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WEC-C modelling of Yarragil 4X an undisturbed forested catchment

WEC-C MODELLING OF YARRAGIL 4X — AN UNDISTURBED FORESTED CATCHMENT

by

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Cover photograph:

Forest of the Yarragil 4X catchment

by Lidia Boniecka

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Summary

Yarragil 4X is a small experimental catchment within the Northern Jarrah Forest of the south-west of Western Australia. It was modelled using the distributed, deterministic WEC-C model to assess the model's applicability to the catchment; test its sensitivity to variations in forest cover; and provide a model that could be applied in future 'what-if' land management studies.

The most important conclusion was that the generic parameter set used (first developed for the Cameron catchments also in the Northern Jarrah Forest) created a reasonable history match to stream yields for the Yarragil 4X catchment. It was recognised, however, that this parameter set was suboptimal and a catchment-specific parameter set would probably provide a superior history match. The study also found the model's predictive ability highly dependent on LAI (Leaf Area Index) estimation. The LAI values used were derived from Landsat MSS and TM data. The initial map defining vegetation up to 1988 was markedly different from subsequent maps. It is likely that a different map for the initial LAI would result in a different parameterisation of the model to the catchment. Despite the above uncertainties regarding the final model's accuracy, its development provided an insight into the hydrological processes of jarrah forest catchments and how these may be simulated. The uncertainties were significant, and the developed model must be considered preliminary. Three recommendations were put forward to improve this situation.

1. Use aerial photographs to define initial LAI estimates, particularly those for the 1980s, and revise the present LAI maps. Other studies have successfully used aerial photographs to define early LAI.

2. Apply the WEC-C model to the Yarragil 6C catchment and create a single parameter set which achieves the best history match for both catchments. Such replication would help resolve the issues surrounding LAI estimation as well as help validate the final parameter set.

3. Investigate the poor match of observed and simulated flows in the years 1988, 1994, 1999 and 2000. For 1988 and 1994 the mismatch may be fire-related; however, there is no obvious explanation for 1999 and 2000.

1 Introduction

1.1 Background

Yarragil 4X is a small experimental catchment within the Northern Jarrah Forest of the south-west of Western Australia. A significant percentage of this forest is within the potable water supply catchments of Perth and this has resulted in a strong focus on the issue of streamflow enhancement through forest management such as stand thinning (Steering Committee for Research on Land Use and Water Supply 1987; Stoneman & Schofield 1989). Until recently Yarragil 4X has acted as a control in paired catchment studies for other experimental catchments of the Yarragil Brook, e.g. Moulds et al. (1994) review of the treated catchment Yarragil 4L.

As part of developing the understanding of jarrah forest hydrology beyond that which can be gained from monitoring streamflow, stream salinity and groundwater levels there has been considerable research into processes, e.g. Ruprecht & Schofield (1990a & b). Combining the knowledge from process research with that from catchment monitoring into an integrated understanding of jarrah forest hydrology requires simulation modelling. The study presented here details one such exercise where the Water and Environmental Consultants – Catchment model (WEC-C) has been applied to the Yarragil 4X catchment.

1.2 Objectives

The objectives of the modelling were to:

- apply the WEC-C model to the Yarragil 4X catchment using the generic parameter set developed for other catchments within the Darling Plateau
- assess the model accuracy and suitability through matching with observed catchment data
- run initial tests of the model's sensitivity to variations in forest cover
- provide the model to other researchers for use in 'what-if' modelling of various land management scenarios and their effects on groundwater levels, streamflows and stream salinities.

2 Catchment description

2.1 Location, form and climate

The Yarragil 4X experimental catchment is approximately 120 km south of Perth and 20 km south-east of Dwellingup (Fig. 1). It is part of the Yarragil Brook group of catchments which were established to study the effects of forest structure and composition on stream water quality and yield (Shea et al. 1975). The gauging station and piezometer network were upgraded by Alcoa World Alumina Australia in 1984 when the catchment was selected as the control catchment for a potential bauxite mining trial. This trial was relocated to the Cameron catchments in 1990.

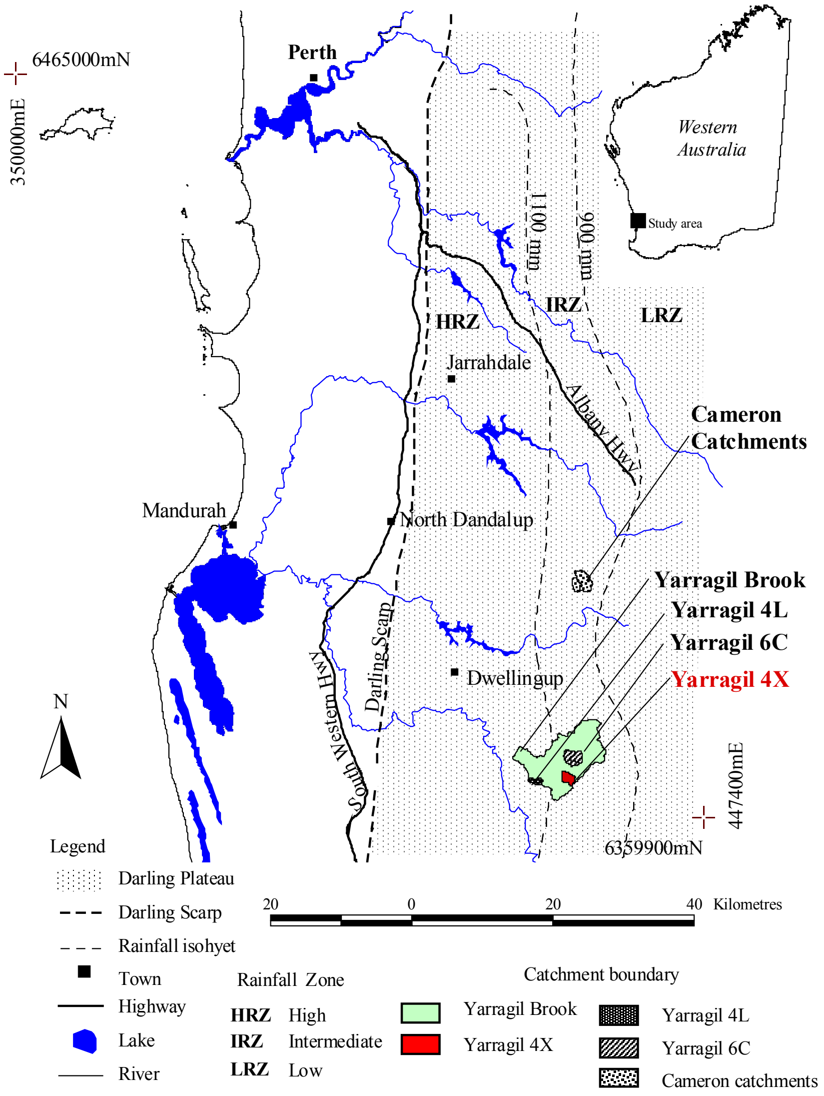

Figure 1. Location of the Yarragil 4X catchment

Yarragil 4X is a small catchment of 2.73 km^2 with a defined stream channel at the outlet. Valley flank slopes are moderate and grade into broad valley floors (Fig. 2). Yarragil 4X is within the Intermediate Rainfall Zone (IRZ) of the Darling Plateau and had an average annual rainfall of 910 mm for the period 1980–2001. Based on Luke et al. (1988), the average Standard Class A pan annual evaporation for the catchment is equal to that for Dwellingup which is estimated as 1580 mm (without correction for the effects of the bird guard). The climate of the Northern Jarrah Forest is Mediterranean, characterised by dry hot summers and wet cool winters with the most of the rain falling between May and October.

