cell was calculated based on vegetation cover and field saturated capacity which ranged from 1×10^{-6} to 3×10^{-4} m/day.

An assessment of land use, groundwater salinity, topographic position and soil type was used to gain a first order approximate of recharge. An initial assessment suggests that cleared areas, with permeable surface soils and with lower groundwater salinity levels, are likely to have higher recharge rates. Bores in the upper-slopes (SP1 and SP2) fit this category. However, relatively high recharge rates may also occur on sites with deeper water levels (thick regolith) and saline groundwater (SP4, SP5 and SP6) such as deep duplex soils.

Recharge rates *estimated* using the chloride-evaporation index method (Allison and Hughes, 1978; Mazor and George, 1992) assumes that groundwater chloride concentration is in equilibrium with the incoming flux from rainfall (taken as 5 mg/L). The results suggest a range from greater than 20 mm/year near SP1 to less than 0.1 mm/year at SP6, with a mean value of 0.15 mm/year for the catchment. These rates are more likely to represent pre-clearing conditions and not the existing conditions. The hydrograph analysis in the eastern and northern Wheatbelt suggests that the rate of recharge is one to two orders of magnitude higher than this value. The hydrograph analysis suggests that the rate of recharge post-clearing varies from 5% to 12% depending on the climate and location of the catchments (Nulsen, 1998). In this study, the recharge rates were calculated for each individual cell based on the hydrogeological properties and the type of vegetation cover. The results of recharge rates were then compared with those obtained from hydrograph analysis in other parts of the Collie catchment and the Wheatbelt.

The recharge rates for each cell were simulated using MAGIC (Mauger, 1996) over one year of average rainfall in monthly time steps. The year started at the beginning of August when soil-water content was expected to be at its maximum. Assuming steady state conditions, the soil water stored at the end of the 'average' year equals the water stored at its commencement. To estimate the soil-water store for August, a run of the model commenced with saturated soil. Two years were then run in sequence with average rainfall to produce soil stores that were used as the initial condition for the third year that represented the true 'average' year. The output of the monthly time step simulation was the potential recharge from each cell to the saprolite horizon. Potential recharge became actual recharge if there was sufficient capacity for deep groundwater flow away from the site, the capacity being determined by the transmissivity and hydraulic gradient at the site. The average recharge calculated from groundwater balance represented 9% of the average rainfall in the catchment. This value is consistent with recharge values of other parts of the Collie catchment (Johnston, 1987), and catchments in the Wheatbelt of Western Australia (Nulsen, 1998).

5.2 Calibration and results of steady state model (MODFLOW)

The steady state model was calibrated using the observed groundwater heads from the Spencer Gully and Harrington Farm. The observed versus estimated depths to the watertable from simulation (Fig. 8) suggest

that the standard error of estimates is 0.6 m with 95% confidence level and RMS (Root Mean Squared) of 4.1%.

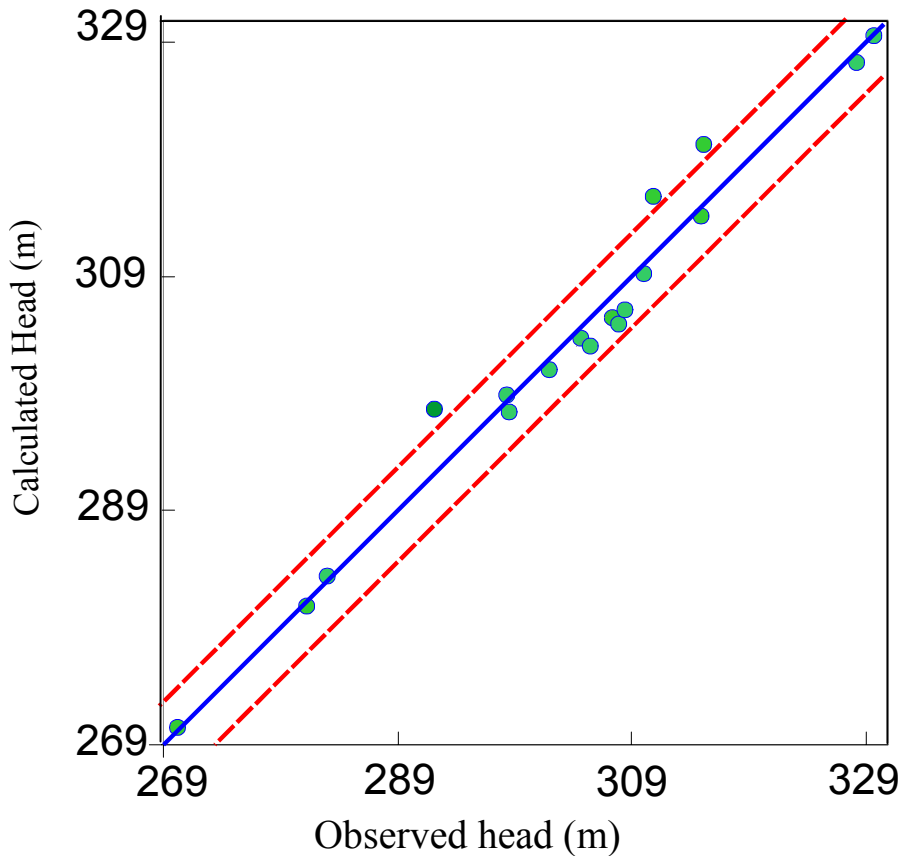


Figure 8. Correlation of simulated heads vs observed heads in metres above AHD. The 95% confidence interval is represented by the two dashed lines.

The optimisation of the model was carried out using the WinPEST package to test the impact of the hydraulic parameters on the correlation between observed and calculated groundwater heads. The values of hydraulic parameters from WinPEST were similar to values used in the model. Only small variations of 0.02 m/day in vertical hydraulic conductivity values were required to optimise the output of the model.

