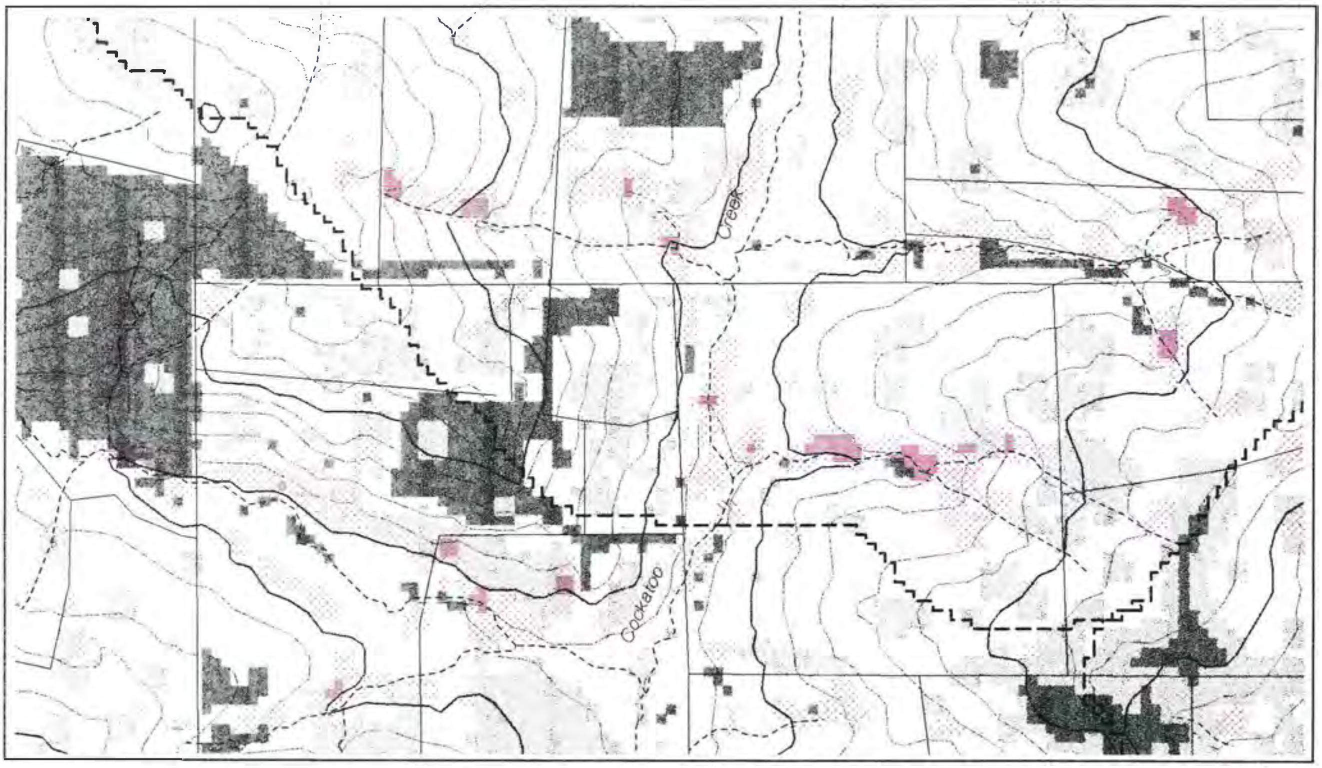
Modelling Dryland Salinity with the M.A.G.I.C. System



Water Resources Technical Series

Water and Rivers Commission Report WRT7 1996

Water and Rivers Commission

WATER AND RIVERS COMMISSION
HYATT CENTRE
3 PLAIN STREET
EAST PERTH
WESTERN AUSTRALIA 6004
TELEPHONE (09) 278 0300
FACSIMILE (09) 278 0301

Cover illustration shows part of a plan entitled:

FARM PLANNING GUIDANCE PLAN
AREAS OF POTENTIAL DEEP GROUNDWATER DISCHARGE
KENT RIVER CATCHMENT
(From modelling with M.A.G.I.C. System)

NATIVE VEGETATION OR SIMILAR
SCATTERED TREES
DISCHARGE > 12, 24, 60 mm/yr

Modelling Dryland Salinity with the M.A.G.I.C. System

G.W. MAUGER, M.I.E.Aust

Water and Rivers Commission
Resources Investigation Division

Water and Rivers Commission
Water Resources Technical Series
Report No WRT7

Reference Details

The recommended reference for this publication is:

Mauger G.W. 1996, *Modelling Dryland Salinity with the M.A.G.I.C. System,* Water and Rivers Commission, Water Resources Technical Series No WRT 7

ISBN 0-7309-7264-X
ISSN 1327 - 8436

Text printed on recycled stock ,
Onyx 100% recycled 100gsm
Cover, Media Satin 250gsm
November, 1996

Contents

SUMMARY

A Personal-Computer-basedprocess has been developed to analyse the hydrological effects of vegetation in catchments where dryland salinity may occur. The process uses a system of computer programs and data organisation called M.A.G.I.C. (for Microstation And Geographic Information Computation). The process commences with raw data as digitised polygons, Landsat Thematic Mapper (TM) data, and several regional parameters that are the same in all locations. From the raw data, the raster processing program RASCAL computes quantities needed as input to a model of the catchment, using 25 x 25m cells. Slope and drainage distribution information are generated from contours. TM data is used to identify forested and pasture areas and to distribute leaf areas within each. RASCAL then executes the model which is basically a two-layer groundwater simulation with inputs of rainfall and evapotranspiration.The surface layer is simulated as one average year in monthly timesteps, and the lower layer is a steady state analysis. The resulting estimates of deep groundwater movement, together with constraints defined by other data, lead to a prediction of where trees should be planted to reduce deep groundwater discharge. The effects of proposed planting on average streamflow and deep groundwater discharge from catchments can also be assessed. Outputs of the process include display of gridded map data on computer screen, tabulations, and maps produced through computer drawing packages. Development of the process has been within the Wellington and Denmark Catchment Areas in the South West of Western Australia.

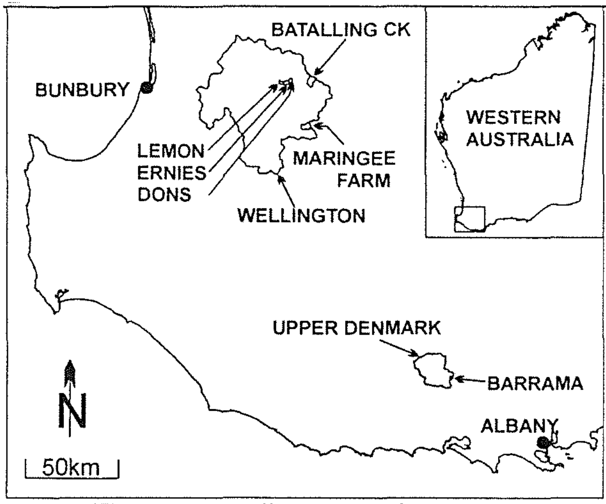


Figure 1: Locality Map of Catchments

1. INTRODUCTION

Dryland salinity in the South West of Western Australia has been monitored closely over the last 20 years. Scientists consider that they have a sound understanding of the physical processes leading to its occurrence, and have been studying various methods to counter its detrimental effects. The major effects are the loss of agricultural productivity on land subject to saline seeps, and the reduced value or total loss of water resources due to the increased salinity of streams that drain salt-affected land. Methods to reduce the problem include controlling the recharge to deep groundwater, controlling deep groundwater discharge, or growing salt-tolerant plants on affected land to use the land in its saline state.

The Water Authority of Western Australia has been involved in research programmes and trials of techniques for planting trees for controlling deep groundwater discharge. The analytical process reported in this paper is to assess the hydrological effectiveness of existing revegetation, to estimate the likely benefits of proposed planting, and to give advice about where revegetation would be most effective for reducing salinity, especially stream salinity.