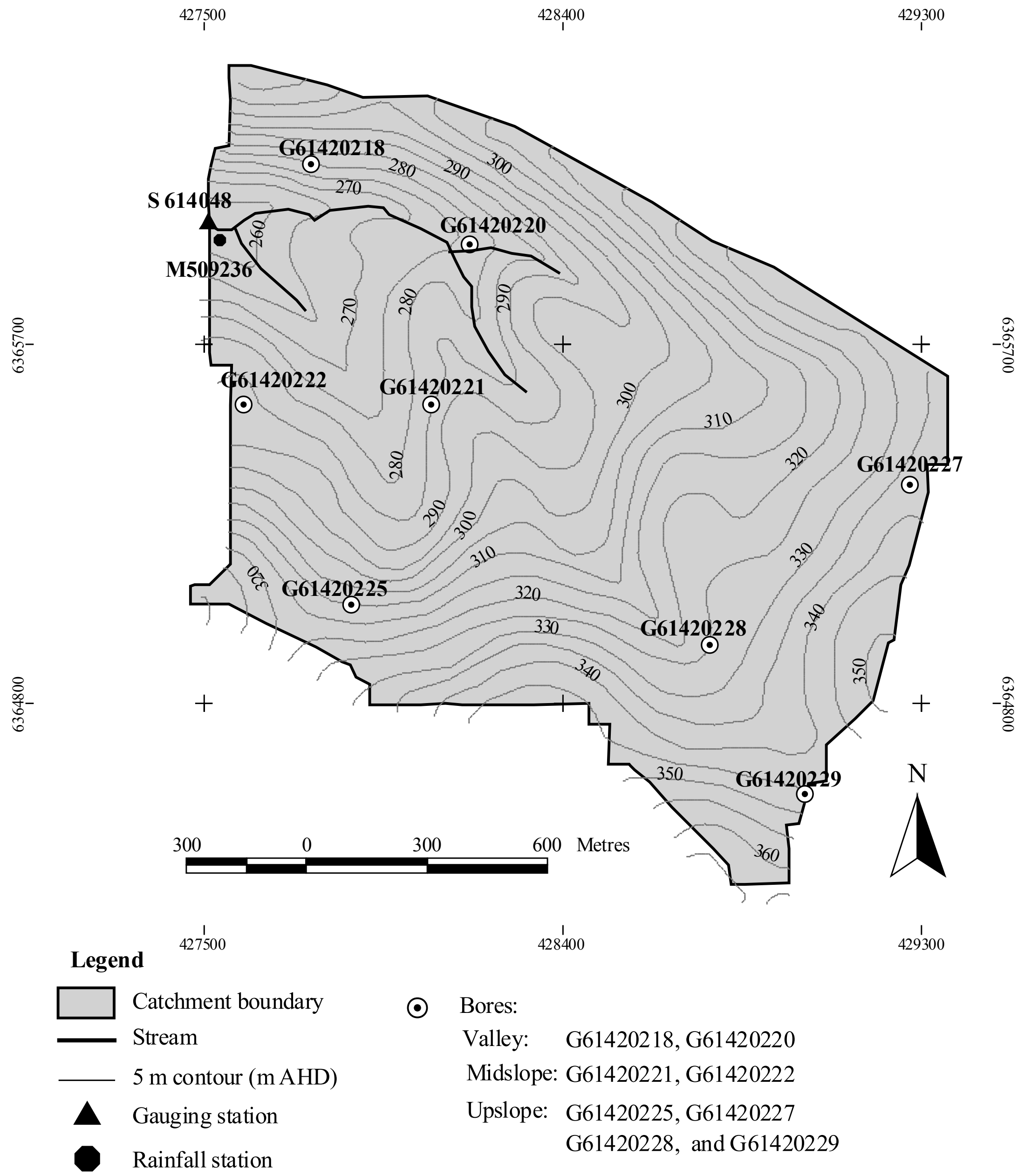

Figure 2. Topography and bore locations within the Yarragil 4X catchment

2.2 Soils and geology

Geologically, the catchment is located within the south-western province of the Archaean Yilgarn Block, and, while no comprehensive descriptions of the geology and soils of the catchment have been made, they are assumed to be typical of the Darling Plateau. That is a primarily granitic bedrock that has been divided by intrusions of numerous sheet-like doleritic dykes that vary in thickness from a few millimetres to tens of metres. Deep *in-situ* weathering has produced a soil profile with expected depths 10–40 m, average about 25 m. On the side slopes, the soil profile consists of a surface layer of sandy-gravel 0–2 m deep (average 0.4 m) overlying a duricrust 0–3 m thick, (average about 1.5 m); the duricrust generally is underlain by a mottled zone that includes an alumina-rich friable layer that transitions into a deep, pallid, sandy-clay zone (Fig. 3). This pallid zone is divided from the parent rock by the weathering zone which, with a significantly greater sand fraction than the pallid zone, acts as the lateral conducting layer for the main aquifer. The valley floor profile often lacks the duricrust and is usually more silty. Peat is commonly found in the swamp areas. Vertical preferential water flow structures, in the form of sand-infilled root channels, are very common and typically extend from the duricrust to the weathering zone.

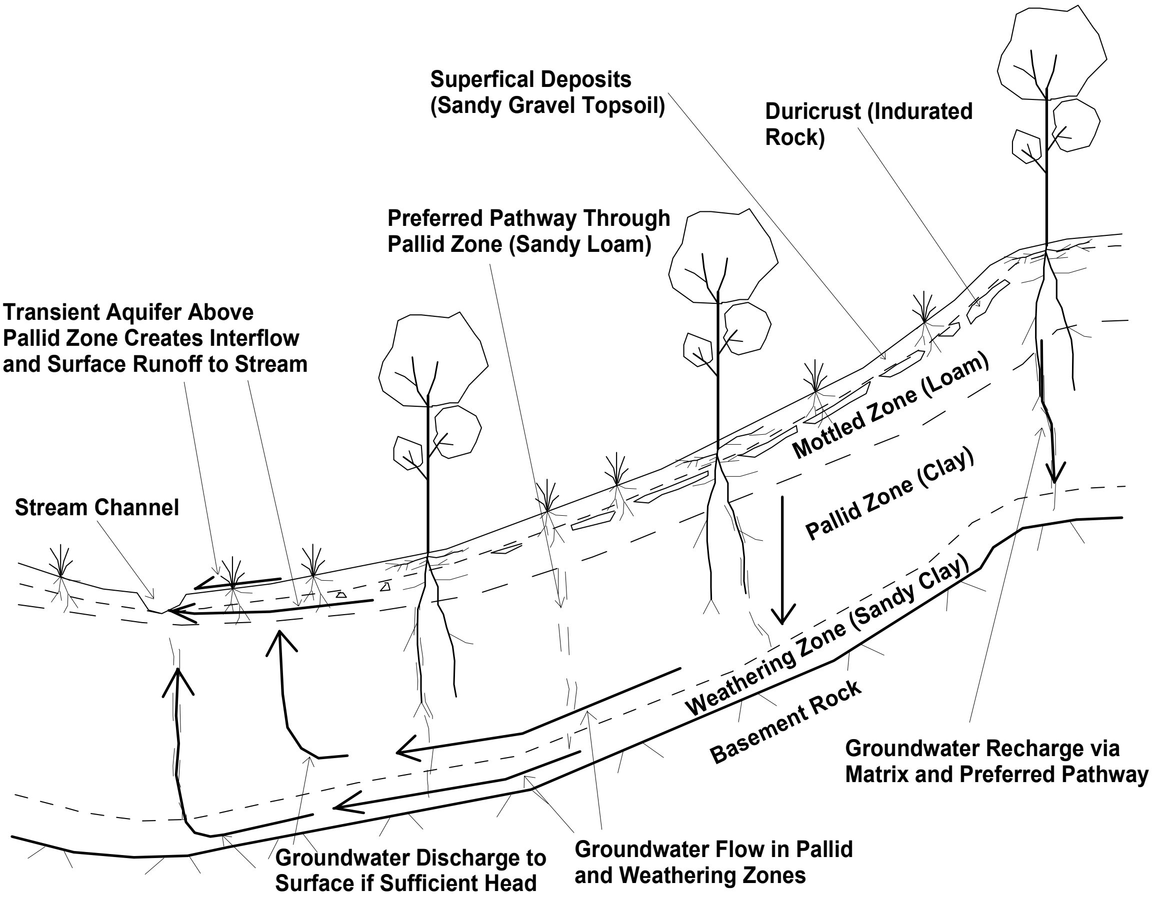

Figure 3. Schematic of soil layering and hydrology for a typical hillslope section in the Darling Plateau (after Croton & Bari 2001)

2.3 Vegetation

Jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) dominate the Northern Jarrah Forest (Ovington & Pryor 1983) and are common within the Yarragil 4X catchment. The major understorey vegetation species include subdominant trees and shrubs (*Banksia, Allocasuarina* and *Persoonia* species) (Herbert et al. 1978). Before monitoring started in 1984, the catchment was subject to standard forest management activities including burning and logging. Since then there have been prescribed burns in 1987, 1988 and 1993 (Kinal pers. comm.).

2.4 Observation bores

In 1984, eight bores were drilled in the catchment by Alcoa World Alumina Australia to estimate soil profile depth, soil salt storage and to establish monitoring piezometers (Fig. 2). Water level monitoring of these piezometers began in 1985 and groundwater salinity data were collected in 1985 and 1986. Table 1 lists the bore details. The soil salt storage data for the piezometers are presented graphically in Appendix 2. Sampled salt storage values were in the range 0.05–4.5 kg/m^3.

Table 1. Observation bore data

Piezometer ID	*Easting*	*Northing*	*Depth drilled (m)*	*Depth to water in 1985 (m)*	*Layer reached*	*Location in catchment*	*Monitoring period*
G61420218	427500	6366000	32.8	22.2	Clay	Valley	1985–97
G61420220	427900	6365800	24.5	10.9	Dolerite	Valley	1985–97
G61420221	427800	6365400	29.5	14.4	Clay	Midslope	1985
G61420222	427330	6365400	34.2	22.7	Clay	Midslope	1986–95
G61420225	427600	6364900	38.6	23.5	Clay	Upslope	1985–86
G61420227	429000	6365200	25.1	Dry	Granite	Upslope	Dry in 1985
G61420228	428500	6364800	33.0	32.8	Clay	Upslope	1985–94
G61420229	428740	6364425	30.0	Dry	Granite	Upslope	1985–87

3 The WEC-C model

WEC-C, a distributed deterministic catchment model, has been described in detail by Croton & Barry (2001) and example applications of the model to Darling Plateau catchments have been given by Bari & Croton (2000), Croton & Bari (2001), and Beverly & Croton (2002). WEC-C employs a rectangular grid of uniform cell size in the lateral plane combined with a system of soil layers in the vertical to represent the regolith of a catchment (Fig. 4). The catchment is delineated by defining as active only those cells within the catchment divide. All parameters are defined locally in each model cell so that all available data on catchment variability can be directly incorporated into the model. The unit of time for input of evaporation and rainfall data is daily; however, to maintain stability and accuracy the model operates on a much shorter internal time-step.