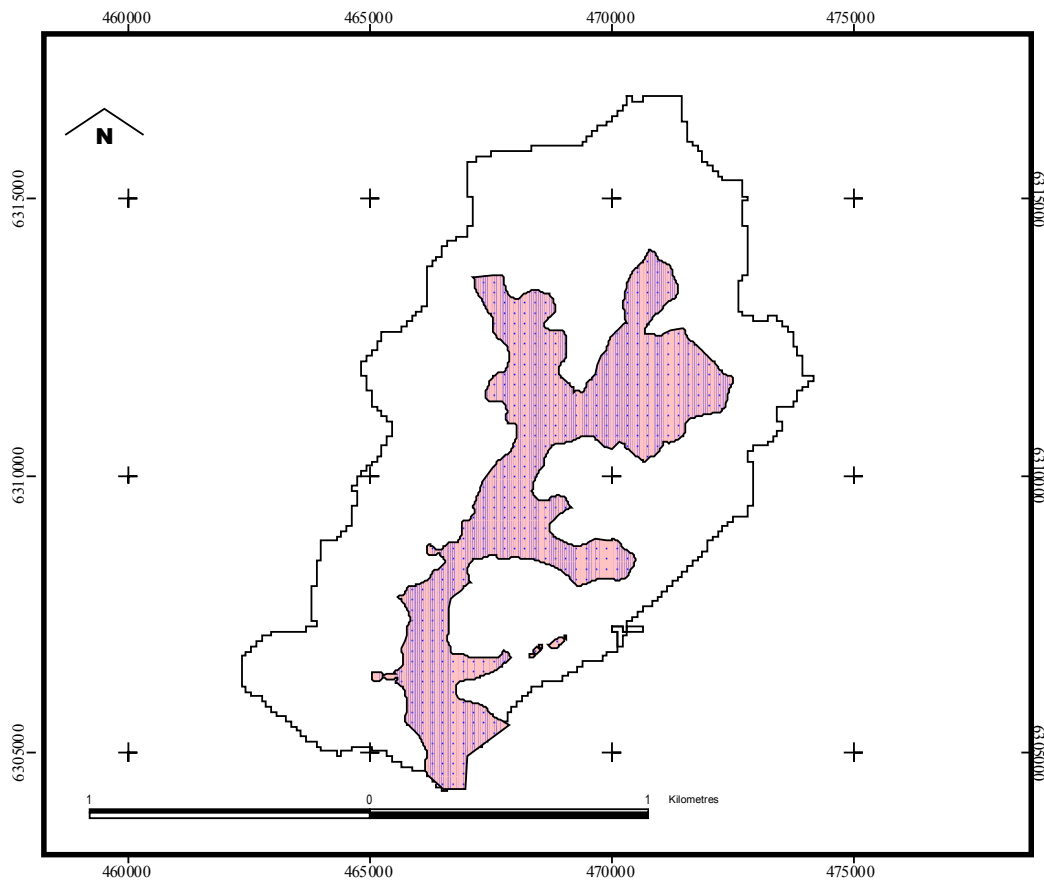


Figure 9. Groundwater modelling results

The shaded area (about 25% of the catchment) indicates where the watertable is predicted to be less than 2 m deep, the critical depth for land salinisation.

The results of the modelling in terms of the depth to watertable are shown in Figure 9. Approximately 25% of the catchment has a watertable < 2 m deep at hydraulic equilibrium. Field investigations and watertable measurements in the few bores located in this area suggest that the current extent of salinity in the catchment may closely resemble these results. Whether the catchment has reached equilibrium or not is discussed further in the following sections. The results of the model run suggest that the average groundwater velocity is 15 m/year, resulting in a travel time over the length of the catchment of ~ 170 years. This value is much higher than the groundwater velocity in the eastern Wheatbelt catchments, which is due to the steeper hydraulic gradients in the Spencer Gully.

The recharge rate is the most critical and determinate factor in the model for mapping the steady state shallow watertable (< 2 m deep). The recharge rate in the current study was calculated on an individual cell basis and the yearly average recharge values across the catchment are consistent with average yearly recharge values calculated by hydrograph analysis (Nulsen, 1998). The calculated recharge rate of 55 mm/year is assumed to be the upper limit and is a conservative value for the Spencer Gully catchment. The predicted area underlain by shallow watertable represents the maximum extent of land salinisation.

5.3 Numerical Modelling (MAGIC)

Since identical conceptual hydrogeological models were used to run the MODFLOW and MAGIC models and if the calculation methods were equivalent, the locations and rates of deep groundwater discharge should be the same from both MAGIC and MODFLOW models. In MAGIC model, groundwater flows are calculated by a simplified method. Water moved down-slope (as determined from surface topography) at rates that are limited by the transmissivity and surface gradient. If inflow from up-slope areas exceeds the capacity for flow downstream at any site, the difference is assumed to flow vertically upwards as deep groundwater discharge. If inflows from up-slope are less than the downstream capacity, any potential recharge at the site will be added to the flow downstream up to the limit of the downstream flow capacity.

The above calculation of discharge did not account for the pressure required to achieve the vertical flow rate. Comparison with the MODFLOW results indicated the need to expand the discharge area in response to development of pressure required for discharge. Thus, the MAGIC model has been modified so that discharge is spread over all areas up-slope of a site where discharge is needed, such that the groundwater level is uniformly graded over the discharge area. At all points in the discharge area, the head difference of the groundwater level minus top-of-clay level, applied to the transmissivity and depth of the clay layer, equates to the rate of discharge at that point. While agreement is generally good, the MODFLOW results should be considered more accurate and preferred when designing any works that depend on accurate location of discharge areas. The advantage of the MAGIC analysis is that it can be applied quickly to gain a general estimate of the extent of land subject to discharge of deep groundwater.

5.4 Effect of dykes and faults on groundwater flow

Magnetic data provide information on lithological and mineralogical variation (granite basement, faults and dykes) within the unweathered crystalline basement rock. Combined, these interpretations may allow deductions on porosity and permeability variation and, therefore, enable the development of a hydrogeological model of how groundwater may occur and move through the regolith profile across different lithologies. Numerical simulation incorporating the dykes and faults with their respective hydraulic parameters may provide information on their impact on the distribution of shallow groundwater and, subsequently, the development of saline areas within the catchment.

The hydraulic conductivity contrasts between regolith materials derived from migmatite, granitoids and dolerite dykes are greatest at the weathering front (saprock) and less significant in the overlying sandy clay profile. The saprock (developed over dolerite dykes) may form an effective barrier to groundwater base flow depending on the topography and the geometry of the dyke with respect to hydraulic gradients (McCrea et al., 1990). These controls are also important in determining the ability of faults to constrain the movement of groundwater. Therefore, in this model, the hydraulic conductivity of saprock (developed over dolerite dykes) was ascribed a value of 0.008 m/day, which is two orders of magnitude lower than that nominated for the saprolite horizon (Clarke et al., 2000). The hydraulic conductivity values used for the saprolite (developed above saprock) was the same for migmatite, granitoids and dolerite dykes. Conversely, the hydraulic conductivity of faults, regardless of lithology, was one order of magnitude higher (Clarke et al., 2000).

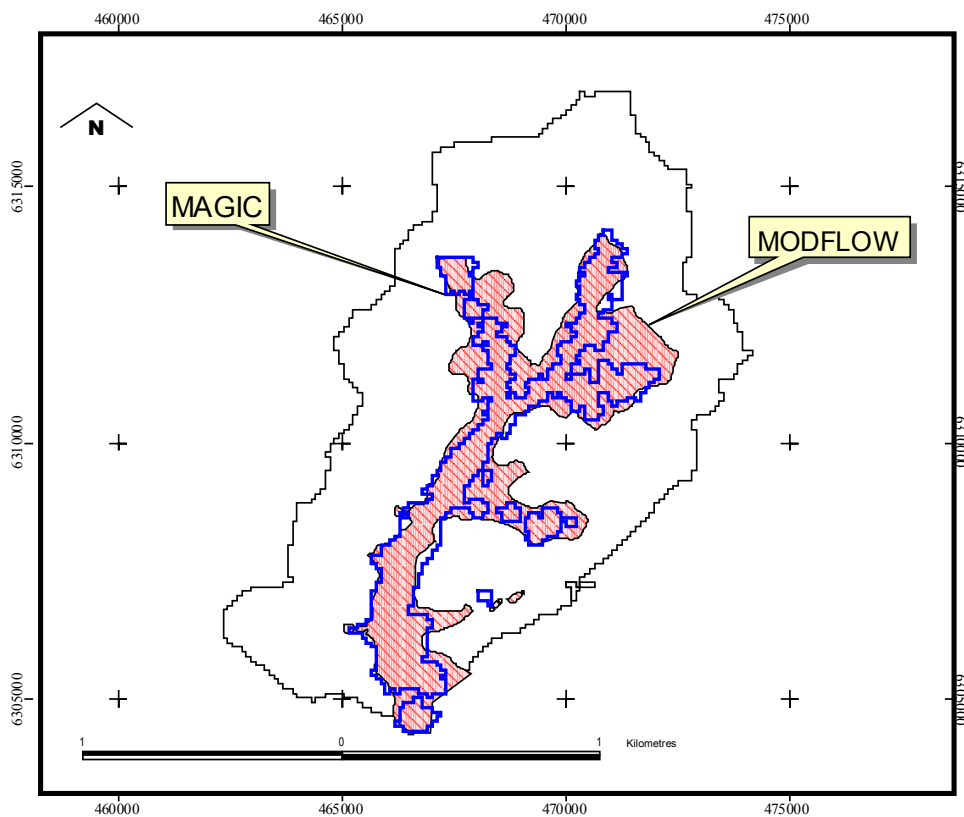


Figure 10. Comparing areas of discharge simulated by MODFLOW and MAGIC.