A Geographic Information System approach has been taken. The resulting process allows information to be provided at scales of tens of metres, useful for farm planning, while effects can be integrated for whole catchments with areas of hundreds of square kilometres. The process has been developed within two catchments in the region, Wellington Catchment and the Upper Denmark Catchment (Figure 1).
The Wellington Catchment contains several experimental catchments run by the CSIRO and the Water Authority that have provided valuable data and understanding of the salinity process. In 1974, in a zone where rainfall is about 700mm, three experimental catchments were set up close together, each about 3 sq.km and fully forested. After an initial monitoring period of three years, Lemon Catchment had its western (downstream) half totally cleared, Don's Catchment had a variety of clearing treatments, and Ernie's Catchment remained uncleared as a control. These catchments have been used to validate the analysis process.

The Water Authority has also planted about 7000 ha of trees on previously cleared land, some following empirical guidelines and some in experimental patterns. Two relatively small catchments of about 15 sq. km each, Batalling Creek and Maringee Farm, have gauging stations with flow and salinity records. Planting of trees on 20% of the cleared area in these catchments has progressed through the 1980s. These catchments have been used to validate assessment of the effectiveness of established revegetation.

In the Upper Denmark Catchment, a cooperative programme between the Department of Agriculture, Department of Conservation and Land Management, the Water Authority and the farmers in the catchment, resulted in farm plans being prepared for many of the farms. The farm plans showed areas where trees were to be planted to combat salinity as well as provide other farm benefits. The areas were determined from soil mapping, application of general principles of salinity control and negotiation with the farmers. These plans have been used to test the process that analyses proposed planting. The experimental catchment being run at Barrama provided data for model calibration.

2. CONCEPTUAL MODEL

The analysis process is essentially a numerical representation of the physical catchment, i.e. a model. The model is based on the predominant soil profile of salinity-affected areas in the South West of W.A.

In general, the soil profile is the result of very deep weathering in situ. Rock that was originally igneous or metamorphic has been decomposed to clay and quartz grains to depths of up to 50 m, but usually about 20 m. Although deep for a weathered profile, the depth is small compared to the topographic relief, and so as a first approximation, bedrock levels can be assumed to be parallel to the ground surface. The degree of weathering decreases over the bottom few metres before reaching fresh rock. Most of the profile more than a few metres below the surface has quite a variable permeability when measured at a small scale, due to variations in clay and quartz proportions and the degree of weathering.

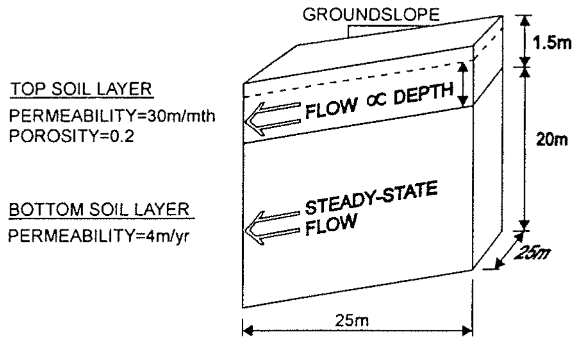


Figure 2: Typical Cell Properties for Groundwater Flow

However, at the scale of even a small catchment, the permeability of the soil in bulk is in the order of $10^{-7}ms^{-1}$ (3m/yr) (Peck et al.).

Down to a depth of 1-4 metres the clay fraction has been greatly reduced, resulting in a layer of much higher permeability, at about $10^{-5}ms^{-1}$ (300m/yr) (Sharma et al.). Within this layer, laterisation may occur, which often appears as an apparently solid caprock. However the caprock nearly always has large holes in it and has little influence on water movement when considered over distances of tens of metres.

One consequence of the high permeability of the surface is that rainfall rarely exceeds the infiltration capacity, so that direct run-off is only significant from saturated areas in valley floors. Movement of infiltrated rainfall as unconfined groundwater flow in the sloping surface layer is significant.

Plants easily use water in the surface layer. However, over most areas this water is used by plants, or drains away, well before the end of summer. To survive over summer, plants must be able to reach water absorbed into the deeper clayey soils. The water is absorbed, i.e. infiltrates, into the deeper clay while the surface soils are wet. It is the absorbed water that becomes the recharge to deep groundwater when deep-rooted vegetation is cleared. A total recharge of about 100mm/yr has been estimated by the rate at which the piezometric surface rises after clearing (Peck and Williamson), and from the shape of the 'salt bulge' in the soil profile (Johnston). This rate is much lower than the average permeability of the deep weathered layer, but may be explained if it is assumed that much of the clay missing from the surface layer has been washed vertically down to fill areas of higher permeability.

The outcome of these concepts is to represent the soil profile as two layers as illustrated in Figure 2. Both layers have a slope equal to the surface slope. Soil depths and permeabilities are constants in the model. Values for the top soil layer are typical for the region. The bottom soil layer is set by calibrating modelled deep groundwater discharge to the value estimated by dividing gauged salt flux by typical deep groundwater salinity.

3. RASCAL PROCESSING

The author has developed a system of computer programs and data management that includes use of the proprietary drawing package Microstation. The system is called M.A.G.I.C., for 'Microstation and Geographic Information Computation' and generally operates in a Personal Computer environment. Microstation is used to archive, edit and present data in polygon form. The principal program for operating on gridded data is RASCAL (RASter CALculation). It allows new 'maps' to be generated by modifying or combining one or more maps represented by gridded data. To operate on the maps, it reads commands from a file prepared by the user with any editing program. An appropriate sequence of commands for RASCAL executes a catchment model. All the maps that RASCAL operates on in one run of the program are held in one file that is called a 'RASCAL project'.

4. STAGES IN THE ANALYTICAL PROCESS

In the following, the major stages in analysing a catchment are shown, with a box containing typical map numbers and titles that are generated in a RASCAL project. These maps are the principal products of the stage. Other maps may be created in the process that do not need to be kept permanently.

The major stages in analysing a catchment are:

- Convert raw data to equivalent maps in a RASCAL project.

3	TM BAND 3
4	TM BAND 4
5	TM BAND 5
11	RAINFALL
12	PAN EVAPORATION
21	ELEVATION
22	LAKES
32	AREAS PLANTED TO SHALLOW ROOTED PERENNIALS
33	AREAS PLANTED TO DEEP ROOTED PERENNIALS
34	AREAS WHERE TREE PLANTING PERMITTED

- Compute maps required as input to the hydrologic model.

```
102 ASPECT
103 PLAN CURVATURE
105 DRAIN REDUCED SLOPE
107 SLOPE
116 DRAINAGE DIRECTIONS
117 DISPERSED DRAINAGE CODES
130 INFILTRATION RATE TO DEEP G/W
120 GREENNESS
303 TREE GREENNESS
304 PASTURE (FULL LAI=2.7)
```

- Execute shallow groundwater model.

```
241 CUMULATIVE RUN-OFF LESS EVAP
242 TOTAL PASTURE ET
243 STREAMFLOW
244 STORAGE LOSS
245 END APRIL SHALLOW STORE
246 FINAL STORAGE
```

- Execute deep groundwater model.

```
251 CUM. NET RECHARGE
252 FINAL DEEP DRAINAGE
253 DEEP G/W THROUGHFLOW
254 DEEP G/W SURPLUS RECHARGE
255 SMOOTHED SEEPAGE VOLUME
256 SMOOTHED DEEP DISCHARGE
257 SMOOTHED THROUGHFLOW
258 SMOOTHED SURPLUS RECHARGE
```

- Predict sites where tree planting is required.

```
331 DEEP G/W DRAWN BY PLANTED TREES
332 PLANTED DISCHARGE
333 PLANTED TREE GREENNESS
```

- Re-run shallow and deep groundwater models to confirm prediction. (Maps 241-258 and 303-304 are first copied to map numbers 201-219 and 123-124 so that outputs of the re-run can be compared with the original analysis if desired.)

- Convert raster maps to polygons for presentation in Microstation.

```
425 CLASSED SEEPAGE RATES
426 ORIGINAL TREE COVER
427 PROPOSED SITES FOR TREE PLANTING
428 STREAMS WITH CATCHMENT > 100 HA
```

- Prepare maps and tables of results.