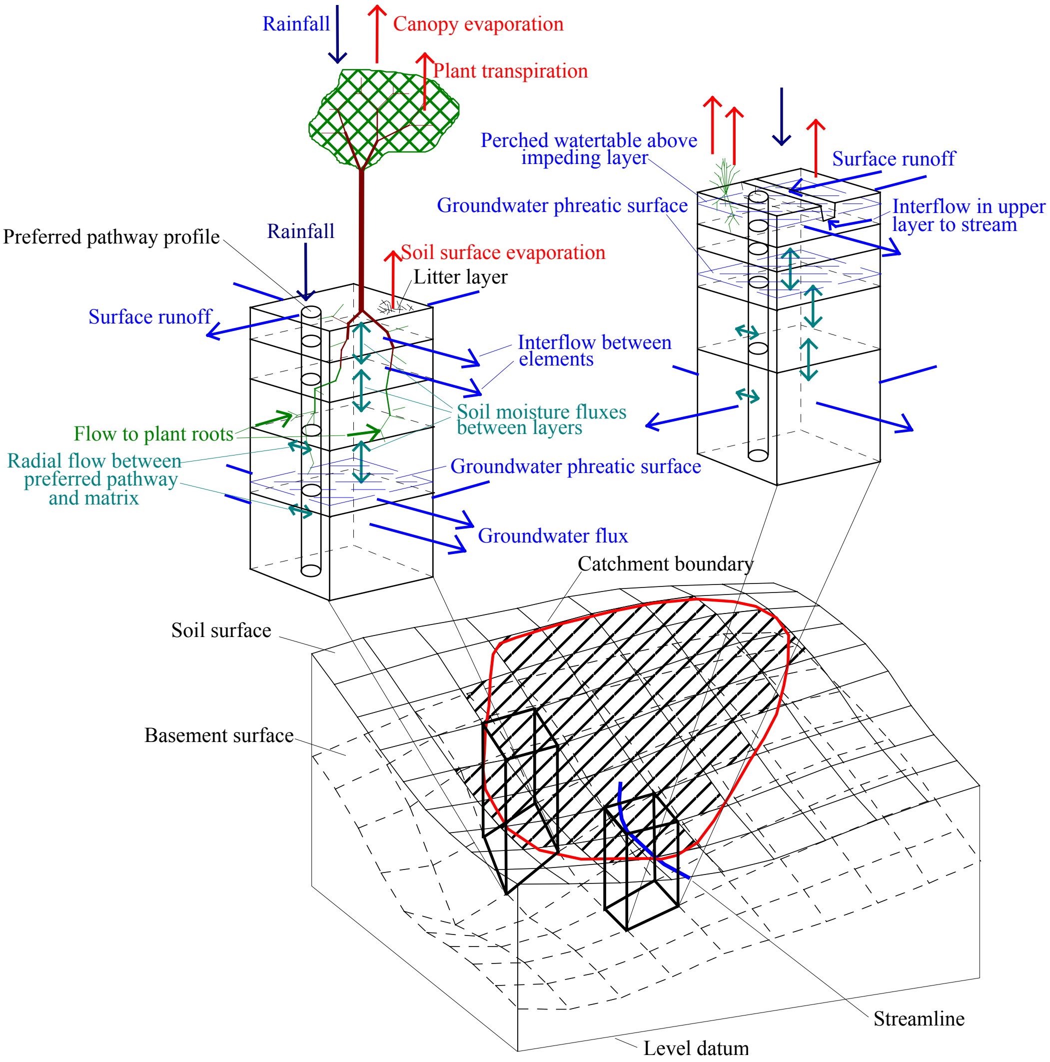

Figure 4. Schematic of model layout and processes modelled (after Croton & Barry 2001)

4 Model set-up and data requirements

4.1 Time-series data requirements of the model

The WEC-C model is run on a daily time-step by the input of rainfall and evaporation data. Using these inputs, in combination with descriptive data such as LAI, the model creates a series of outputs that define the simulated state of the catchment in terms of measurable items such as groundwater levels, streamflows and stream salinities. The comparison of simulated values with measured records forms the basis of the model calibration and validation processes.

4.1.1 Rainfall and pan evaporation

Rainfall data were available from the Yarragil 4X rain gauge (M509236) from 17 April 1984. As the simulation process requires a ‘spin-up’ period to allow the internal storages within the model to stabilise, the records were extended back to 1 January 1980 using data from Marradong (M509308). Missing records were filled using data of the closest available pluviometer, M509433, in the Yarragil North catchment. Daily pan evaporation data, provided by the Department of Conservation and Land Management (CALM) at Dwellingup, were used without correction for bird guard.

4.1.2 Streamflow and salinity

Continuous streamflow records from the catchment gauging station (S614048) were available from 1 January 1984. Continuous measurement of stream salinity began in 1991 with the installation of a conductivity cell. Before this samples were collected manually. In March 2000, CALM took over the data collection role from WRC.

4.1.3 Evapotranspiration and vegetation cover

Evapotranspiration (ET) is the dominant component of the water balance of the Northern Jarrah Forest and far exceeds stream yields (Schofield et al. 1989). The average stream yield in Yarragil 4X over the study period from 1984 to 2001 was 1.7% of rainfall, while the down-valley groundwater flow was estimated at about 0.3%. Neglecting storage effects, this leaves approximately 98% of the water balance. As most of this is lost by ET its accurate simulation is essential to the successful simulation of the catchment hydrology as a whole. In turn the correct estimation of the vegetation cover and its temporal changes are essential to the estimation of ET.

The transpiration demand function used in WEC-C is described by potential transpiration (PT) per unit LAI (Equation 1):

$$PT = A * \ln(E) + B \qquad (\textit{Equation 1})$$

where:

E = pan evaporation in mm

A and B are constants which, in this study, were: A = 0.65; B = 0.6. These values of A and B were obtained from previous WEC-C modelling studies in the Darling Plateau.

Equation 1 is scaled by LAI to estimate total transpiration within the model. LAI was calculated from historical vegetation data provided by CALM and Landsat MSS and TM images. Eight Landsat TM scenes were available: February 1988, 1990 and 2000; January 1992, 1994, 1996 and 1999; and December 1997. These images were used to create a sequence of LAI maps. Midsummer images were used because: at this time in the season the vegetation is normally not yet water stressed; the midsummer climatic variations between years tend to be less than for other times of the year; and the solar elevation is at its peak, so the loss of information from shadowing is reduced.

As the model was run from 1980, before Landsat TM imagery was available, the initial LAI estimates were calculated using historical CALM information together with two Landsat MSS images (December 1981 and December 1983) to develop a history of forest LAI for this period.

The model presented in this study uses the following LAI maps:

- **an initial LAI map** used for the first seven years of simulation (from 1980 till 1987) and produced from historical CALM data combined with the Landsat MSS images

- **Landsat TM LAI maps** used for the remaining 14 years of simulation and derived from the eight Landsat TM images.

To test the sensitivity of the model to vegetation changes, two alternative cases were simulated: constant LAI and single LAI. The constant LAI case used two LAI maps: a) the initial LAI map for the first eight years of simulation, b) the 1988 Landsat TM map, not updated, for the remainder of the simulation. For the single LAI case, the 1988 Landsat TM map was applied to all years, from simulation commencement in 1980 till completion in 2001.

4.2 Model set-up

4.2.1 Catchment discretisation

A seven-layer model was used: the first layer was top soil, the second the duricrust on the valley flanks and part of the mottled zone in the valley floor. The third layer included bauxitic and mottled zones, while the fourth to sixth layers were the pallid zone. The seventh layer was the weathering zone. The bedrock was assumed to be impervious and its surface was the model base.

A map of the soil profile depth was developed by Kriging on a 50-m grid the borehole depth data provided by the eight drill holes listed in Table 1. This gave a soil profile depth range of 23–39 m. The profile was then divided into layers. The first layer thickness was set to a uniform 0.4 m (Table 2). The second layer was assumed to be 1.5 m thick on the valley flanks thinning to 0.4 m in the valley floor. The thickness of the third layer was set to 3.6 m on the valley flanks and to 0.8 m in the valley floor. The maximum thickness of the bottom layer was 5.0 m. The layers 4, 5 and 6 were assigned depths equal to 33% of the remaining profile thickness.

The entire catchment soil profile was divided into two continua: matrix and preferred pathway. For simplicity, only four soil types were used on the valley flanks for the matrix: a gravelly sand with saturated hydraulic conductivity (K_{sat}) of 3000 mm/day for layer one, the duricrust with K_{sat} of zero for layer two, a loam with K_{sat} of 250 mm/day for layer three, and a clay with K_{sat} of 5 mm/day for the pallid and weathered zones (layers four to seven). Preferred pathways, occupying 5% of the profile, had gravelly sand with K_{sat} of 3000 mm/day in all layers (Table 2). The layering of the valley floor was similar to the valley flank with two notable exceptions for layers two and four. In layer two the duricrust was substituted with a loam with K_{sat} of 250 mm/day. Layer four (the top layer of the pallid zone) had the properties of an impeding layer: clay with K_{sat} of 1.25 mm/day for the matrix, and a loam with K_{sat} of 125 mm/day for preferred pathway. The percent occupancy of the preferred pathway was reduced from 5 to 1 %, in layer four of the valley floor.

Table 2. Assumed soil profiles for the valley flank and the valley floor of the Yarragil 4X catchment

Valley flank soils

Layer	*Thickness (mm)*	*Soil matrix*		*Preferred pathway*		
		Type	*K_{sat} (mm/day)*	*% Profile*	*Type*	*K_{sat} (mm/day)*
1	400	sandy gravel	3000	5	sandy gravel	3000
2	1500	duricrust	0	5	sandy gravel	3000
3	3600	loam	250	5	sandy gravel	3000
4	33% of balance	pallid clay	5	5	sandy gravel	3000
5	33% of balance	pallid clay	5	5	sandy gravel	3000
6	33% of balance	pallid clay	5	5	sandy gravel	3000
7	5000 maximum	weathering zone	5	5	sandy gravel	3000

Valley floor soils

Layer	*Thickness (mm)*	*Soil matrix*		*Preferred pathway*		
		Type	*K_{sat} (mm/day)*	*% Profile*	*Type*	*K_{sat} (mm/day)*
1	400	sandy gravel	3000	5	sandy gravel	3000
2	400 (1000)	sandy gravel	3000	5	sandy gravel	3000
3	800 (1600)	loam	250	5	sandy gravel	3000
4	33% of balance	impeding layer	1.25	1	loam	125
5	33% of balance	pallid clay	5	5	sandy gravel	3000
6	33% of balance	pallid clay	5	5	sandy gravel	3000
7	5000 maximum	weathering zone	5	5	sandy gravel	3000

The form of the soil-moisture characteristic curves, that is the ψ–θ and θ–K relations, have a marked effect on the outputs of the model. All data for the Darling Plateau was reviewed (Raper & Croton 1996) and curve forms similar to those of Campbell (1974) as modified by Hutson and Cass (1987) were selected. The selected curve forms were preliminary and further work is recommended.

The first three layers were assigned a lateral conductivity (K_{lat}) value of 15 m/day for everything except the duricrust which was assigned a $K_{lat} = 0$. The value of 15 m/day was also used by Croton & Bari (2001) and, while it appears high, is considered reasonable. These values gave the best fit between the model output hydrograph shapes and the observed data. For the pallid zone a graduation with K_{lat} values of 0.0, 0.045 and 0.09 m/day for layers four, five and six respectively were used. These values, derived from Clarke et al. (2000), were also applied by Croton & Bari (2001) with the graduation of K_{lat} based on the observation by Martin (1988) that the lower section of the pallid zone appeared coarser and should be transitional. The weathering zone, layer seven, was assigned K_{lat} value of 0.75 m/day (Croton & Bari 2001; Clarke et al. 2000).