The results of the model run incorporating dykes and faults suggest that the spatial distribution of shallow groundwater in the Spencer Gully catchment is not significantly affected or controlled by these geological features (Fig. 11). The only area where shallow groundwater extended after incorporating dykes and faults into the steady state model is in the north-eastern part of the catchment (which coincides with the major continuous northwest-southeast-trending dyke), and is less than 1% of the total area modelled as being underlain by a watertable at < 2 m depth.

The results suggest that few of the dolerite dykes are likely to form effective barriers to groundwater movement. This is primarily due to their orientation with respect to the direction of groundwater flow with some of the north-west dykes to the south of the area likely to act as conduits rather than barriers. The lateral continuity of many of the dykes also appears to influence their inability to form barriers. The discontinuous nature of the dykes may, to a certain extent, be the result of masking effects due to magnetite destruction as alteration fluids passed through structural and lithological weaknesses within the basement rock.

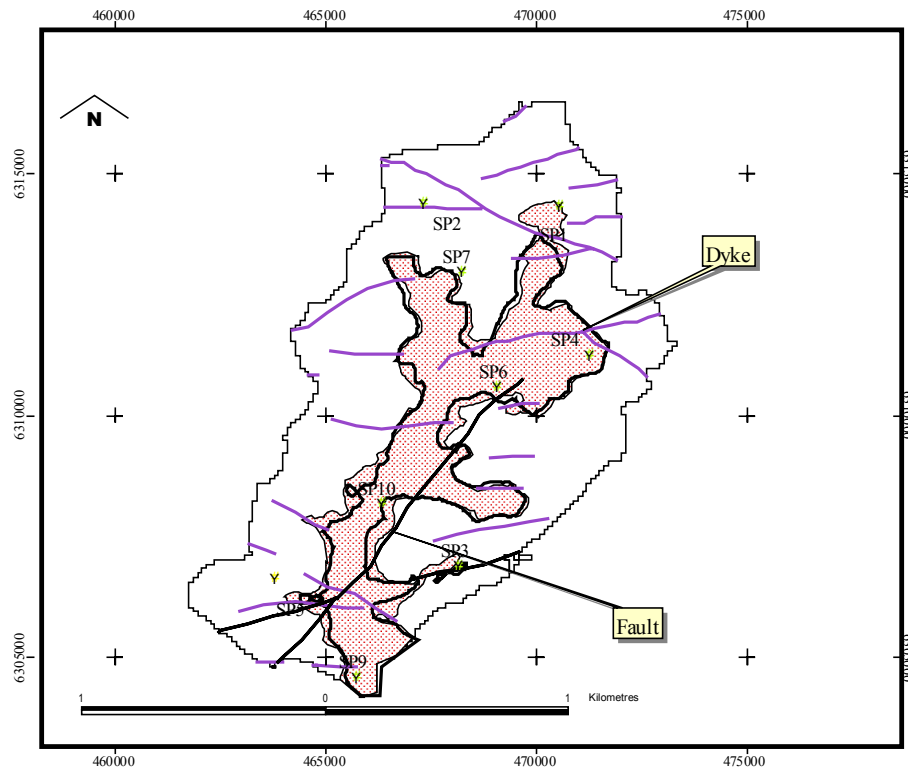


Figure 11. Shallow watertable before (dotted area) and after (heavy black outline) incorporating dykes and faults.

The extent of shallow watertable increased from 25% to 26% of the catchment.

5.5 Transient Model (MODFLOW)

The steady state simulation provided the spatial distribution of the groundwater across the Spencer Gully catchment. However, the important unknown is how long it will take the catchment to reach the state where the watertable level does not rise further. The comparison of the steady state results using the current watertable as the initial head with that of the transient model in terms of watertable depth in consecutive time steps may provide information regarding the time required for the watertable to stabilize.

The transient model was constructed to run over 150 years and was divided into 3 stress periods comprising 5, 30 and 150 years. These stress periods were further subdivided into 10 time steps to test the impact of various engineering options on smaller time scales. The watertable depth over 30 years for four observation bores is shown in Figure 12. The simulated results suggest that the watertable will gradually rise for the initial 20 years and then stabilize. The maximum watertable rise occurs at the catchment boundaries, for example, the watertable in bores SP1 and SP2, on the northern part of the catchment, will rise ~7 m above the current level. Because the watertable at the catchment boundaries is > 10 m below

the natural surface, this increase will have a minimal impact on the current depth to watertable in the valley floor which is the main area affected by salinity (Fig. 12).

On the other hand, the incremental increase in the head of ~ 1 cm/year for the bores SP9 and SP10 in the valley floors is less than the error margin calculated for the calculated heads in the MODFLOW model. Therefore, the likely impact of a relatively small rise in watertable would be insignificant in terms of the spread of shallow watertable (< 2m) beyond the current level. The 8000-day mark when the watertable stabilizes may represent the time taken for the catchment to reach steady state (when there is no further rise of the watertable across the catchment).

The transient model of the Spencer Gully catchment can also be used to test the impact of various salinity management scenarios to increase groundwater discharge from the catchment. The effects of engineering intervention schemes —drains, relief bores and abstraction bores—were tested in various time steps and their impact on water balance and lowering watertable are delineated in the following sections.

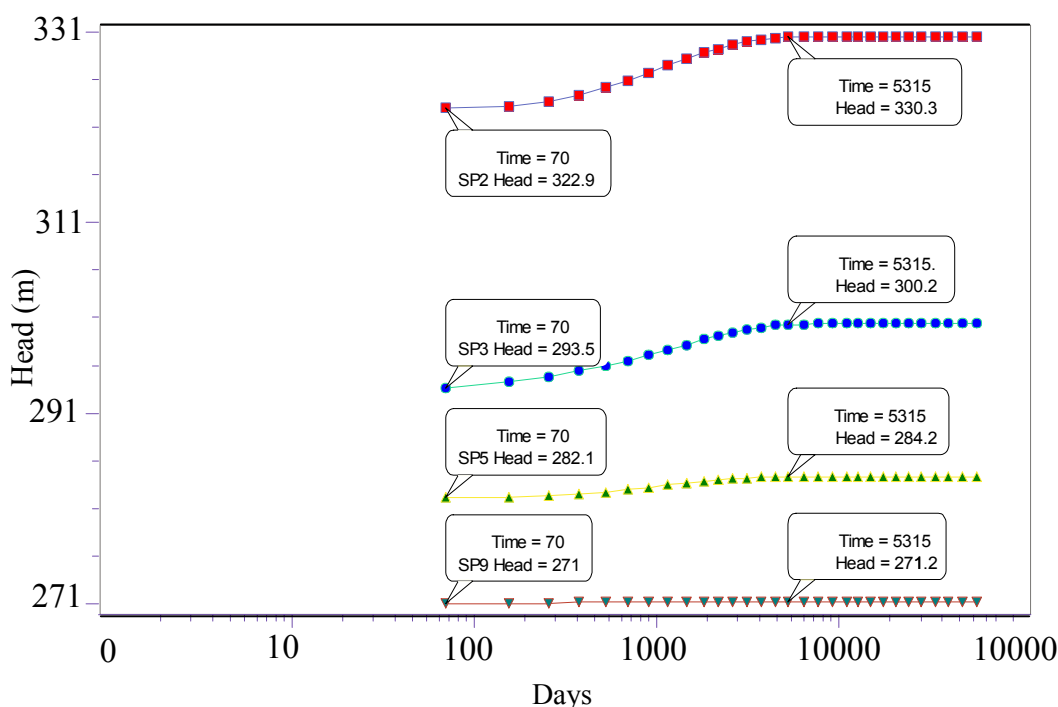


Figure 12. Watertable rises in four bores.