5. BASIS OF COMPUTATIONS

5.1. Elevation, Rainfall, Pan Evaporation

Interpolated values at the centres of grid cells are computed from the digitised lines of equal value ('contours'). A cross-section profile is constructed in a direction perpendicular to a contour which is adjacent to the point being estimated. Cubic curves are fitted to the profile to match two contours either side of the point. The final value is the average from profiles based on the two nearest contours to the point.

In the case of rainfall and pan evaporation, the data represented the long term annual average totals. In calculations that required monthly values, the proportions of the twelve monthly long term averages at a site representative of the region were applied to all cells, thus scaling the values in proportion to the annual total at each cell.

5.2. Slope, Aspect, Plan Curvature

A polynomial surface fitted to 3x3 grid cells is evaluated to estimate these quantities for the centre cell (Heerdegan and Began).

In groundwater flow calculations, the ground slope is used as an approximation of the hydraulic gradient driving the flow. When converting flow velocity to the volume of water to be transferred to an adjacent cell, the width of the flow path is proportional to the cos of the angle between the aspect and the nearest cardinal direction (N, S, E or W). To avoid repetition of calculations, the slope map is multiplied by this cos to produce a map called the 'drain-reduced slope' map that can be used by all groundwater flow calculations.

5.3. Drainage Directions

Drainage direction is represented by a value between 1 and 8 indicating to which adjacent cell water should drain. A cell's aspect is the primary data used. Corrections are applied so that a drainage path approximates true aspect directions (Figure 3). Where a depressed area ('sink') is identified, elevation is used to find the lowest point around the rim of the area. The path of drainage from there to the lowest point in the sink is marked in reverse, so that drainage which reaches the bottom of the sink will be passed out of the sink via the overflow point. The resulting map is called a 'sink-free' drainage map in which the path from any cell can be traced to the edge of the map.

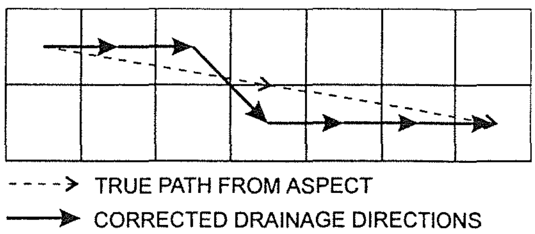


Figure 3: Example of Corrected Drainage Directions

5.4. Dispersed Drainage Codes

When each cell has a single drainage direction, flow paths may diverge. Transfer of information along flow paths will not reach cells between diverged paths. Calculation of dispersed drainage information ensures that upstream effects are passed on to all downstream cells that are influenced. The total drainage from a cell is divided into ninths, so that portions can be expressed with a single digit. A calculation is made, based on the plan curvature and aspect, which apportions the drainage to up to 3 adjacent cells, one of which must be the sink-free drainage direction. The results are written as a single integer that is read as a 'code' (Figure 4). An extra digit is used with some cells that are very strongly convex, to show that one extra cell on each side of the group of three should also receive some drainage. Where two adjacent cells appear to drain to each other, the conflict is resolved. However, poorly defined drainage areas may generate circular paths of drainage involving 3 or more cells. Such paths stop the progress of integration along drainage paths using the dispersed drainage map. In such cases, the sink-free drainage map is used to carry the integration on to completion.

8	1	2
7	0	3
6	5	4

A dispersed drainage code of 3427 in cell at 0 would drain
3 portions of flow to cell at 7
4 " " " " " " 8
2 " " " " " " 1
i.e. 1st portion in direction of right digit, then move clockwise

Figure 4: Example of Dispersed Drainage Code

5.5. TM Data

Landsat Thematic Mapper (TM) data is provided in 'scenes'. The TM scene used for this analysis is a midsummer scene (late December or early January). At this time, ephemeral grasses have died, but tree canopies are not greatly stressed by summer drought. Thus, it provides good discrimination of trees in conditions not greatly influenced by climatic variations from year to year.

The scene is preprocessed by the agency supplying the data so that cell positions are at known geographic coordinates. The format of the data is 'Band Interleaved by Line' (BIL), which refers to the sequencing of the data in the file supplied. The analysis to find greenness only needs Bands 3, 4 and 5 of the seven available. Program LSDEX reads the BIL format data, extracts these bands only for the project area required, and writes each band as a separate file that can be loaded into the RASCAL project file. The data values in each band are called 'reflectance'.

When a different scene of TM data is acquired, either for a different region or from a different year, the reflectances of identical materials may differ due to differences in atmospheric conditions or rescaling of the reflectance values that is done before supplying the data. Thus, new data needs to be calibrated to find values of pure components. A linear transformation of the values can be found by fitting key features of the data distributions, principally the values for deep clear water, bare sand and bare clay.

5.6. Greenness

The ground surface in each cell is assumed to consist of a mixture of four different components, namely sunlit green leaves ('greenness'), dry grass, bare sandy soil and shade. The values of reflectance in each of the 3 TM bands must be known for each of these components. A linear transformation of the reflectance values for a particular cell can estimate the proportions of each of the pure components in that cell (Mauger (6) applied the process to find three components from two Landsat Multi-Spectral Scanner Bands). Only greenness is computed for this process.

5.7. Land Surface Classification

Land surface types are classified by reference to the greenness map and TM Bands 4 and 5. Values that set boundaries between classes were found by comparing results with air photographs. Band 4 less than 35 (in Wellington catchment) was classified as 'water'. Figure 5 shows how other cells were classified as 'native forest', 'pasture only', 'pasture and trees', or 'clay' according to their values of Band 5 and greenness. Refer to Appendix 10.2 for formula definitions of native vegetation and pasture.

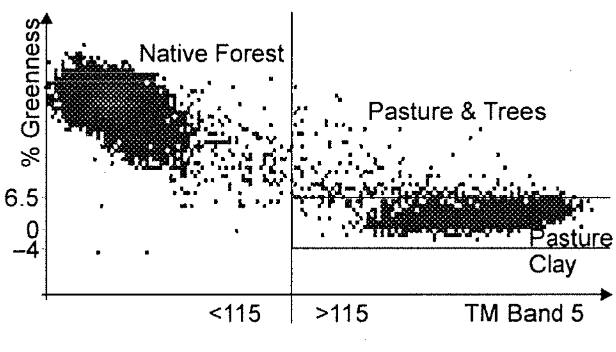


Figure 5: Scatter Diagram Showing Classification Regions

5.8. Planned Planting Areas

Areas of land to be planted are defined by irregular polygons digitised from farm plans. This data needs to be 'gridded' to generate cell values according to which polygon they lie within, and the results loaded into the RASCAL project.

5.9. Tree Transpiration

The density of the natural jarrah-marri forest that originally covered the catchments was such that average annual transpiration equalled average annual rainfall less minor amounts of streamflow and interception losses. Within State Forest areas, variation in greenness linked to rainfall and pan evaporation is evident in Landsat TM scenes, but logging and burning of the forest also has significant local effects. Data supplied by the Department of Conservation and Land Management (CALM) gave the dates when areas were last logged or burnt. From this data, a regression analysis was performed covering the whole Wellington Catchment, using the technique reported in Mauger (6). The 'natural' greenness is estimated from the equation without terms for logging or burning, viz.:

$$G = .0087\,R - .0051\,E + 35.8$$

where G = greenness index (%)
R = average annual rainfall (mm)
E = average annual pan evaporation (mm)

On the assumption that leaf area is proportional to greenness at a particular place, the annual transpiration rate from trees in any cell, was computed as:

$$\frac{(\text{actual greenness})}{(\text{'natural' greenness})} \times (\text{'natural' transpiration rate})$$

where ('natural' transpiration rate) would use all the water available from local rainfall.

The potential monthly transpiration is calculated by scaling the annual total in accordance with the monthly proportions for pan evaporation. However, when no more water is available in the top soil layer, 60% of the rate is used to calculate the volume drawn from the bottom soil layer, representing the effects of drought stress.