A soil salt storage profile based on the borehole data (Appendix 2) was put into the model. The first three layers of the matrix were assigned storage of 0.3 kg/m^3 for the matrix; a bulge in layers four and five of 2.0 kg/m^3; and tapering of the bulge to 1.0 kg/m^3 in layer six. The first three layers of the preferred pathway were assigned uniform values 0.3 kg/m^3, while layers four, five and six used a value of 0.5 kg/m^3. The seventh layer, the weathering zone, was given a typical groundwater salinity of 675 mg/L for both matrix and preferred pathway. The salinity of rainfall was assumed to be 8 mg/L (Hingston & Gailitis 1976).

4.2.2 Initial conditions

The initial groundwater level map was derived from the measured groundwater level data. This map was extrapolated from just eight piezometers within the catchment. To develop a map of soil moisture initial conditions, the model was run for a number of dummy simulations using the 1980 to 2001 data. The final simulations started in 1980 while the model outputs were compared with observed data from 1984 to 2001. These extra four years at the outset of simulation buffered the effect of possible errors in the initial conditions.

4.2.3 Best parameter set

For practical purposes the Yarragil 4X parameter set is identical to that used previously in studies of the Cameron catchments (Fig. 1) and it is essentially a generic parameter set rather than one specifically developed for the Yarragil 4X catchment. An infinite number of parameter sets are possible for complex, distributed, deterministic models such as WEC-C due to their many degrees of freedom. Therefore, a successful model application must be based on experience and move forward through any parameter optimisation in a logical manner that considers not only the accuracy of gross outputs like streamflow, but also suitability of internal processes. A trial and error approach cannot be adopted.

5 Simulation results and discussion

The model was run for 22 years from 1980 till 2001 using as input data the observed rainfall and evaporation records and information on vegetation changes.

The results presented below are:

- graphs of observed and simulated groundwater levels (Section 5.1)
- comparison of observed and simulated daily and monthly streamflow, daily stream salinity and daily salt load (Section 5.2)
- comparison of observed and simulated annual streamflow, stream salinity and salt loads (Section 5.3).

5.1 Groundwater levels

The eight piezometers in the catchment were divided by their location into three groups: two bores in the valley floor (G61420218 and G61420220) (Fig. 5), two bores mid-slope (G61420221 and G6142022) (Fig. 6), and four bores on the upper slopes (G61420225, G61420227, G61420228 and G61420229) (Fig. 7). There was broad correspondence between observed and simulated groundwater levels for all piezometers. The two piezometers in the valley floor (Fig. 5) showed gradual declines in groundwater level, with the model producing similar trends. The groundwater levels for mid-slope piezometers G61420221 and G61420222 (Fig. 6) and the four upslope piezometers (Fig. 7) were all simulated reasonably well by the model.

A good indicator of general model performance, in terms of groundwater levels, is an x-y plot of observed and simulated average groundwater levels (Fig. 8). The correlation coefficient (R^2) for a constrained linear regression is 0.99 and the gradient of 1.00; both indicate a strong relationship.

One feature of a distributed model like WEC-C is that it can produce maps of groundwater depth; Figure 9 shows the depth to water in December 1999. In the valley floor the depth to water range was 0–16 m, while on the mid-slope the depth to water was up to 35 m, with no groundwater on the uplands.

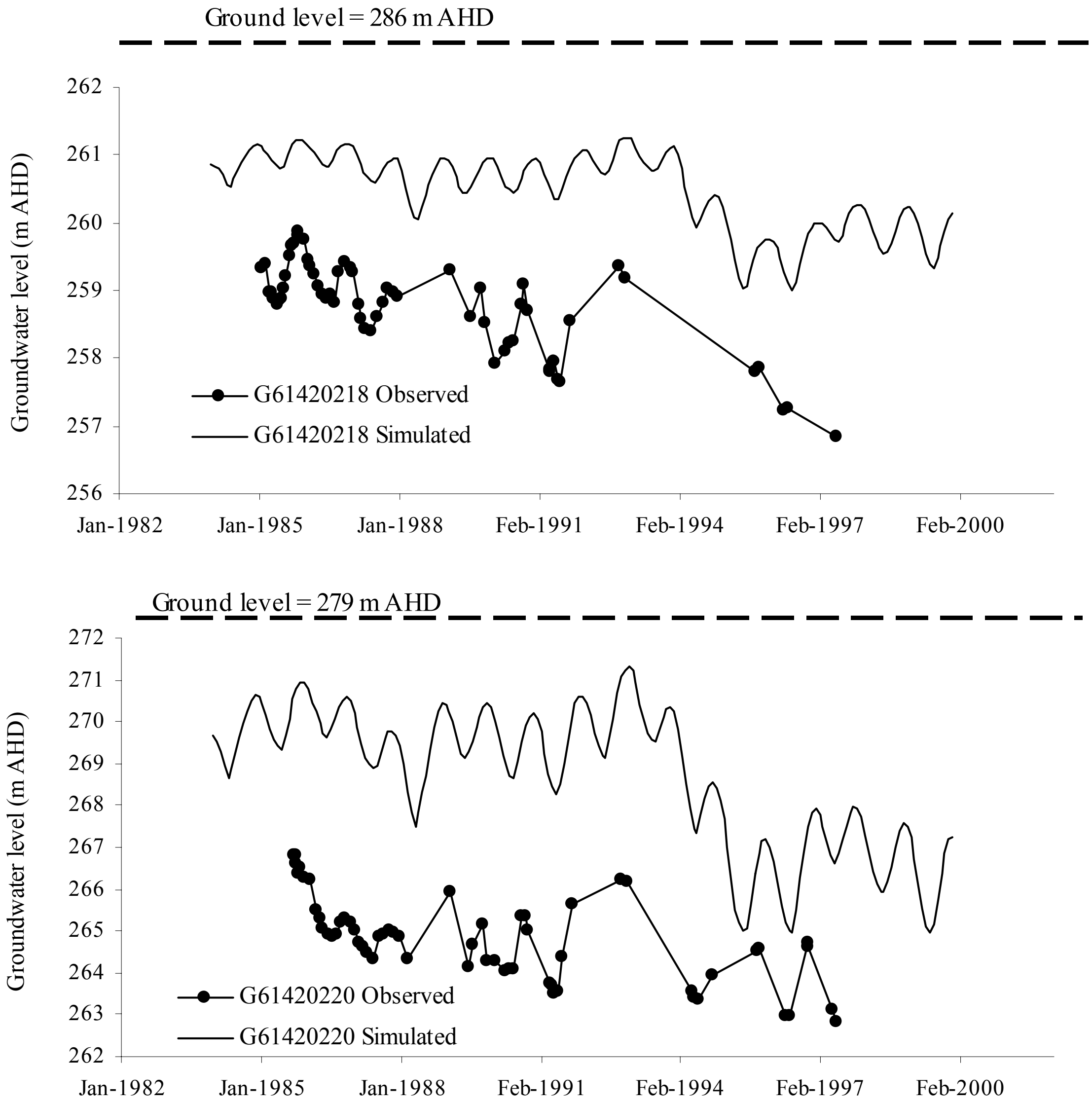

Figure 5. Observed and simulated groundwater levels of the valley floor piezometers