Note that the watertable rises by ~ 7 m in SP2 and only 0.2 cm in SP9.

5.5.1 Groundwater discharge (drains)

The Department of Agriculture designed the groundwater relief drains as part of the surface water management plan for the Spencer Gully catchment. The depth of the drains along the main Spencer Gully Creek was less than 1 m. The objective of the proposed surface water management plan is to control runoff from the upper reaches of the main drainage and divert the runoff to pre-determined safe disposal points that discharge directly to the main catchment watercourse/drain. The discharge of surface runoff

may protect the low-lying areas of the catchment from intensive surface runoff and saline groundwater seepage.

In this investigation the effectiveness of the drains in lowering the watertable were simulated by constructing a 2 m deep drain within the main drainage line and within the lower reaches of minor-order watercourses along the main drainage line. The drains were 1.2 km long with a maximum depth of 2 m below the surface and with a gradient of 0.1% along their floor allowing the free flow of shallow groundwater into the main watercourse. It is anticipated that the groundwater entering the drains would consist of both deep groundwater with a potential for upward leakage and shallow groundwater from the upper aquifer.

After 365 days, the watertable is lowered by ~ 1 m in the vicinity of the drains (Fig. 13). The lateral impact is limited to 75 m east and 100 m west of the drain. The maximum lowering of the watertable in the cells adjacent to the drain is < 0.5m.

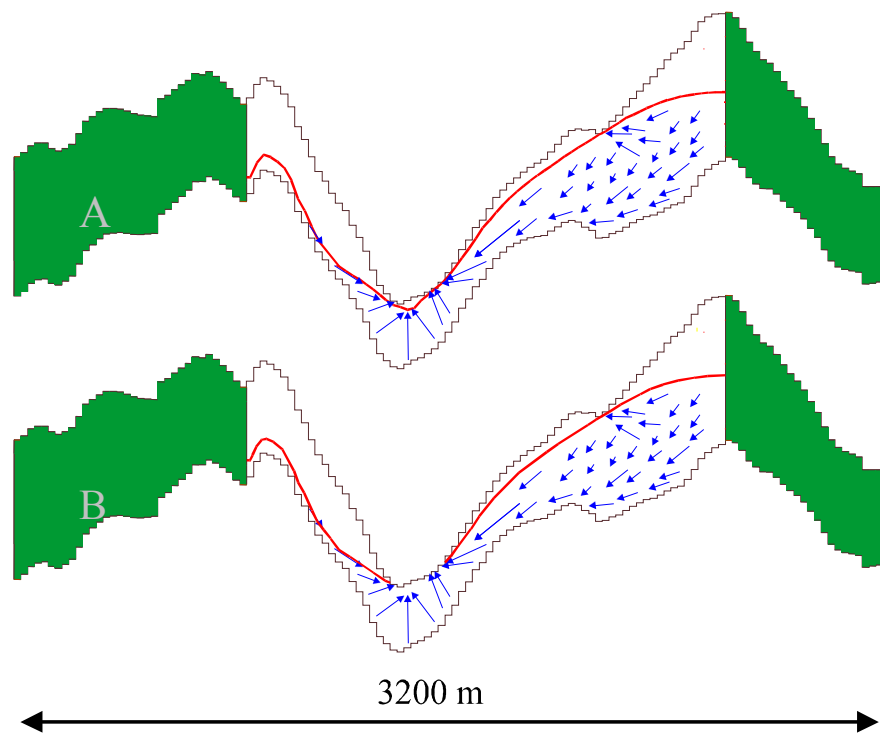


Figure 13. (A) Groundwater discharge to the main drainage. (B) Relatively lower watertable in the drains and the low-lying areas adjacent to drains.

(The vertical exaggeration is 1:25).

The area underlain by shallow watertable has reduced from 25% of the catchment for the base case scenario (steady state condition) to 18% after installation of the drains (Fig. 14). The 7% difference between these two scenarios accounts for ~ 40 hectares of low-lying areas along the main drainage line.

The rate of groundwater discharge via drains is ~130 m³/day compared to the total output from the catchment of 830 m³/day so accounting for 15% of the total output of the water budget. The results of the model suggest that the rate of groundwater discharge via these drains will not increase the total volume of output significantly (~ 9 m³/day). The rate of groundwater discharged from the cells adjacent to the drains will decline to compensate for the enhanced discharge rate from the drains. This is the reason for the fall

of the watertable in the vicinity of the drains. The output component of the water balance for the catchment will not change but the ratio of discharge via different processes will vary.

The impact of the drains on water balance at hydraulic equilibrium is similar to their impact after a year of simulation. There is no temporal variation of watertable observed due to the installation of the drains. Because the rate of groundwater discharge to the drains constitutes only 15% of the total output component of water budget, the impact on increasing surface water salinity via enhanced groundwater discharge is minimal. The drains only act as an alternative conduit for groundwater discharge, compensating for a lower discharge rate from larger surface areas of the catchment.

If the groundwater discharging via the drains is removed by pipes or evaporation basins before discharging into the main creek down-gradient of the catchment, this would reduce surface water salt load by 1.5 tonnes/day (Assuming the average groundwater salinity of 12 000 mg/L multiplied by the calculated rate of groundwater discharge via drains 130 m³/day).

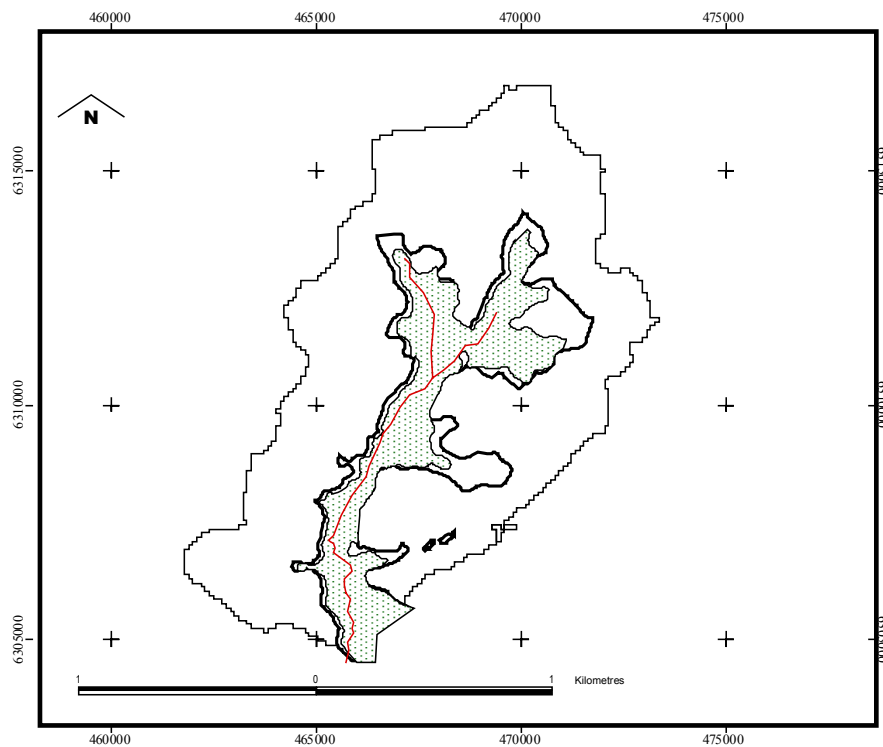


Figure 14. Shallow watertable before drains (white) and one year after drains installed (dotted). Drains in red.