Thus the 'natural' transpiration rate is equal to the annual rainfall reduced by interception losses (15%) and increased by a factor (1.33) to compensate for reduced transpiration under drought stress.

5.10. Annual Pasture Transpiration

Transpiration from pasture is set by assuming a growth cycle represented by a coefficient for each month which proportioned a nominated peak leaf area index (LAI) (Table 1). The potential transpiration in a month is then assumed to be 0.352 times pan evaporation per unit leaf area. Monthly pan evaporation is used in this calculation. When no more water is available in the top soil layer, there is no more transpiration.

The appropriate peak LAI is set by calibration of the run-off estimated in shallow groundwater simulations, against recorded streamflows. In cells that are mixtures of pasture and trees, the fraction of the cell assigned to trees is found as the fraction of actual greenness to natural greenness. The remainder is assigned to pasture.

Months	S	O	N	D	J	F	M	A	M	J	J	A
Fraction Of Peak LAI	1	1	.93	.74	.37	.07	0	0	.07	.37	.74	.93

Table 1: Factors for Annual Pasture LAI

5.11. Shallow Rooted Perennial Pasture Transpiration

The nominated LAI of shallow rooted perennial pasture is maintained at the same value throughout the year. The potential transpiration is then calculated as for annual pasture. Actual transpiration will cease if the top soil layer becomes dry. However, the pasture is assumed to be dormant, not dead, and will recommence transpiration as soon as any more moisture is available.

5.12. Deep Rooted Perennial Pasture Transpiration

Deep rooted perennial pasture has a similar behaviour to shallow rooted perennial pasture, except that it is assumed it can access water in the bottom soil layer down to a nominated depth. When the top soil layer becomes dry, transpiration will be drawn from the bottom soil layer at 60% of the potential rate, representing drought stress. When the volume of water held within the accessible depth is exhausted, transpiration ceases, but will resume as soon as more water is available.

5.13. Infiltration Rate

The assumption that native forest density is in balance with its available water supply is used to estimate the infiltration rate possible from the top soil layer to the bottom soil layer. In each cell of native forest, the maximum deficit in soil moisture recorded in the average year simulation is the volume of water needed at that point for survival of trees. The number of months when infiltration could occur is the estimate of the time for that volume to be provided. The infiltration rate is the volume divided by the time. An average value of 29mm/month has been computed from the Wellington catchment, with some variation associated with local topography. With an average 7 months of infiltration, this implies a total annual infiltration of about 200mm/yr under native forest.

5.14. Model of Groundwater Flow in Top Soil Layer

The shallow groundwater model is required to find the volume of water that would be drawn from, or would recharge to, the deep groundwater in the bottom soil layer, in a year of average rainfall. In addition, it provides an estimate of streamflow generated from the catchment, and identifies areas subject to waterlogging.

Modelling consists of performing a water balance to find the change in water storage in each cell in monthly timesteps for 12 months. The simulated year starts at the beginning of September when the water content of the top soil layer can be expected to be at its maximum. The object is to simulate a year of average rainfall with the initial water storage in the top soil layer equal to final storage. Initial storage is estimated by running two preliminary years, starting with all cells saturated.

Monthly rain is added to the top soil layer after reduction by 15% to allow for interception. Potential transpiration is then subtracted.

Lateral flows in the top soil layer occur as a result of unconfined groundwater flow. The model does not solve pressure equations between cells, but assumes that hydraulic gradients will closely conform to the ground surface contours. Thus lateral flow out from a cell is the product of the top soil layer permeability, the degree of saturation of the cell, the cross-section area, and the drain-reduced slope. The direction of flow is determined by the drainage direction maps. Shallow groundwater flow in from upstream cells is added by the drainage integration process.

After adjustment for lateral flows, any infiltration to the bottom soil layer is subtracted from the top soil layer.

The top soil layer is assumed to be dry if storage reduces to -32mm (storage greater than zero allows groundwater flow). Transpiration from the top soil layer is reduced if necessary to prevent the storage becoming less than 'dry'. If the source of transpiration has been deep rooted vegetation, 60% of the reduction is drawn from the bottom soil layer.

Water in excess of total saturation is assigned to potential run-off.

The difference between infiltration and transpiration demand on the bottom soil layer is its 'net recharge'. During the first year, there is assumed to be no limit to the volume of water that can be accepted by, or drawn from, the bottom soil layer. After simulating 12 months in the top soil layer, the resulting net recharge is used as input to the deep groundwater model, to estimate a rate of deep groundwater discharge (+ value) or the rate at which a cell can accept infiltration (- value), i.e. the balance of lateral inflows and outflows.

The water storage in the top soil layer at the end of 12 months becomes the initial storage for the second year. In the second year, the water balance in the top soil layer includes input of discharge from the bottom soil layer, and limits on the output of infiltration to the bottom soil layer.

A water balance is also performed on the bottom soil layer in the second year. The layer is assumed to be saturated initially. This is represented by zero in the volume accounting. Thus negative volumes represent capacity to receive water. Positive volumes are passed to the top soil layer. The volume is first changed by the net rate of gaining or losing lateral flow as determined by the deep groundwater model. The volume may then be increased by infiltration from the top soil layer, and decreased by transpiration of deep rooted plants.

The deep groundwater model is re-run after the second 12 months using the revised estimates of net recharge.

The third year of simulation has the same basis as the second, starting with storages produced at the end of the second year. In most cases this is an acceptable estimate of the behaviour of the catchment in a steady state with a year of average rainfall. This is indicated by a relatively small difference between initial and final water storage.

5.15. Run-off, Streamflow and Lakes

Potential run-off is identified in any month when calculation of the water balance on the top soil layer of a cell results in a storage volume greater than saturation. However, the actual streamflow will be less due to evaporation from exposed water surfaces before the run-off reaches a gauging point. Transpiration by riparian vegetation may also reduce streamflow if local soils have dried out while the stream is still running.

Additional riparian transpiration is considered to be minor and is not modelled, which may lead to some over-estimation of streamflow. Other evaporation is modelled in an approximate fashion as follows:

- On cells not within lakes, any positive difference between the evaporation expected for an open water surface in that month and transpiration from any pasture on the cell, is subtracted from the potential run-off. The maximum amount subtracted is the potential run-off so that a negative result is not possible. This means that extra evaporation will not cause the total evapotranspiration from sources close to the ground to exceed open water evaporation. It is assumed that the remaining run-off will drain out of the catchment within the month. This may not be so in some extensive swamp areas, leading to an over-estimate of streamflow in such cases.
- On cells within lakes (identified from digitised maps of lakes), the total open water evaporation for a year is subtracted from the total potential run-off for the year. This may produce a negative value. The result for individual cells has little significance, but when run-off is integrated over the whole catchment, streamflow reported at the outlet of the lake takes account of evaporation from the lake. If this streamflow is negative, it indicates that the lake would reduce in level in a year of average rainfall. If such a lake is in an upstream part of a larger catchment, the negative amount contributes to an estimate of the long term average streamflow for the whole catchment, but would not be included in an estimate of total streamflow in a year of average rainfall.
- On cells that contain major stream channels, extra evaporation is subtracted as if the cell contained a lake whose area equalled the channel area. To apply this, a map of channel areas may be derived from a map of streamlines that were digitised or generated from terrain analysis.

Annual average streamflow is estimated by integrating adjusted run-off over the catchment area.

5.16. Deep Groundwater Model

The annual net recharge is the input to the deep groundwater model. Positive values are potential recharge that may flow downstream, to the limit of the cell's deep groundwater flow capacity set by its transmissivity and slope. Negative values occur where transpiration demand on the bottom soil layer exceeds local infiltration, and represents a net demand on the deep groundwater.

The excess of summed inflows from upstream cells over a cell's flow capacity plus transpiration demand becomes deep groundwater discharge at the cell. Groundwater flow to downstream cells is called 'throughflow'. Potential recharge which cannot infiltrate because throughflow is at capacity is called 'surplus recharge'. In cleared areas that have significant surplus recharge, the total deep groundwater discharge is almost proportional to transmissivity (i.e. the product of permeability and soil depth).