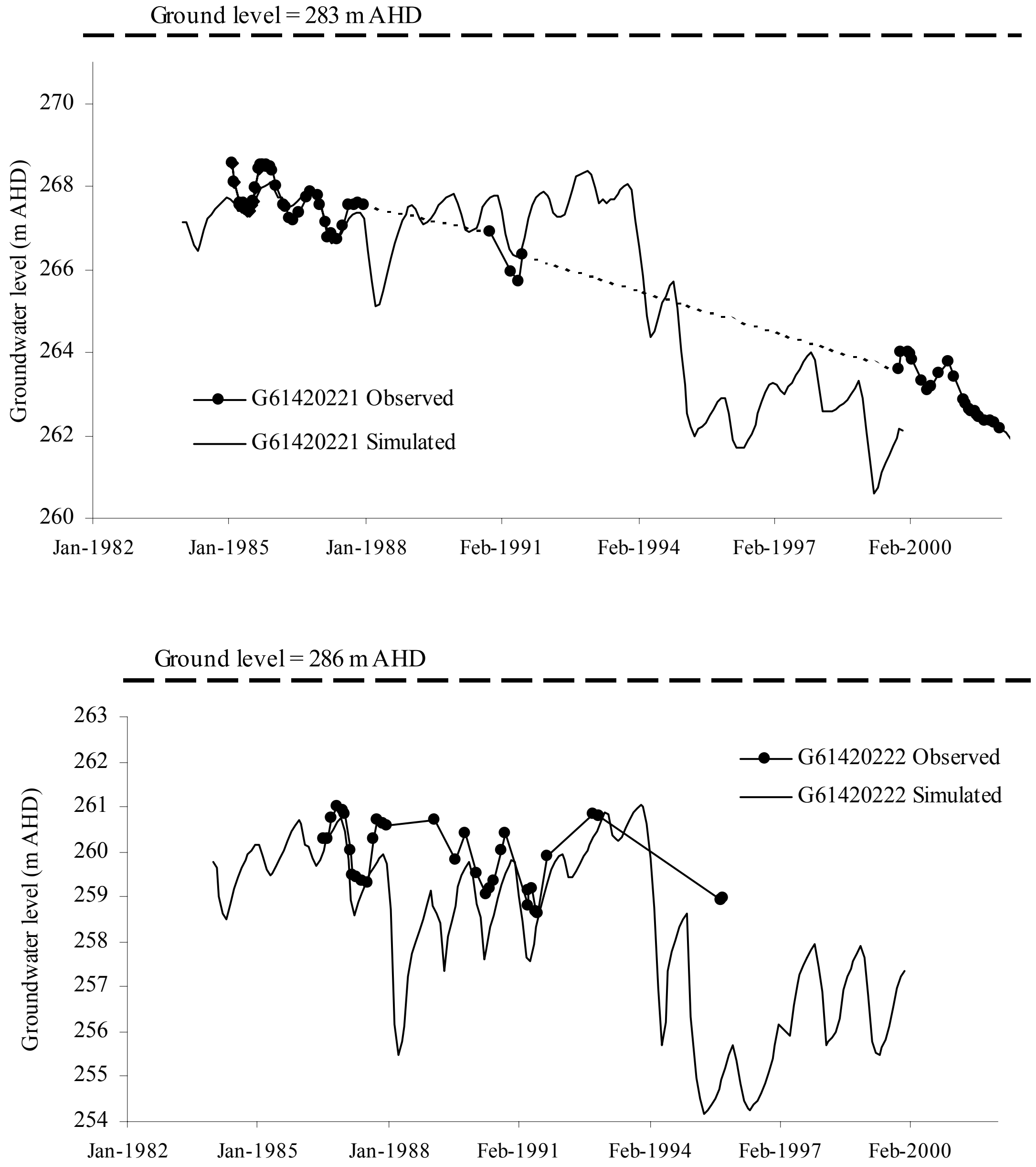

Figure 6. Observed and simulated groundwater levels of the mid-slope piezometers

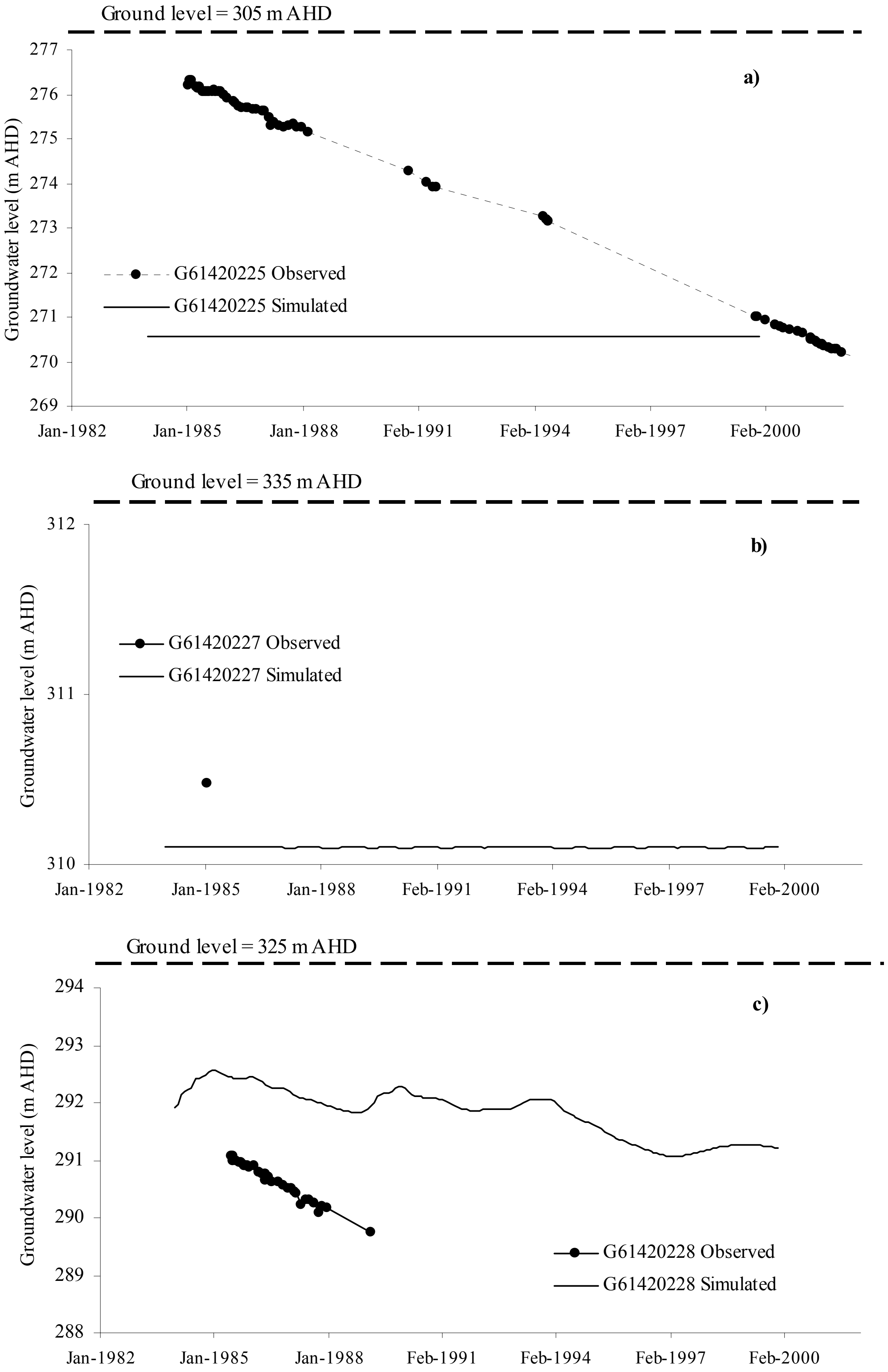

Figure 7a, b, c. Observed and simulated groundwater levels of the upper slope piezometers

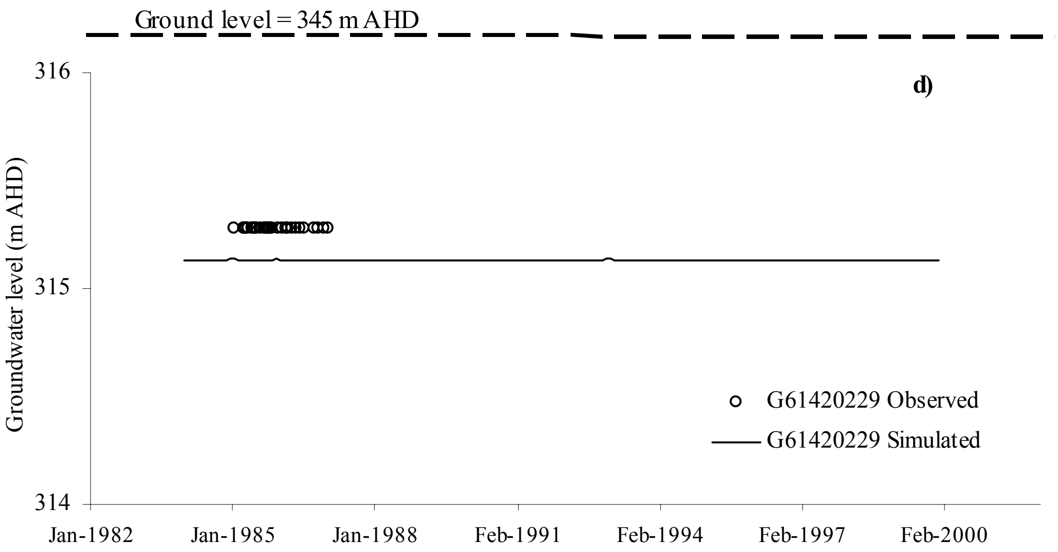

Figure 7d. Observed and simulated groundwater levels of the upper slope piezometers

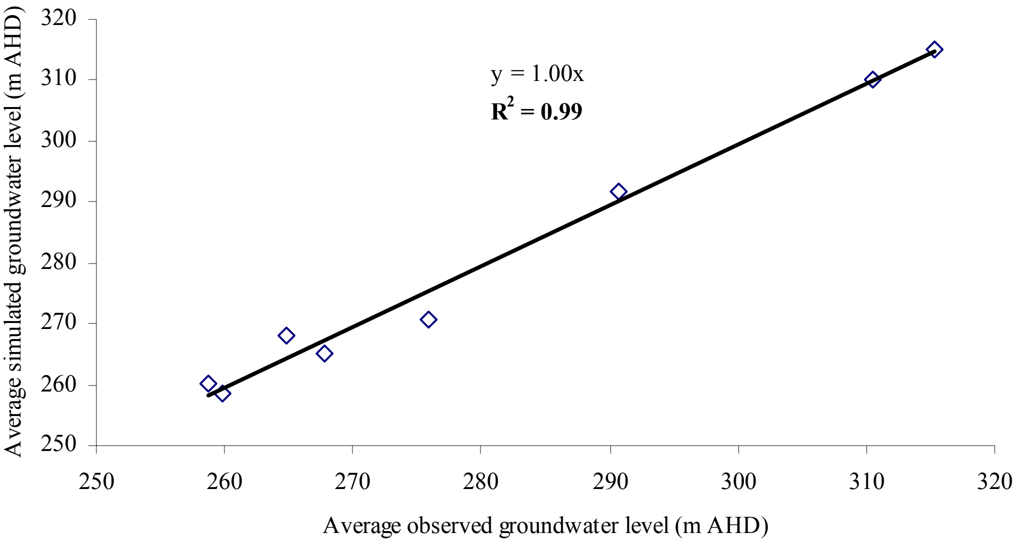

Figure 8. Comparison of the average observed and simulated groundwater levels of the eight piezometers