The drains are on the lower slopes and flanking the main drainage line. The extent of shallow watertable 365 days after installation of the drain is shown as the dotted area. The extent of shallow watertable of the base case scenario (no drain) is also shown for comparison.

5.5.2 Drains and relief bores

The groundwater head observed in the two piezometers (SP9 and SP10) in the main drainage line is above the natural surface. This is due to the relatively low hydraulic conductivity of the saprolite horizon that

overlies the main aquifer and thereby restricts groundwater flow from the main aquifer into the main drain. The effect of groundwater discharge from 15 free-flowing bores on lowering the groundwater head and, consequently, lowering the watertable was tested in the transient model. The relief bores were distributed along the main constructed drains so the elevation difference between the groundwater head and the base of the drain would enhance groundwater discharge. The relief bores were treated conceptually as constant head boundaries and the head was set to equal the base elevation of the drain. The effectiveness of the relief bores is shown in an east-west cross section (Fig. 15 A & B and Fig.16). There is neither difference in the location of the watertable in cross sections nor the extent of shallow watertable distribution due to the installation of relief bores.

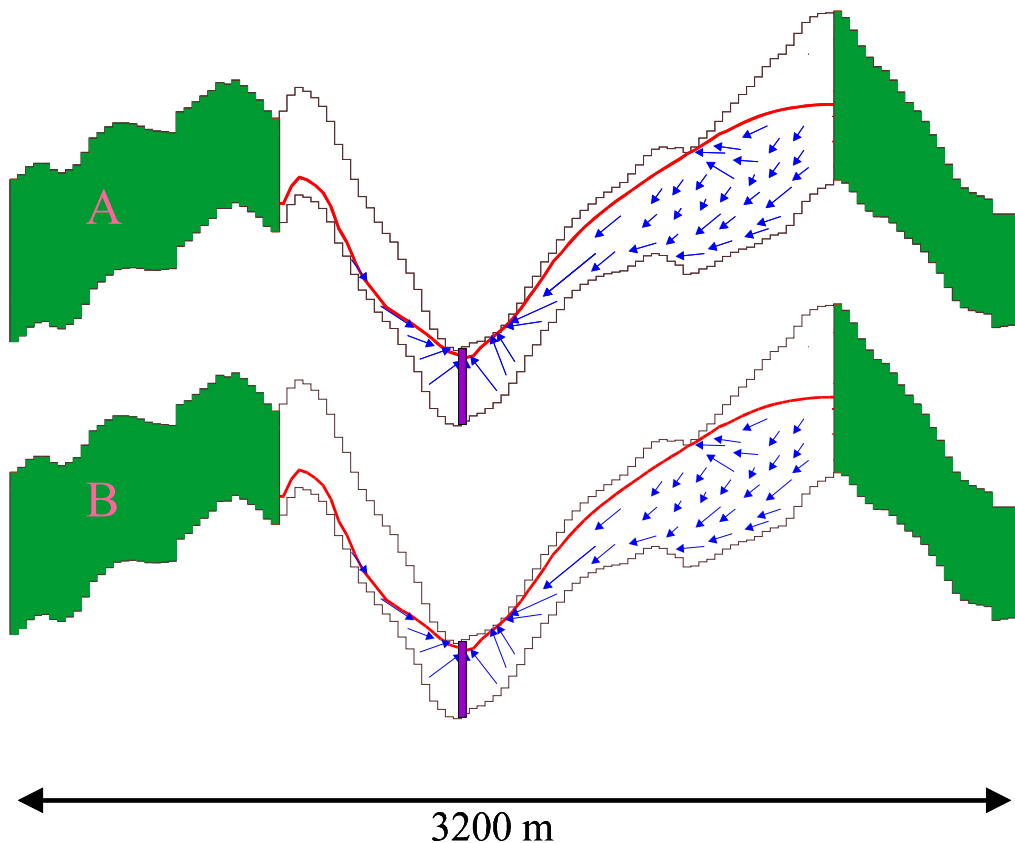


Figure 15. (A) Before installation of relief bores and (B) after —no change in groundwater head

(The vertical exaggeration is 1:25)

Although the volume of groundwater discharging via the relief bores is $40 \text{ m}^3/\text{day}$ accounting for $\sim 5\%$ of the output component of groundwater balance, the lateral impact on lowering groundwater is minimal. This is because the relatively higher groundwater head represents the hydraulic head in the main aquifer where the boreholes are located, and lowering the head at a specific point in the landscape does not necessarily translate to lowering groundwater heads by the same level in the surrounding areas. The groundwater head in the surrounding areas will decline by a lesser rate than that in the relief bores (Similar concept to the cone of depression).

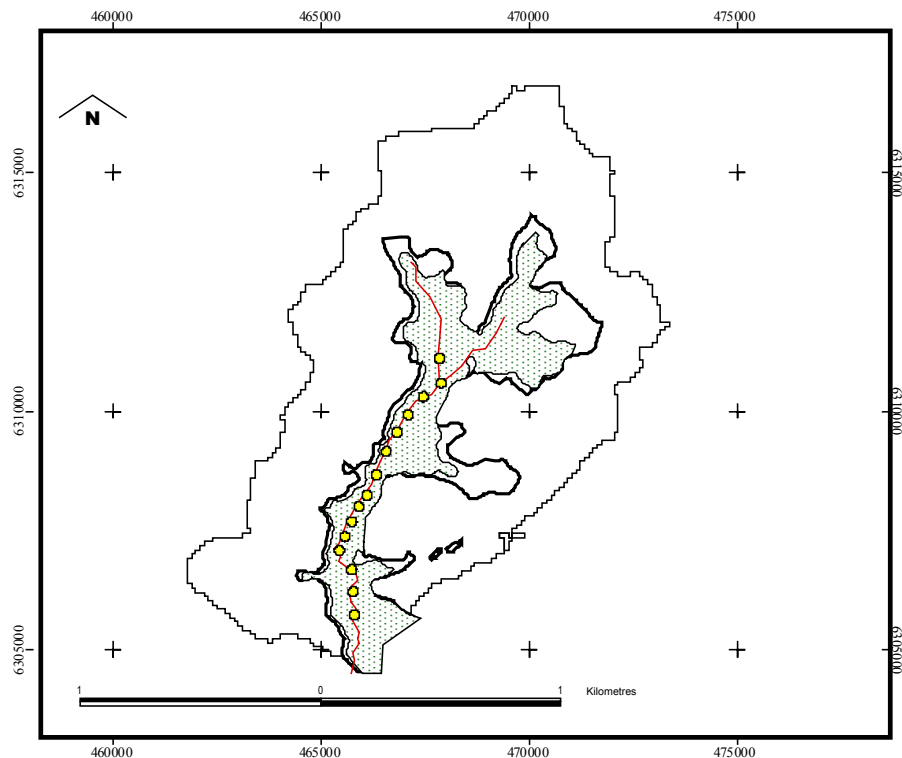


Figure 16. Dotted area shows the shallow watertable 1 year after 15 relief bores (open circles) are installed.

Note that the results are identical to Figure 14. The extent of shallow watertable of the base case scenario “steady state condition” (the clear area) is shown for comparison).