As with the shallow groundwater model, the hydraulic gradients driving lateral flow are assumed to conform to ground surface topography. This characteristic has been observed by piezometers in many research sites, but it is possible in some situations for gradients to differ significantly from the ground surface, in direction as well as magnitude. These situations arise where a low water table area is near a high water table, for example:

- a sudden change to a high permeability zone when proceeding downstream, or
- an area of high transpiration demand adjacent to areas of high recharge.

Flow directions could also differ significantly from reality in extensive, nearly flat areas where lateral flow rates are small.

A comparison has been made with a MODFLOW (MacDonald and Harbaugh) analysis that indicates the size of errors associated with the approximate analysis (Appendix 10.1). However, the difficulties and limitations in using MODFLOW make it undesirable for routine use, especially as the errors introduced by not modelling the above situations precisely is considered to be similar to the errors associated with other approximations used.

5.17. Formulae for Computations

The formulae that implement many of the computations described in this chapter are presented in Appendix B.

6. PREDICTION OF TREE-PLANTING TO REDUCE DEEP GROUNDWATER DISCHARGE

The object of the prediction computations is to identify sites where trees will be most effective in reducing deep groundwater discharge, subject to constraints reflecting landowner's preferences or the ability of trees to grow in various situations.

Criteria for site selection that may be set by the operator are:

1. Areas where trees may be planted if required. Trees may not be planted in other areas regardless of consequences.
2. Maximum deep groundwater discharge rate permissible before treatment is required.
3. The fraction of the depth of the bottom soil layer that can be reached by planted trees (due to limitations on rooting depths)

These criteria allow various tree planting strategies to be tested. A simple strategy would allow trees to be planted anywhere that was currently pasture. A more complex strategy may require several 'passes'. Soil maps could define areas suitable for different types of trees. Shallow rooted trees that need good soils could be sited first. After analysing the effects of those trees, deeper rooting, more salt-tolerant species could be sited to address remaining discharges.

The calculation has two stages. First, the cells where trees are required are found, together with the annual draw on deep groundwater that these trees must provide. This stage includes an assessment of the reduced deep groundwater discharge expected. Secondly, an estimate is made of the greenness that the trees must have. This takes account of the water that the trees must use from the top soil layer as well as the bottom layer to produce the required net demand on deep groundwater. The greenness represents tree density and can be compared to native forest density by its ratio to 'natural' greenness at the site.

Confirmation of the prediction of tree siting and greenness is made by modifying the maps of total tree greenness and pasture, and re-running the shallow and deep groundwater simulation. The shallow simulation is also needed to give an estimate of the reduction in streamflow to be expected from the planting.

7. OUTPUT

Numerical results, such as streamflow or areas to be planted, are extracted directly from RASCAL projects. Table 2 compares some results from modelled catchments with gauging records. Data can be viewed on screen with program SEERAS, and screen images can be captured to be printed on paper if required. Cross-tabulations can be produced by program RASCAL using command OVROUT. However, to show features of interest against a map-base of, say, roads and property boundaries, the data would need to be converted to polygon form and loaded into Microstation. The RASCAL command MAP generates polygons which enclose groups of cells of constant value. A map may need to have ranges of cell values classed before using MAP, to simplify polygons. Imported into a Microstation design file, the polygons may be shaded and plotted with other map data. An option in the

Catchments:	Barrama	Lemon	Batalling Ck
Area (ha)	94	346	1639
Gauged Flow (mm)	75	70	46
Modelled Flow (mm)	77	73	49
Bottom Soil Layer Calibration:			
Permeability (m/yr)	8	4	2
Depth (m)	20	20	20
Modelled Discharge (mm)	28	16	11
Discharge after Planting:			
Predicted (mm)	5	5	5
From re-run model (mm)	4	2	3

Table 2: Example of Results

RASCAL command INTD also allows drainage lines to be output as polygons so they can be mapped in Microstation. Figure 6 shows a typical map that can be generated.

8. CONCLUSION

The objective of identifying sites for tree-planting to combat dry-land salinity was addressed by developing a hydrologic model. The model is represented in a raster-based Geographical Information System running in a Personal Computer. The development of the model considers all the analytical processes required. The process starts with Landsat TM data supplied by a bureau, and digitised polygons representing contours and other mapping data, and finishes with reporting results and preparing maps. The model identifies the deep groundwater discharge that is likely to develop if the current state of clearing in the catchment was maintained indefinitely. This discharge mobilises the salt responsible for dry-land salinity. The process then goes on to

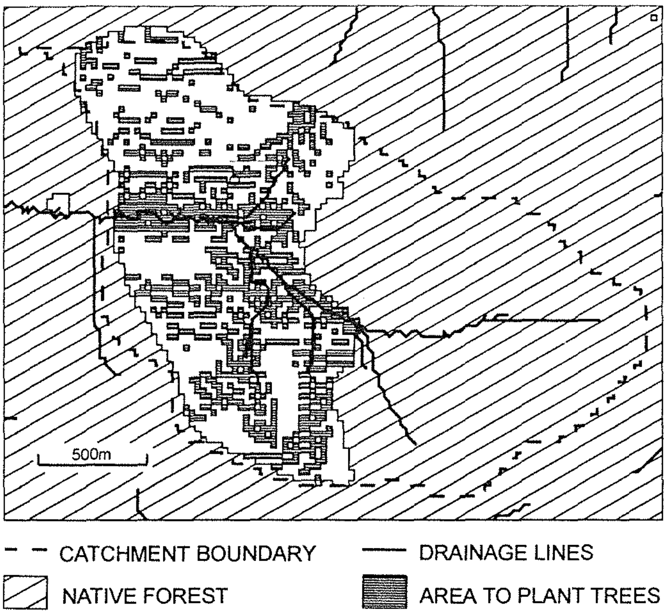


Figure 6: Identified Tree Planting Sites in Lemon Catchment

estimate where and at what density trees should be planted to reduce the discharge while meeting constraints defining areas suitable for planting. Integration along drainage directions gives estimates over whole catchments of the total deep groundwater discharge and surface run-off to compare with stream gauging records and to assess the effects of proposed tree-planting.

9. ACKNOWLEDGEMENTS

The author thanks Alex Gower and Vijay Arumugasamy for their assistance in development and documentation of the whole analytical process.

10. REFERENCES

PECK,A.J., YENDLE,P.A. and BATINI,F.E., "Hydraulic Conductivity of Deeply Weathered Materials in the Darling Range, Western Australia", 1980, Aust. J. Soil Res., 18, 129-138

SHARMA,M.L., BARRON,R.J.W. and FERNIE,M.S, "Areal Distribution of Infiltration Parameters and some Soil Physical Properties in Lateritic Catchments", Oct 1987, J. Hydrol., 94, 109-127

PECK,A.J. and WILLIAMSON,D.R., "Effects of Forest Clearing on Groundwater", Oct 1987, J. Hydrol., 94, 47-65

JOHNSTON,C.D., "Distribution of Environmental Chloride in Relation to Subsurface Hydrology", Oct 1987, J. Hydrol., 94, 67-88

HEEDEGAN,R.G. and BERAN,M.A., "Quantifying Source Areas Through Land Curvature and Shape", 1982, J. Hydrol., 57, 359-373

MAUGER,G.W., "Landsat Evaluation of the Impact of Logging, Burning and Dieback in the Jarrah Forest of South Western Australia", April 1988, I.E.Aust. Trans Multi-Disciplinary Eng, Vol GE12 No 1, 24-29

MACDONALD, M.G. and HARBAUGH, A.W., "A Modular Three-dimensional Finite Difference Groundwater Flow Model", 1988, United States Geological Survey Open File Report 83-875

APPENDIX A - MODFLOW FORMULATION OF DEEP GROUNDWATER MODEL

To test the degree of error introduced by the approximate groundwater flow calculation used in the M.A.G.I.C. model, MODFLOW (MacDonald and Harbaugh) was used to perform the calculation of lateral flows and discharge from the deep groundwater in the bottom soil layer.