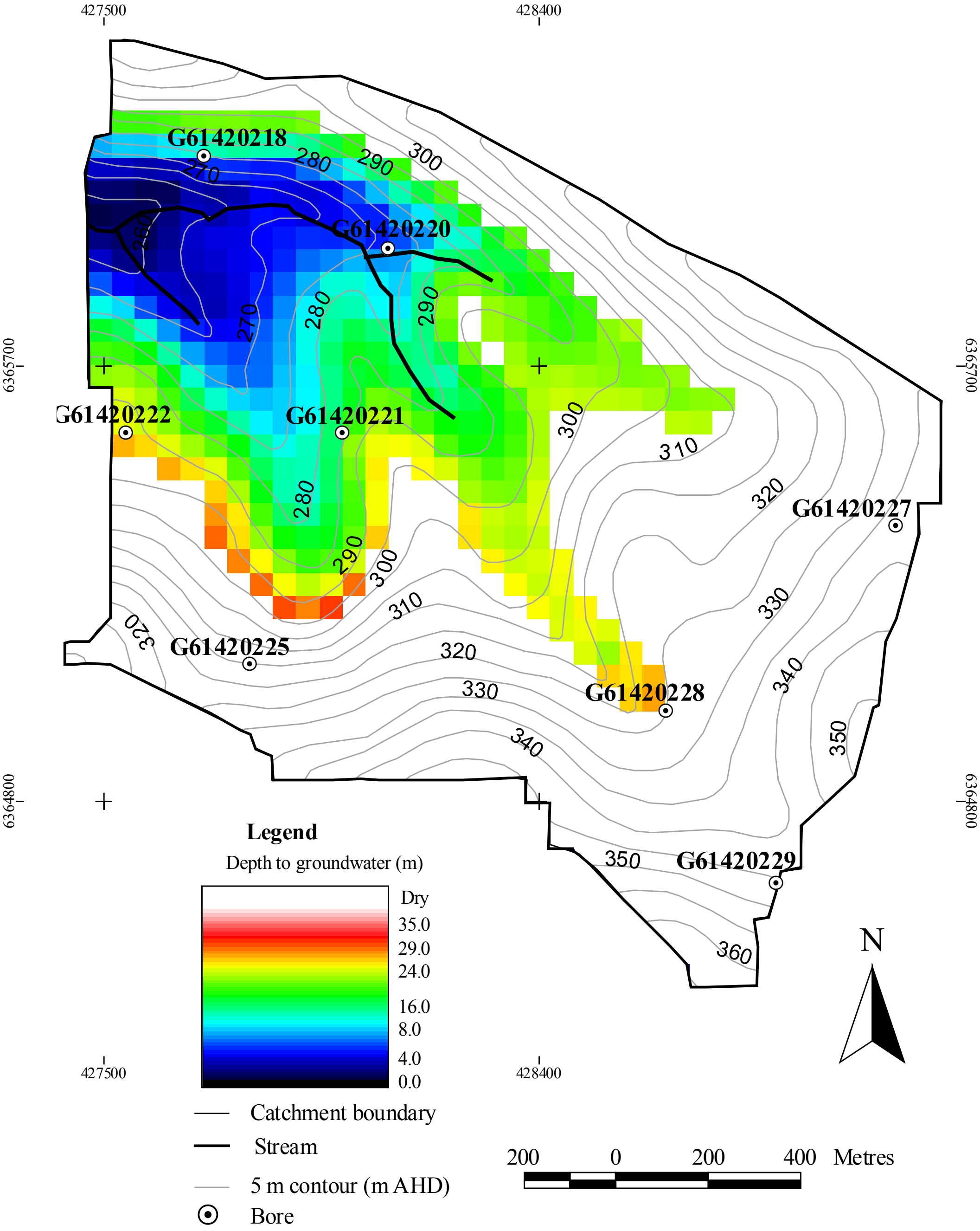

Figure 9. Modelled depth to groundwater in December 1999

5.1.1 Discussion

Although groundwater level data for the catchment were not extensive, their comparison with simulated outputs still indicated that the model predicted well the general form of the groundwater system**.** Since a deterministic model like WEC-C does not restrict the simulated groundwater system in any way other than by the flow equations on which the model is based, the simulated groundwater system is free to deviate to unrealistic levels if the hydraulics of the model are such that these levels are the solution of the flow equations. In the case of Yarragil 4X, the simulated levels remained close to observed and imply that, while the model hydraulics are not completely accurate, they are nevertheless close to actual. The R^2 value of 0.99 between observed and simulated average groundwater levels was particularly reassuring.

5.2 Daily and monthly streamflow and daily salt yields

The daily observed and simulated streamflow, stream salinity and stream salt loads corresponded well for most years, although there was a consistent tendency to underestimate peak flows (Fig. 10). The slope term of 0.73 in the regression plot of daily observed and simulated streamflow was depressed by the universal underestimation of flows above 1.0 mm/day.

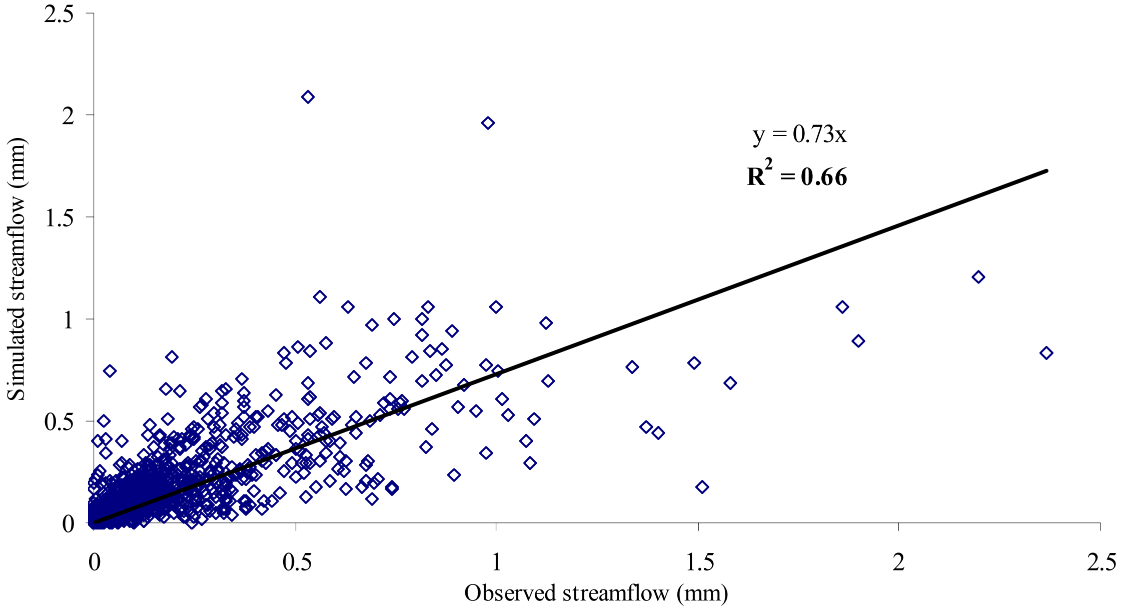

Figure 10. Comparison of observed and simulated daily streamflows

As expected, the relation between observed records and simulated values improved from daily to monthly (Fig. 11). The slope term improved to 0.87; while this still indicates underestimation, it is a better result than the 0.73 for the daily plot. The time-series monthly plot (Fig. 12) showed that the model reasonably matched flows at the beginning and end of each year. The overall shape for most years was also well represented, with a few isolated years poorly matched.

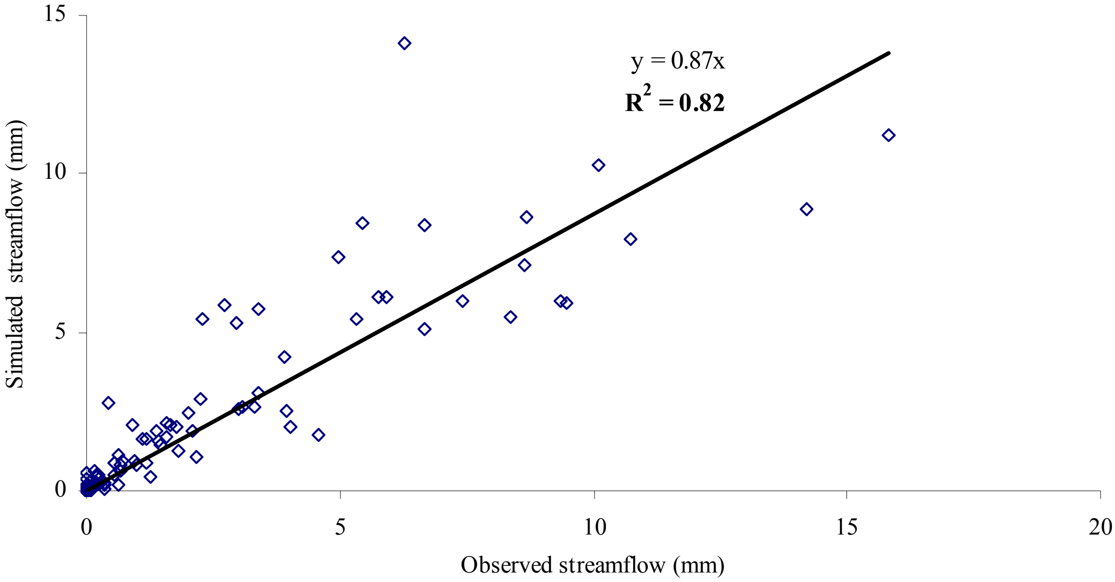

Figure 11. Comparison of observed and simulated monthly streamflows

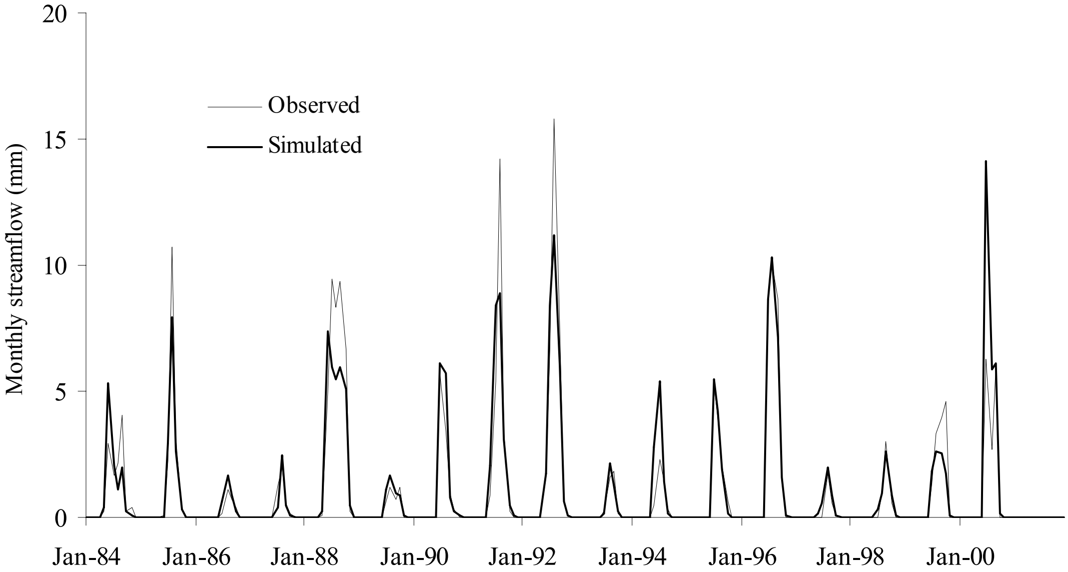

Figure 12. Time series plot of observed and simulated monthly streamflows

For most years the daily observed and predicted streamflow, stream salinity and stream salt loads corresponded reasonably well. The match in the lower-flow sections of the streamflow hydrograph in the low-flow year 1986 (Fig. 13) was poor, with the model tending to maintain greater recession flow and baseflow than was observed. For the high-flow year 1992 (Fig. 14) the overall prediction was good. The extreme differences in scale between the presented plots of low and high flow years are important when assessing model performance; the maximum values are 0.12 and 1.5 mm respectively. Modelled and observed daily salinity values tended to match in the low and high flow years.