5.5.3 Groundwater discharge via abstraction bores

Groundwater discharge via a series of abstraction bores was tested as a possible groundwater control strategy. The bores were placed along the relief drain used in the previous two sections to test the effectiveness of drains and relief bores in lowering watertable in the catchment (Fig. 17). As rising watertable primarily affects the low-lying areas where the watertable is shallow, it was necessary to focus such a strategy where the results of pumping would probably be most effective.

Twelve bores with the maximum capacity of 25 m³/day per bore were incorporated into the model. The bores could nominally produce 300 m³/day which might be the upper limit for the groundwater abstraction considering the relatively low transmissivity values of the main aquifer, but the model simulation calculated the optimum rate and, consequently, the rate of groundwater discharged based on bore location, hydrological input parameters and boundary conditions of the model.

The optimum placing of the bores to be effective in lowering the watertable was found to be at spacing ranging from 100 m to 180 m along the drains. However, an unlimited combination of the number of bores, spacing and discharge rates could be tested to provide the most effective watertable control.

The maximum rate of groundwater discharge for the twelve bores was 180 m³/day. Although the groundwater was lowered over a substantial distance from the abstraction bores (~ 150 m), the depth to the groundwater in these areas was still ≤ 2 m which is the critical depth in terms of land salinisation.

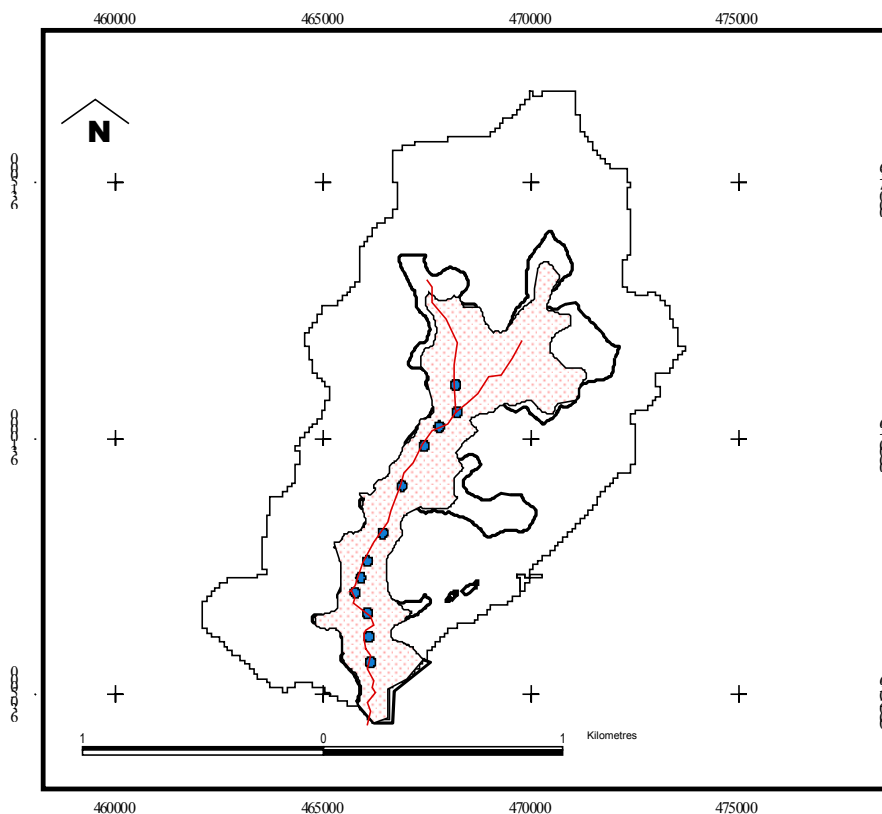


Figure 17. Abstraction bores (filled circles) in the drains

The extent of the shallow watertable is shown as the dotted area superimposed on the base case scenario.

Groundwater flow paths and time steps following the implementation of the scheme are depicted in the east-west cross section (Fig. 18). Modelling suggests that groundwater pumping significantly lowered the watertable. The area characterised by groundwater < 2 m deep has decreased from 25% of the catchment at steady state before the groundwater pumping to ~ 18% after two years of continuous pumping.

The cross sections in the Figure 18 represent the watertable depth at 70 days, 1 year, 20 years respectively from the commencement of groundwater pumping. The maximum lowering of groundwater is reached after two years of pumping and after this the depth to the watertable remains constant.

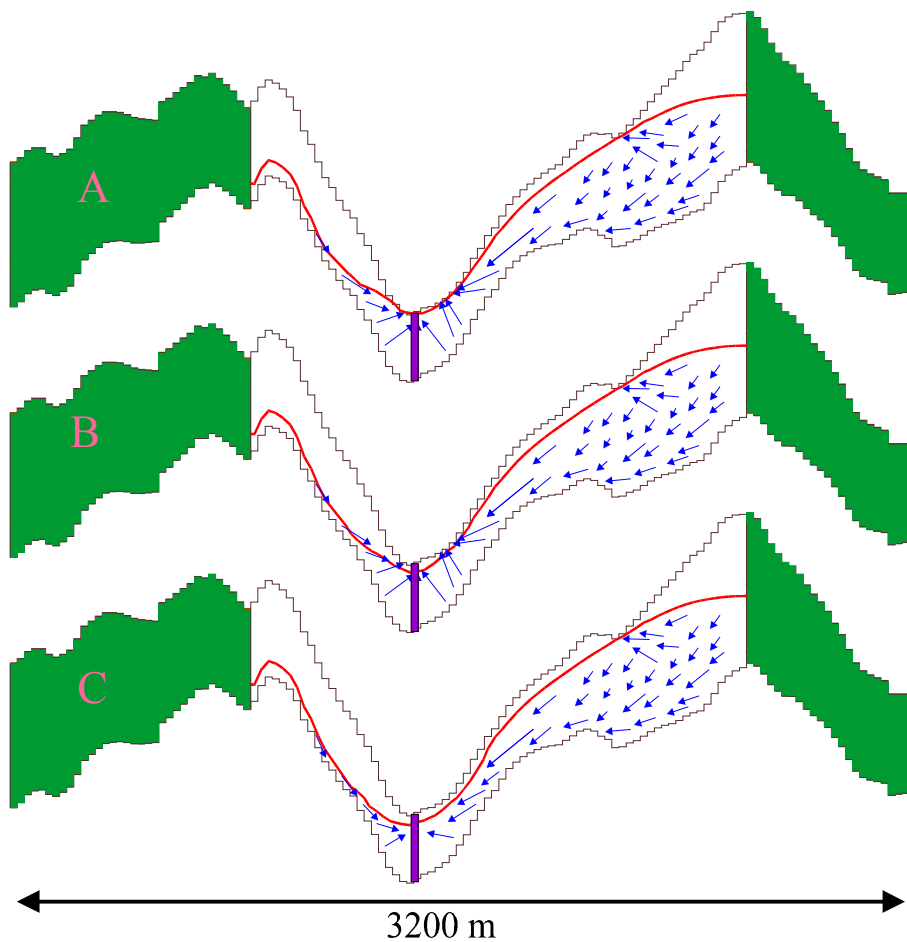


Figure 18 A, B & C. The impact of an abstraction bore on lowering watertable at 70, 365, 7500 days

(The vertical exaggeration is 1:25)

5.5.4 Combination of drains and abstraction bores

Although the results of the previous three model runs showed that the manipulation of groundwater balance by groundwater discharge intervention schemes would be effective in lowering the watertable in low-lying areas, it was thought that the combination of these intervention schemes might prove even more beneficial.