The overall form of the model was a 20m thick 'blanket' of soil whose top surface conformed to the topography. Cells were all 25m x 25m in plan view, the same as for the M.A.G.I.C. model. The soil had a uniform permeability of 5m/yr, except for an area of higher permeability associated with a fault zone. In the fault zone, permeability was set to 25m/yr The 'blanket' was subdivided into 5 layers so that vertical flows would be effectively represented. The vertical conductance between layers was set to be equivalent to the horizontal permeability.

The analysis was 'steady state', so that changes in volumes of water stored in the soil were not part of the analysis. It represented the condition that would be reached after a long period of receiving the recharge at the specified rates. The analysis was specified as one 'stress period' of length one year in one time step.

The top layer was defined to be unconfined (type 1), while the other layers were defined as confined or unconfined (type 3). Initial heads in all cells were set equal to the ground surface at the cell's position. Drying and wetting of cells was permitted.

Boundary conditions specified that all cells were 'active' (code 1), and there were no constant head cells. Consequently a no-flow boundary was assumed around the rectangular perimeter of the data as defined by the RASCAL project area. Thus there was no assumption that a topographic watershed would also be a watershed for the deep groundwater flow system.

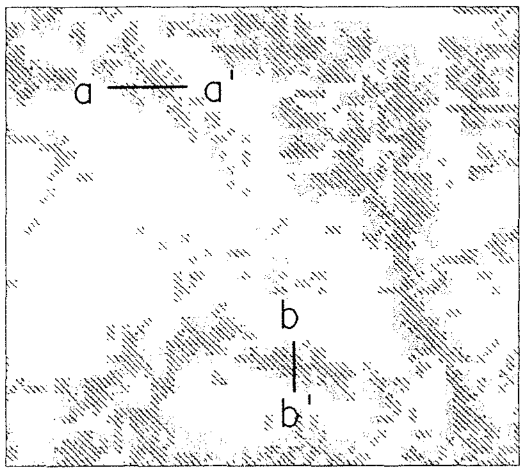
To allow water to discharge to the ground surface, MODFLOW's DRAIN module was used. At every cell in the top layer, a drain was set at the level of the top of the cell. The flow resistance into the drain was set to be equivalent to half the layer thickness with permeability 5m/yr over the plan area of the cell, representing flow from the centre of the top layer to the surface.

The net recharge at each cell as calculated from the shallow groundwater model was applied as a fixed rate of flow using MODFLOW's RECHARGE module. The recharge was applied to the highest layer that was not dry. Negative values represented a net demand on the cell by transpiration of deep rooted vegetation. When noting the rate of discharge of deep groundwater, the flow reported in drains should be reduced by any positive recharge at the cell because this water will not have entered the deep groundwater flow system before joining the drain.

MODFLOW's equation solving module that was used was the conjugate gradient solution package (PCG), preconditioning option 2 (NPCOND=2), an option that avoided testing the Cholesky diagonal. This closed to a head difference accuracy of 1mm after 12 iterations.

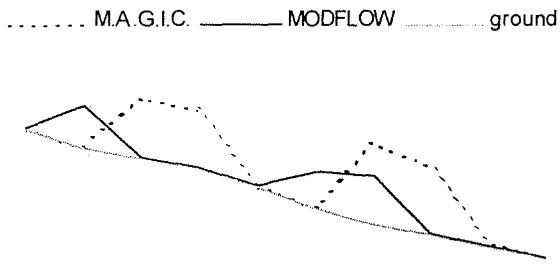
Points of comparison between the MODFLOW results and the M.A.G.I.C. results were:

- **Discharge** occurred substantially at the same sites, as shown in Figure A1. The differences arise from two effects. Firstly, M.A.G.I.C. reports discharge from a cell that cannot carry the input flows, while MODFLOW reports discharge from cells flowing into such a cell. Thus MODFLOW discharge appears to be displaced one cell upslope from M.A.G.I.C. discharge, as shown in Figure A2a. Secondly, due to the presence of high pressure that develops at the base of the primary discharge cell to drive water out of the ground, MODFLOW tends to produce discharge from adjacent cells. This is shown in the profile from a test analysis of a sloping plane meeting a level plane where the ground is completely saturated (Figure A2b). About 20% of the discharge is spread to adjacent cells. In general, the interaction of pressures between cells causes a slight spreading of the discharge computed by M.A.G.I.C., as shown by Figure A2c. Within the major catchment in the project area, total discharge computed by MODFLOW was 7% greater than that computed by M.A.G.I.C., and the number of cells where discharge was occurring was 23% greater.

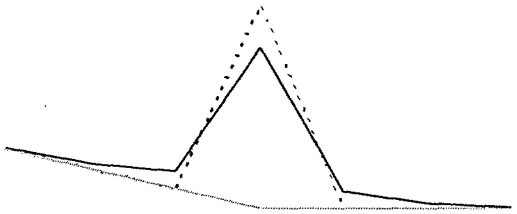


M.A.G.I.C. MODFLOW

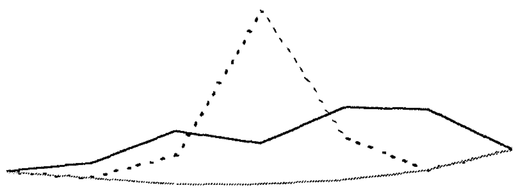
Figure A1: Plan of Discharge Areas



a) Hillslope (Section a-a' in Figure A1)



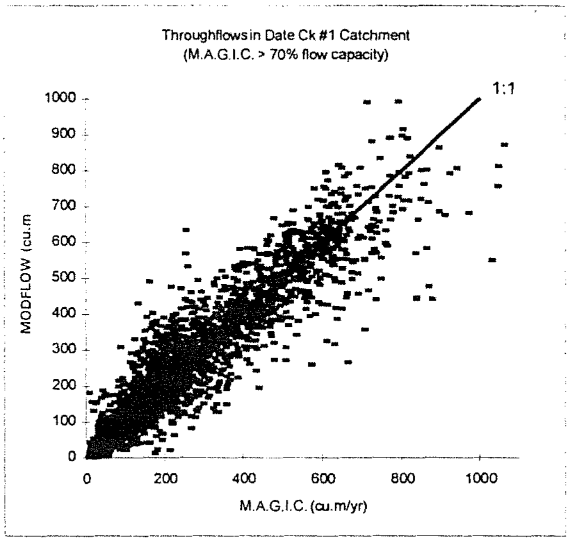
b) Planes meeting (test case)



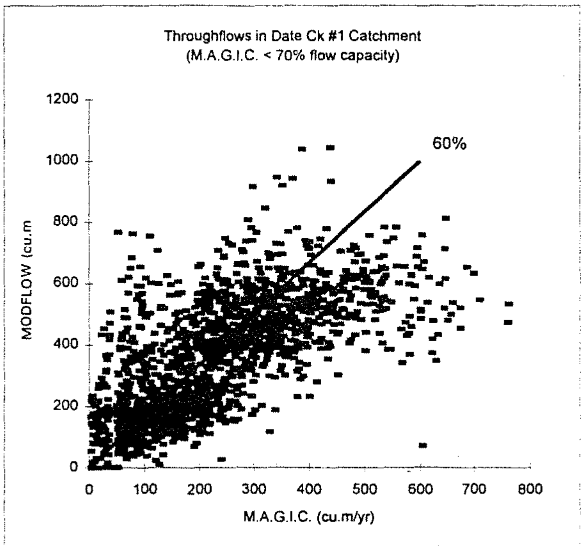
c) Valley (Section b-b' in Figure A1)

Figure A2: Profiles of Discharge

- **Throughflows** in saturated areas were strongly correlated (r^2=0.87), lying near the line of equality in the scatter diagram (Figure A3a). (Note that when converting MODFLOW's orthogonal flow components into throughflow, the 'drain-reduction' factor for non-orthogonal flow directions must be applied.) However, in areas where throughflow was small compared to the flow capacity (i.e. transmissivity times surface gradient) of the soil, MODFLOW produced higher throughflows than M.A.G.I.C. The effect was most pronounced where throughflow calculated by M.A.G.I.C. was less than 70% of the flow capacity of the site. At these sites, M.A.G.I.C. throughflow was about 60% of the MODFLOW value (Figure A3b, r^2=0.34). Unsaturated sites occur under stands of trees and at the upstream edge of the fault zone (high permeability). Such areas would have low head compared to adjacent saturated areas, causing diversion of flow into them. MODFLOW would correctly simulate this effect, but M.A.G.I.C. would not because of the assumption that surface drainage directions define groundwater flow directions. Once saturated conditions are reached when proceeding downstream, the effect has no further influence. Within the affected area, the MODFLOW analysis may give slightly more discharge because saturation is reached sooner. This may account for some of the 7% higher discharge noted above.



a) Near saturation



b) Low degree of saturation

Figure A3: Comparison of Throughflows

APPENDIX B - FORMULAE FOR COMPUTATIONS

In the main report, the computational processes are presented descriptively. In this Appendix, corresponding formulae are given in a format similar to that used for commands in the M.A.G.I.C. system.