The general overestimation of salinity values at low flows was illustrated by comparing the streamflows and salt loads for 1992. The flow was represented well across the whole year. The load peaks were predicted well but loads at low flows were overestimated thus indicating salinities that were too high.

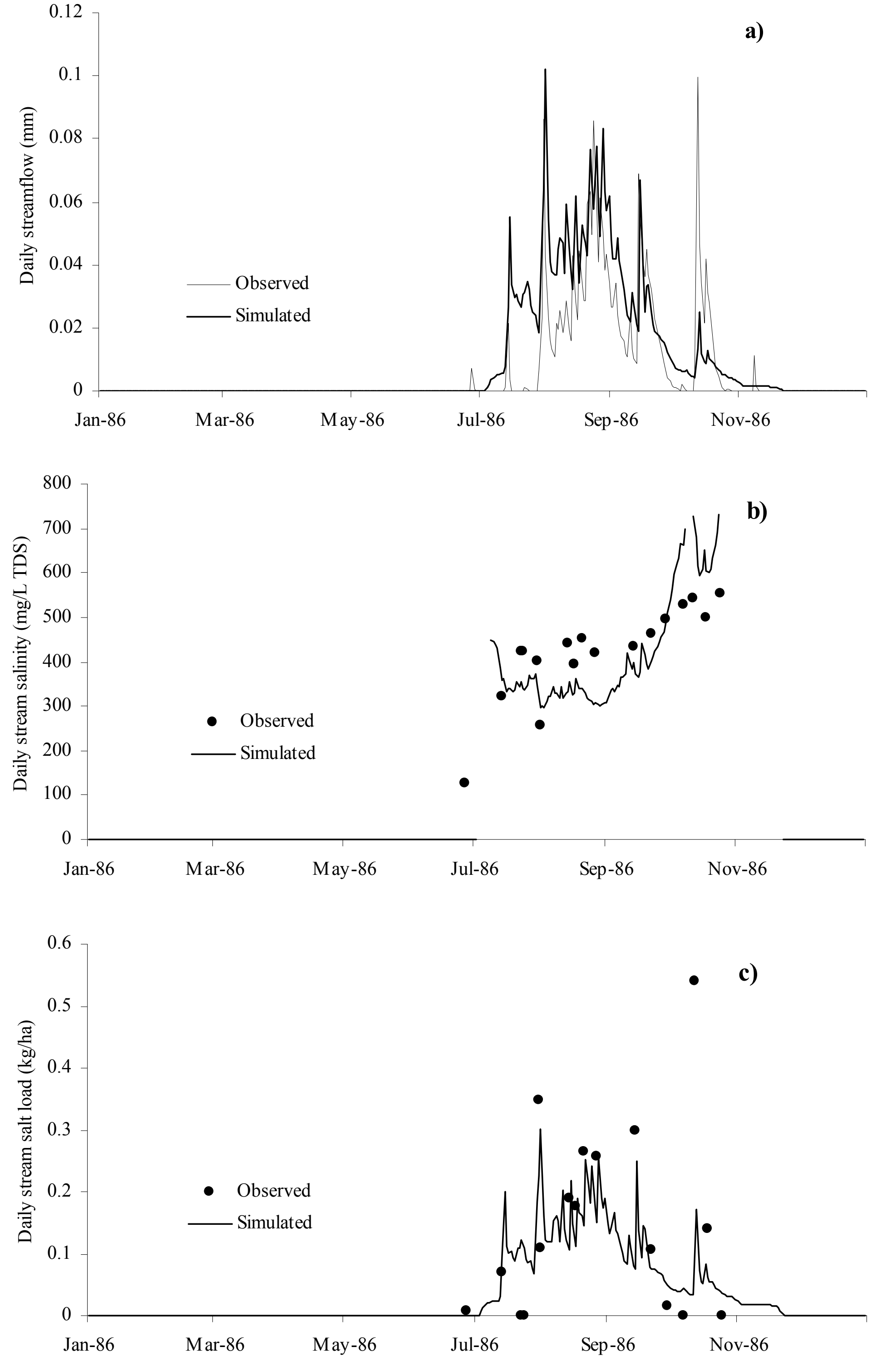

Figure 13a, b, c. Comparison of observed and simulated daily a) streamflow b) salinity and salt load in the lowest flow year (1986)

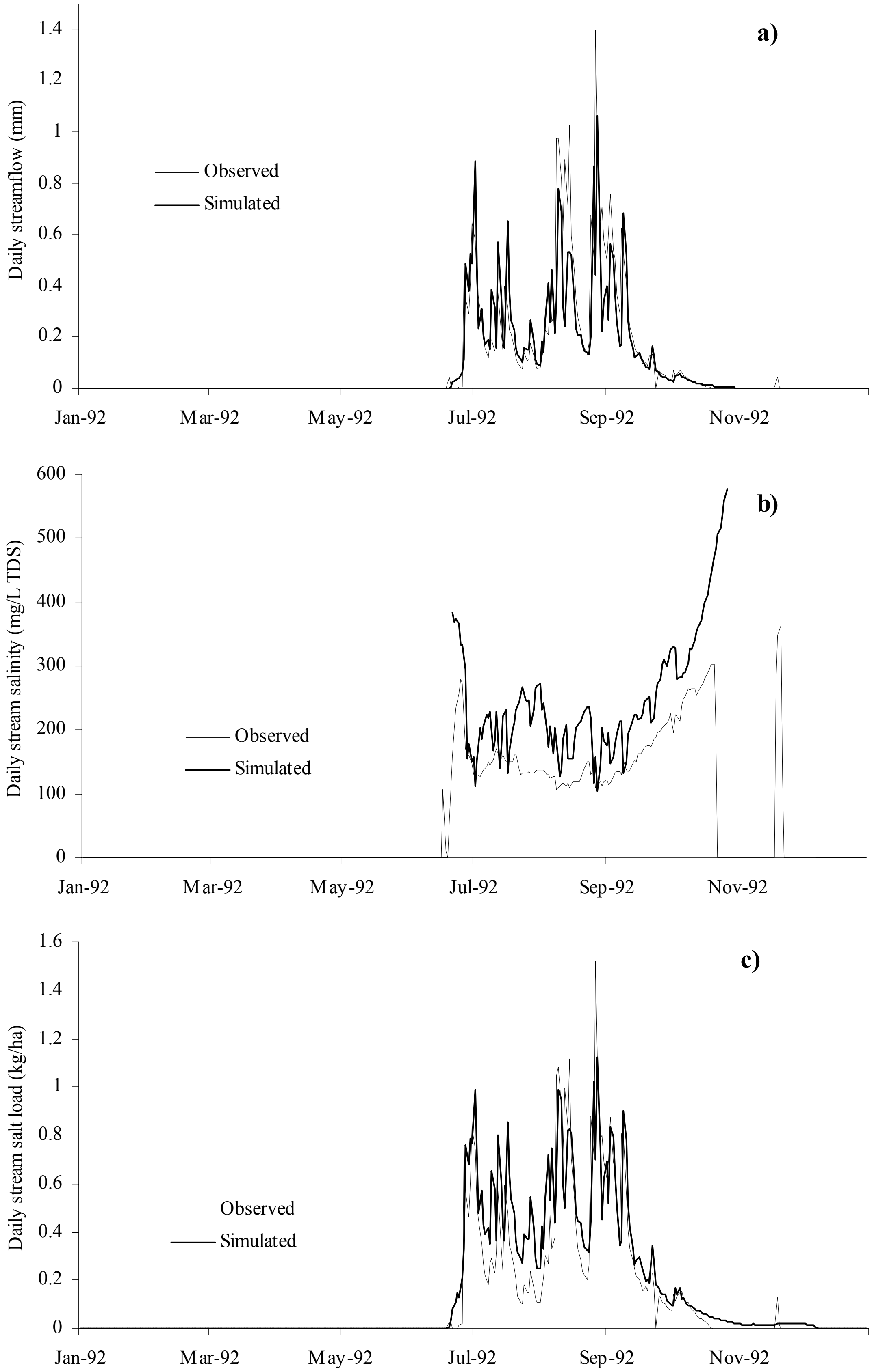

Figure 14a, b, c. Comparison of observed and simulated daily a) streamflow, b) salinity and c) salt load in the high-flow year (1992)

5.2.1 Discussion

For most years the observed daily peak flows were higher than simulated flows. The model represented daily streamflows in low-flow years well, but did not match the winter peaks for the highest flow year 1988.

Monthly time-series plots for jarrah forest catchments need to be viewed with caution, as the Mediterranean climate generates strong seasonality which tends to create a false impression of accuracy: even so, the time-series monthly plot (Fig. 12) indicated interesting model behavior. For example, the higher observed than simulated flows of 1988 directly followed the forest burn-off in 1988, while the lower than observed 1994 flow followed the winter burn-off in 1993. It is possible that the former indicated a reduction in ET due to the recent burn, and the latter indicated an increase in ET following a post-burn flush of leaves. However, there is no obvious explanation for the significant underestimate of flow in 1999 and overestimate of flow in 2000 even though the total annual rainfall in both years was the same.