The effect of the combination of the groundwater discharge via drains and abstraction bores is shown in Figure 19. The area with watertable depth of < 2 m is relatively small but only $\sim 1\%$ less than for each individual scenario (Fig. 14 & Fig. 17). The results of the water balance suggest that the volume of water discharging from the deep aquifer direct to the drains would be approximately halved from $170 \text{ m}^3/\text{day}$ to $90 \text{ m}^3/\text{day}$ due to the groundwater abstraction from the bore field. So the fall in watertable is mainly because groundwater is discharged from 12 points in landscape rather than diffusion through larger low-lying areas of the catchment. The increased groundwater discharge of these intervention schemes replaces the natural groundwater seepage from the low-lying areas. This is mainly because the catchment is close to equilibrium.

Table 2. Comparison of modelled options

	Modelled Engineering option	Catchment with critical depth watertable < 2m	Regained area	Discharge (m ³ /day)	Comments
1.	Base case scenario	25%	N/A	N/A	
2.	Groundwater discharge through 1.2 km of drains (max 2 m deep). 1 year of operation.	18%	40 hectares of low lying land along main drainage line	130	Discharge via drains is an alternative to natural discharge over larger areas.
3.	Drains and 15 relief bores within drains. Bores flowing 1 year.	18%	Result as for drains alone (No. 2).	135	Results as for drains alone (2).
4.	12 bores spaced 100 to 180 m apart along in drains. Pumped for 2 years.	18%	40 hectares of low lying land along main drainage line	180	Pumping longer than 2 years does not lower the watertable further.
5.	Drains plus pumped bores	17%	42 hectares of low lying land along main drainage line	180	Groundwater is discharged at 12 points.

Assumed recharge rate = 55 mm/yr

Assumed critical depth for salinisation = 2 metres from surface

This catchment is close to equilibrium. The increased groundwater discharge in these interventions restricts the natural groundwater discharge from larger low lying areas to chosen sites at drains, relief bores and pumped bores.

6 The influence of recharge rates on the shallow watertable

Modelling indicates that the spatial distribution of the shallow groundwater depends primarily on the recharge rates and the depth to groundwater nominated as critical to land salinisation. Because the average recharge rate (55 mm/year) used in the numerical models was calculated on the climatic and hydrogeological conditions of the catchment, the interpretation of the results and depth to groundwater should only be used in relative terms (that is, comparing the areas underlain by shallow watertable for each scenario relative to steady state conditions which represents the base case scenario).

To highlight the effect of lower recharge rates on the spatial distribution of groundwater, the MODFLOW model was run with an arbitrary average recharge rate of 18 mm/year. This is 3-fold lower than the average recharge rate used in the base case scenario (55 mm/year) and is only 3% of the annual rainfall in the catchment. The results suggest that only 15% of the catchment would be underlain by shallow groundwater (Fig. 20) approximately half of the base case scenario (~25%). These results highlight that the recharge rate is the critical parameter in determining catchment water balance and, consequently, predicting areas underlain by shallow groundwater.

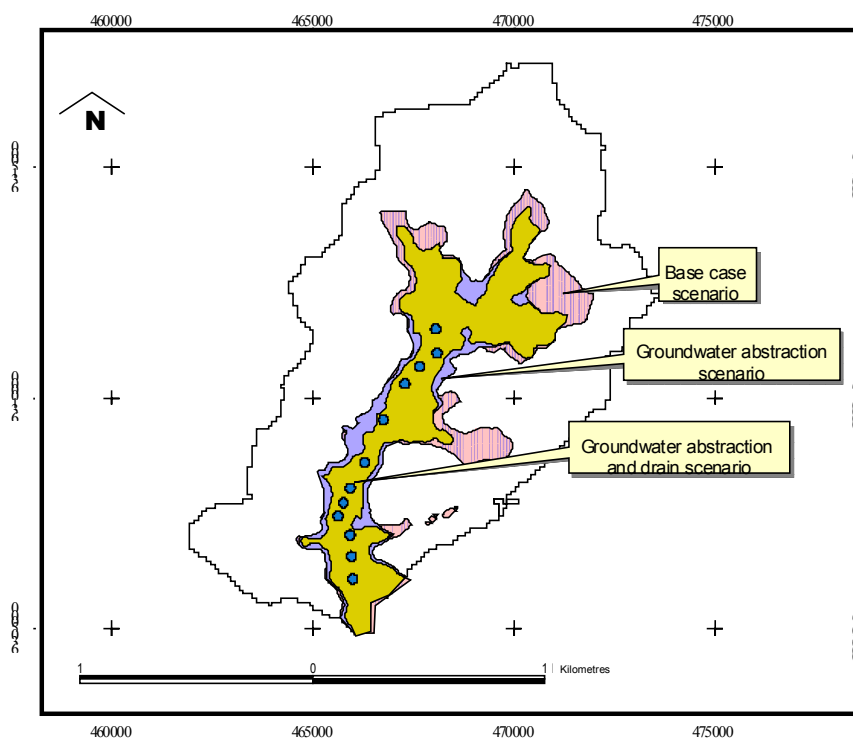


Figure 19. After installation of 12 abstraction bores and the drains, 17% of the catchment is underlain by shallow groundwater.

This is only 1% less than in the previous scenario (abstraction bores only). The base case scenario (no drains or abstraction bores) covering 25% of the catchment is shown for comparison.

The recharge rate used in MODFLOW model is also the critical factor in quantifying the effect of various groundwater discharge scenarios on lowering watertable. Lower recharge rates result in a relatively smaller water budget of the catchment, smaller groundwater discharge volume and smaller area (as percentage) of the catchment underlain by shallow groundwater (Fig. 20).

The depth to the groundwater is the second critical factor in determining extent of the land salinisation in a catchment. Two metres the maximum depth from which groundwater evaporates directly and capillary action brings groundwater to the surface. The salinisation of land depends on the hydrogeological properties of top layer and over-lying soil. The critical depth to groundwater may be 2 m in sandy soil but is certainly < 2 m in clayey soil because evaporation and capillary action occur more slowly. This study was conducted in a sandy clay soil so the threshold of 2 m was deemed appropriate. Figure 21 illustrates the importance of the depth to watertable when determining the extent of area underlain by shallow groundwater.

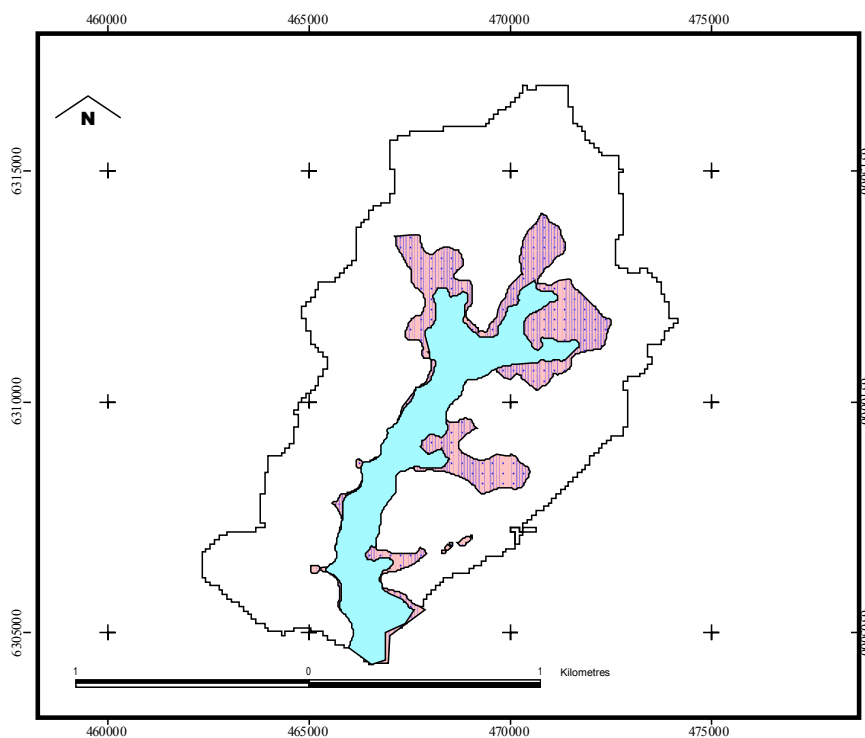


Figure 20. Approximately 15% of the catchment is underlain by shallow groundwater when using an average recharge rate of 18 mm/year

The dotted area shows the base case scenario (55mm/year recharge), about 25% of the catchment.