The formulae generate maps by being applied to every cell in the map. Where a map appears as a variable in a formula, it is referred to by its number prefixed by M. The value used is from the corresponding cell in that map. If the map referred to is the same number as the one being generated, its value in the formula is the same as before the formula is evaluated.

When a map is generated, it is assigned a name to identify it.

Anything written after : in a formula is a comment, not part of the formula. IF formulae are read as "IF(logical expression, result if true, result if false)". A formula may continue over several lines.

Maps may be generated by M.A.G.I.C. functions other than formulae. Where these occur they are stated descriptively.

Results are often achieved by a successive evaluation of functions.

Infiltration, Drain-reduced Slope, Residual Drainage

Infiltration from the top soil layer to the bottom soil layer has been found to be correlated to the degree of flow convergence of shallow groundwater as indicated by the ground surface topography. This is determined by a shallow groundwater drainage integration. Being the first such integration for a project, it is also used to generate the drain-reduced slope, and the map to complete drainage integration if the dispersed mode of integration became blocked.

Move the slope map M105 to M107

Set 'water' content of all cells to 1000, much greater than saturation (saturation=187). Flow out of cells will thus always be the maximum that corresponds to saturation.

M130 becomes INITIAL CELL STATE

1000

Perform shallow g/w integration with dispersed drainage.

Input M117 Dispersed drainage codes
M130 Initial water content
M107 Slope
M102 Aspect
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2

Output M130 Water content after flow
M118 Integration incomplete where value>0
M105 **DRAIN-REDUCED SLOPE**

M116 is Sink-free simple drainage directions

M118 becomes **RESIDUAL NON-DISPERSED DRAINAGE**

IF(M118>0,M116,-99) : -99 signifies no data

Finish shallow g/w integration using residual drainage.

Input M118 Residual non-dispersed drainage
M130 Output from dispersed integration
M105 Drain-reduced slope
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2

Output M130 Water content after flow

M130 becomes FLOW CONVERGENCE

M130-1000

: Apply regression equation to estimate infiltration rate

M130 becomes INFIL RATE EX CONVERGENCE

18-.63*M130

M130 becomes SUMMED INFIL RATE EX CONVERG

To each cell, add values of adjacent cells

M421 is count of how many cells summed (max 9)

M130 becomes **SMOOTHED INFIL RATE EX CONVERG**

IF(M130<0,0,M130/M421)

Tree Greenness and Pasture Leaf Area Index

M4 is TM Band 4

M120 is percent greenness calculated from TM data

M303 becomes **TREE GREENNESS**

IF(M4<35 OR M120<6.5 ,0, : Water, Pasture Or Clay
M120 : Native Vegetation
)

M5 is TM Band 5

M11 is Rainfall

M12 is Pan Evaporation

(.0087*M11-.0051*M12+35.85) is a regression equation estimating the natural greenness of native vegetation at the cell position.

M304 becomes **FULL PASTURE LAI= 2.7**

IF(M4<35 OR M5<115 OR M120<-4 ,0, : Water, Native Vegetation, or Clay
2.7*(1 - M303 / (.0087*M11-.0051*M12+35.85))): LAI of Pasture allowing reduction for any Trees on the cell

Shallow Groundwater Model Initialisation

'Shallow' refers to the top soil layer

'Deep' refers to the bottom soil layer

The first section of analysis initialises working maps, and simulates 12 months to develop estimates of initial shallow storage and net recharge to deep storage. Thus calculations needed only for final results are omitted. At the end of the first 12 months, the deep groundwater model is run to get a first estimate of lateral flow in the bottom soil layer.

M439 becomes PASTURE MAX. TRANSPIRATION (MM)

0.352*M12*M304

M438 becomes PERENNIAL PASTURE TRANSPIRATION (MM)

: Assume 'bays' in maps 32 and 33 show areas of perennial pasture (not lucerne)

: ET for phalaris = pan et/6 (p306, Scott & Sudmeyer 1993)

IF(M32>0 OR M33>0,M12/6,0)

M122 is map of LAI of deep-rooted perennial pasture (eg lucerne)

M435 becomes DEEP ROOT MAX. TRANSPIRATION (MM)

.352*M12*M122

M437 becomes DEEP STORE LIMIT FOR DEEP ROOTS

: (ROOT DEPTH - TOP SOIL DEPTH) * AREA * POROSITY/STD LEAF AREA * ACTUAL LEAF AREA

-(2-1.5)*625*.2/2.7*M122

M436 becomes ANNUAL TREE TRANSPIRATION (MM)

: NET RAIN / NATURAL GREENNESS * ACTUAL GREENNESS

1.33*.85*M11 / (.0087*M11-.0051*M12+35.85) * M303

M412 becomes INITIAL SHALLOW STORAGE

187

M441 becomes INITIAL DEEP STORAGE

0

The following formulae are applied for each month of the year starting in September. The variable RAIN is the coefficient that multiplies annual rainfall in mm to give rainfall volume in cu.m on the cell for the month. EVAP is a similar variable for transpiration and evaporation. GROWTH is the variable that scales the leaf area of annual pasture to simulate the stage of growth in the month.

M412 becomes SHALLOW STORE PLUS RAIN

M412 + M11*RAIN

M421 becomes SHALLOW ROOTED PASTURE ET

: SHALLOW ROOTED PASTURE ET CANNOT CAUSE STORE TO BECOME LESS THAN -20

MAX(0, MIN(M412+20, EVAP * (GROWTH * M439 + M438)))

M422 becomes DEEP ROOT PASTURE ET

EVAP*M435

M412 becomes SHALLOW STORE MINUS TRANSPIRATION

M412 - M421 - M422 - EVAP*M436

Perform shallow g/w integration using dispersed drainage to account for lateral groundwater flow.

Input M117 Dispersed drainage codes
M412 Current shallow storage
M105 Drain-reduced slope
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2

Output M412 Shallow storage after flow

Finish shallow g/w integration using residual drainage.

Input M118 Residual non-dispersed drainage
M412 Output from dispersed integration
M105 Drain-reduced slope
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2

Output M412 Shallow storage after flow

M414 becomes INFILTRATION TO DEEP STORE

MAX(0,MIN(M412,M130))

M441 becomes DEEP STORE (STEP 1)

: OLD STORE + INFILTRATION + .6 OF EXCESS ET ON SHALLOW STORE

M441 +M414 + .6 * MIN(0,M412+20)

M441 becomes DEEP STORE AT END OF MONTH

: IF DEEP STORE < DEEP ROOT LIMIT, PUT BACK DEEP ROOT TRANSPIRATION

IF(M441<M437, M441 + MAX(0, MIN(.6*M422 , M437-M441)) , M441)

M412 becomes SHALLOW STORAGE AFTER INFILT & ET

MAX(-20 , M412 - M414)

M413 becomes RUN-OFF

IF(M412>187,M412-187,0)

M412 becomes FINAL SHALLOW STORAGE

M412 - M413

Typical variable values for catchments in the SouthWest of Western Australia:

MONTH	RAIN	EVAP	GROWTH
SEPTEMBER	.049	.036	1
OCTOBER	.033	.054	1
NOVEMBER	.013	.066	.93
DECEMBER	.008	.086	.74
JANUARY	.005	.091	.37
DECEMBER	.007	.079	.07
MARCH	.012	.070	0
APRIL	.028	.041	0
MAY	.075	.029	.07
JUNE	.112	.022	.37
JULY	.106	.023	.74
AUGUST	.083	.027	.93

Deep Groundwater Model

Perform deep g/w integration using dispersed drainage to account for lateral groundwater flow.

Input M117 Dispersed drainage codes

M441 Net recharge to deep store
M105 Drain-reduced slope
Soil depth 20m
Permeability 5 m/year
Output M442 Discharge (+ve) or capacity for more recharge (-ve)
M253 Throughflow
M254 Surplus recharge

Finish deep g/w integration using residual drainage.
Input M118 Residual non-dispersed drainage
M254 Output from dispersed integration (contains original net recharge in areas not integrated)
M105 Drain-reduced slope
Soil depth 20m
Permeability 5 m/year
Output M442 Discharge (+ve) or capacity for recharge(-ve)
M253 Throughflow
M254 Surplus recharge

Final Shallow Groundwater Model

The final model accounts for water discharged from the deep store into the shallow store, or limitations on the rate of infiltration that the deep store can accept. The map of discharge/recharge produced by the deep groundwater model has most of the information, but the capacity to accept infiltration must exclude any locally added recharge. Thus the following formula is necessary to compute the capacity of the deep store to accept infiltration if it is not discharging.

M442 becomes POTENTIAL RECHARGE & DISCHARGE
: DISCH<=0, SURP RECH - NET RECH + (-VE) DISCH, ELSE +VE DISCH, CONVERTED TO MONTHLY RATE
IF(M442<=0,M254 - M441 + M442 , M442) /12

Initialise maps to accumulate data over 12 months

M420 becomes INITIAL DEEP STORAGE
0
M251 becomes CUM. NET RECHARGE TO DEEP STORE
0
M241 becomes INITIAL STREAMFLOW ACCUMULATION
0
M242 becomes INITIAL PASTURE ET TOTAL
0

Apply the following formulae for each of 12 months, with values of variables RAIN, EVAP and GROWTH as for the initial 12 months.

M420 becomes DISCHARGE ADDED TO DEEP STORE
MIN(0,M420) + M442
M422 becomes SURPLUS DEEP STORE
MAX(0,M420)
M412 becomes RAIN & +VE DISCHARGE ADDED TO SHALLOW STORE
M412 + M422 + M11*RAIN
M421 becomes SHALLOW ROOTED PASTURE ET
: SHALLOW ROOTED PASTURE ET CANNOT CAUSE STORE TO BECOME LESS THAN -20
MAX(0, MIN(M412+20, EVAP * (GROWTH * M439 + M438)))
M242 becomes TOTAL PASTURE ET
M242 + M421
M425 becomes DEEP ROOT TRANSPIRATION
EVAP*M435
M412 becomes SHALLOW STORE MINUS TRANSPIRATION
M412 - M421 - M425 - EVAP*M436

Perform shallow g/w integration using dispersed drainage to account for lateral groundwater flow.
Input M117 Dispersed drainage codes
M412 Current shallow storage
M105 Drain-reduced slope
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2
Output M412 Shallow storage after flow

Finish shallow g/w integration using residual drainage.
Input M118 Residual non-dispersed drainage
M412 Output from dispersed integration
M105 Drain-reduced slope
Soil depth 1.5m
Permeability 30 m/month
Porosity 0.2
Output M412 Shallow storage after flow

M414 becomes INFILTRATION TO DEEP STORE
MAX(0,MIN(M412,M130))
M423 becomes NET RECHARGE TO DEEP STORE
: INFILTRATION + .6 OF EXCESS ET ON SHALLOW STORE
M414 + .6 * (MIN(0,M412+20))
M420 becomes DEEP STORE (STEP 1)
M420 + M423 -M422
M425 becomes DEEP ROOT OVERDRAW
: IF DEEP STORE < DEEP ROOT LIMIT, PUT BACK DEEP ROOT TRANSPIRATION
MAX(0,MIN(.6*M425,M437-M420))
M420 becomes DEEP STORE AT END OF MONTH
M420 + M425
M251 becomes CUM. NET RECHARGE
M251 + M423 - M425
M412 becomes STORAGE AFTER INFILT & ET
MAX(-20 , M412 - M414 + MAX(0,M420))
M413 becomes RUN-OFF
IF(M412>187,M412-187,0)

M115 is a map where cells in lakes have value 0, all other cells have value 1

M241 becomes CUMULATIVE RUN-OFF LESS EVAP

M241 + MAX(M413-M115*MAX(.7*EVAP*M12-M421,0),0)
M412 becomes FINAL SHALLOW STORAGE
M412 - M413

The following formula completes the shallow groundwater model after the above formulae have been executed for 12 months:
M241 becomes RUN-OFF ADJUSTED FOR LAKES
: FOR CELLS IN LAKES, REMOVE ANNUAL EVAPORATION (IN M115, 1=LAKE, 0=OTHER)
M241 - .625*.7*M12*M115

Completion of Catchment Model

The deep groundwater model is run again after the final shallow groundwater model. Input is provided from M251 instead of M441, and output is to M252 instead of M442. Further sequential executions of the final shallow groundwater model and deep groundwater model improve satisfaction of the objective that shallow storage at the end of the 12 months equals the storage at the beginning of the 12 months. In additional iterations, calculation of M442 must use the maps just generated from the deep groundwater model, viz:
M442 becomes POTENTIAL RECHARGE & DISCHARGE
: DISCH<=0, SURP RECH - NET RECH + (-VE) DISCH, ELSE +VE DISCH, CONVERTED TO MONTHLY RATE
IF(M252<=0,M254 - M251 + M252 , M252) / 12
A total of three iterations, including the initialisation model, is usually sufficient.

Prediction of Sites for Planting Trees

Where deep groundwater discharge exceeds a nominated rate, trees can be planted to use the discharge plus a proportion of the deep groundwater throughflow at the site, provided the cell is identified as being eligible for tree planting in a 'criterion' map. The calculations are performed in a special drainage integration process because the effect on deep groundwater must be propagated to downstream cells before they are tested for whether or not trees should be planted.

Perform 'tree planting' mode of g/w integration using dispersed drainage to account for lateral groundwater flow.

Input M117 Dispersed drainage codes
M412 Current shallow storage
M105 Drain-reduced slope
M213 Throughflow
M214 Surplus recharge
M124 Cells>0 may be planted if required
Soil depth 20m
Permeability 5 m/year
Groundwater discharge rate to be exceeded before planting 25cu.m/year
Fraction of deep groundwater throughflow capacity accessible by roots of planted trees 0.3
Output M332 Deep groundwater discharge after planting
M331 Deep groundwater used by planted trees

Finish 'tree planting' mode of g/w integration using residual drainage.

Input M118 Residual non-dispersed drainage
M331 Output from dispersed integration
M105 Drain-reduced slope
M213 Throughflow
M214 Surplus recharge
M124 Cells>0 may be planted if required
Soil depth 20m
Permeability 5 m/year
Groundwater discharge rate to be exceeded before planting 25cu.m/year
Fraction of deep groundwater throughflow capacity accessible by roots of planted trees 0.3
Output M332 Deep groundwater discharge after planting
M331 Deep groundwater used by planted trees

M201 is annual run-off from cell
M202 is ET of pasture to be displaced by planted trees
M333 becomes PLANTED TREE GREENNESS
:Tree must use required g/w + total pasture ET + run-off
IF(M331>0,(M331+M202+M201) :
:compare to use by natural. Vegetation i.e. total rain less interception
/(.625*.85*M11) :
: greenness relative to natural vegetation
*(.0087*M11-.0051*M12+35.85),0)