Peck (1983b) defined the critical depth to watertable where salinity occurs as the depth at which a flux of 0.1 mm/day could be sustained from a non-irrigated, or dryland, soil. Calculated critical depths ranged from less than 1 m to more than 6 m depending on soil type (Peck, 1978). In Western Australia, Nulsen (1981) found that the critical depth to a watertable throughout the Wheatbelt ranged from 1.5 to 1.8 m depending on crop type.

MODFLOW results indicate that the area underlain by a shallow watertable is probably about 25% of the catchment under the base case scenario when the critical depth is taken as 2 metres but changes substantially when different critical depths are nominated.

Figure 21 indicates the variability of the depth to a shallow watertable, and area, for base case recharge rate of 55 mm and the deep drain scenario. At a critical depth of 2 m, the affected area is 25% of the catchment but goes down to 17% after drains are constructed. If the critical depth is chosen as 1.5 m, the 'at risk' area reduces to approximately 21% of the catchment, while at 1 m and 0.5 m, the area is 17 and 12% respectively.

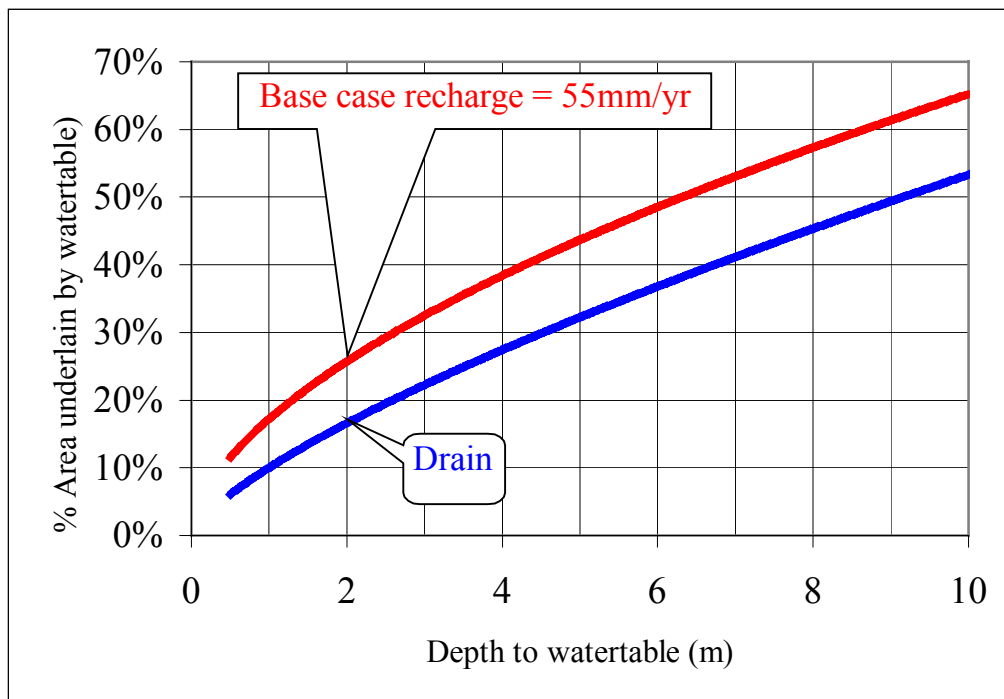


Figure 21. The area underlain by 2 m deep watertable drops from 25% to 17% of the catchment after installation of the drains.

7 Conclusions

- The steady state modelling results suggest that the area underlain by the shallow watertable (< 2 m deep) will extend over 25 % of the catchment at equilibrium. This does not necessarily translate to the saline area but the critical depth of 2 metres represents the threshold where groundwater evaporates directly or indirectly by capillary action resulting in further salinisation of groundwater.
- The hydrogeology of the Spencer Gully catchment is typified by a complex vertical zonation but can be described by three main horizons. At the bedrock weathering front above bedrock the saprock ranges in thickness from 0.9 m to 6 m and forms an important 'layer' in the profile with respect to groundwater flow as it has a relatively high hydraulic conductivity. Where this layer develops, it is overlain by saprock, which is generally compact, has lower hydraulic conductivities and its thickness ranges from 7 m to 16 m. The overlying saprolite horizon semi-confines the basement aquifer and has an average thickness of 13 m. The top layer consists of sand and clay and its thickness ranges from 0.5m to 2 m.
- The spatial distribution of shallow watertable at steady state mapped by desktop analysis is remarkably similar to that obtained from numerical modelling. Desktop analysis and first-hand prediction of the distribution of shallow watertable are essential for salinity management because they provide information on the conceptual hydrogeological model that can be used in numerical simulations.
- MODFLOW proved to be an effective tool to map areas underlain by shallow watertable (Salinity Risk Areas). While its accuracy obviously depends on the datasets and assumptions made in the conceptualisation of the catchments, it is a useful quantitative tool to compare the results of different scenarios relative to the steady state model. The groundwater balance estimation and the impact of various salinity intervention scenarios on catchment water balance can only be achieved using numerical models.
- The comparison of MODFLOW and MAGIC simulations enabled modification of the algorithms within MAGIC and so better identify discharge areas. While the MAGIC analysis gave reasonable estimates of water balance quantities at the small-catchment scale, the indicated locations of discharge should be considered less accurate than those produced by MODFLOW.
- The model results suggest that dykes and faults have limited impact on the distribution of shallow groundwater. This is considered to be primarily due to the orientation of the dykes and faults with respect to the direction of groundwater flow. The limited effect of geological structures appears to be due to the apparent lack of lateral continuity in many of the dykes. This may be the result of masking affects of magnetite destruction. Only one dolerite dyke is likely to form an effective barrier to groundwater movement.
- The two-metre deep drains and abstraction bores have a significant impact on the distribution of groundwater. The drains lower the watertable in adjacent cells by up to one metre. The abstraction bores lower groundwater in up to four cells adjacent to the bores. Such lowering of the watertable would be beneficial in solving waterlogging problems on the low-lying areas. Relief bores had an

insignificant impact at the scale simulated in this investigation. They lowered groundwater head only to the tops of the bores so that the groundwater head was still be at the surface in the surrounding areas.

- As they increase the discharge rate from the catchment, groundwater-discharge intervention schemes drive the catchment to equilibrium faster. It is essential to calculate the time required for the catchment to reach equilibrium, particularly for larger scale catchments. If the salinity management priority is to gain time by implementing recharge intervention scenarios, discharge intervention scenarios might be omitted.
- The impact of engineering scenarios on output component of water balance in catchments that have reached or close to equilibrium is minimal. The groundwater discharged by engineering options will only substitute for natural groundwater discharge from larger low-lying areas of catchments.

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