5.3 Annual streamflow and salinity

The model was run for 22 years (1980–2001) and the results compared with observed data for the period 1984–2001. In most years the modelled and observed annual streamflows matched well (Fig. 15). The overall fit of the model to annual streamflow was good with R^2=0.85 (Fig. 16). The underestimation of higher flows observed in daily and monthly flows was also present in the annual flows. However, the simulated and observed means of both were 12.7 mm and the medians were 10.5 mm for observed and 11.0 mm for simulated.

The observed and modelled annual salinities were not strongly correlated (R^2 = 0.31) (Fig. 16b). Nevertheless, it can be seen from Figure 15 that salinities in three years (1997, 1998 and 1999) were significantly overpredicted while all other years corresponded reasonably well. If these three years were removed from the correlation, the R^2 would equal 0.74.

The annual water balance from the simulation is presented in Table 3. Total evapotranspiration (ET) averaged 920 mm/yr for the 18-year period 1984–2001 while rainfall averaged 902 mm/yr. This means the model implies a slight reduction in soil water storage from both saturated and unsaturated zones: 18 mm/yr, or 324 mm in total.

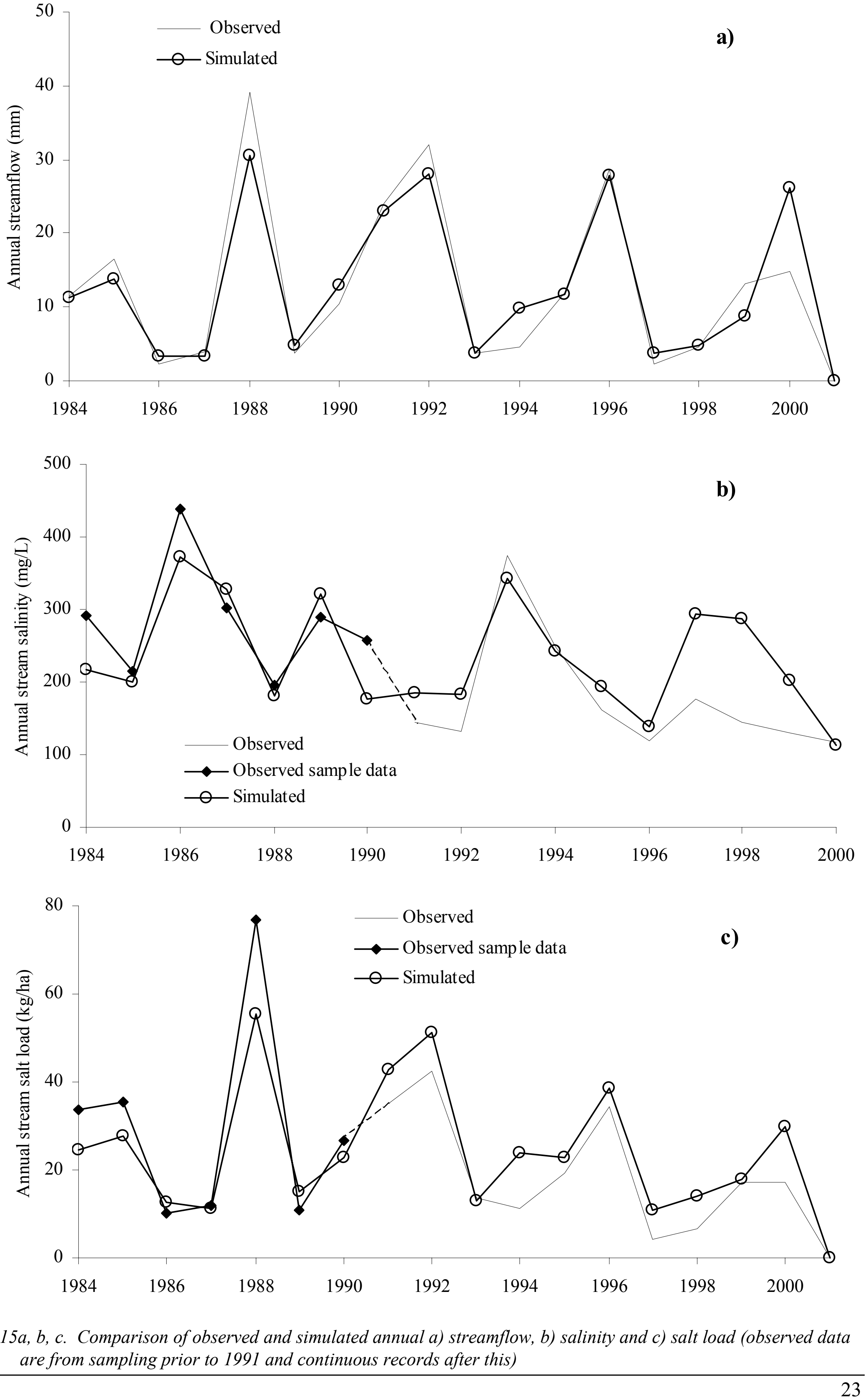

Figure 15a, b, c. Comparison of observed and simulated annual a) streamflow, b) salinity and c) salt load (observed data are from sampling prior to 1991 and continuous records after this)

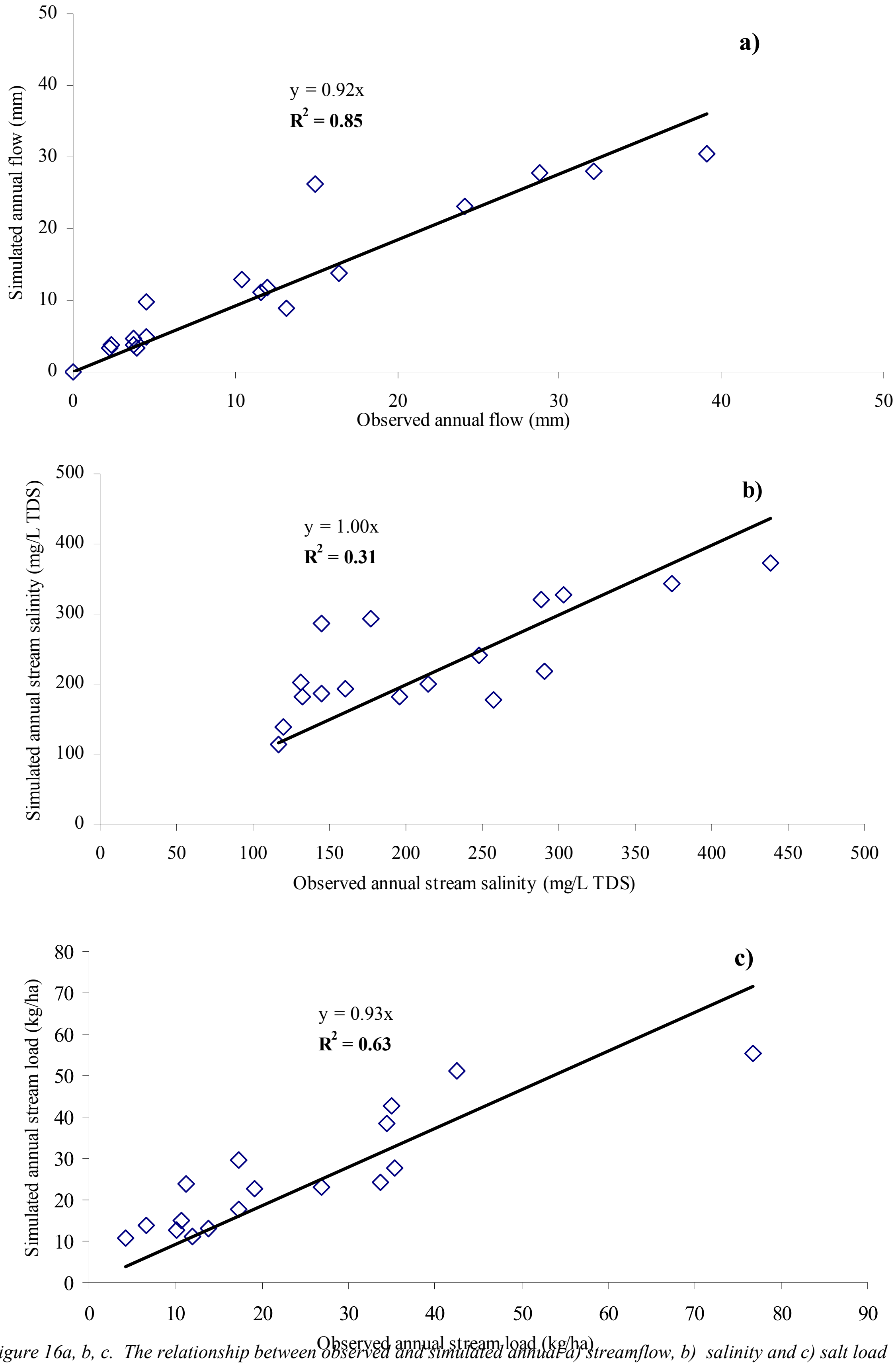

Figure 16a, b, c. The relationship between observed and simulated annual a) streamflow, b) salinity and c) salt load

Table 3. Annual water balance components (mm) for simulation using LAI derived from historical and Landsat TM data

Year	*Rainfall*	*Interception*	*Soil evaporation*	*Transpiration*	*ET*	*Gw loss*	*Modelled flow*	*Observed flow*	*Error**	*Error %**
	(mm)									
1984	946	94	153	682	929	2.6	11.2	11.6	-0.4	-3
1985	921	90	153	692	935	2.6	13.9	16.4	-2.6	-16
1986	759	87	148	612	847	2.6	3.4	2.3	1.1	47
1987	730	75	135	584	793	2.6	3.4	4.0	-0.5	-14
1988	1184	114	110	728	953	2.6	30.5	39.1	-8.6	-22
1989	882	115	101	796	1012	2.6	4.7	3.7	1.0	27
1990	958	119	103	744	967	2.6	13.0	10.4	2.5	24
1991	1080	113	111	754	978	2.6	23.1	24.1	-1.1	-4
1992	1068	108	112	761	981	2.6	28.0	32.1	-4.1	-13
1993	829	122	97	803	1022	2.6	3.8	3.7	0.1	4
1994	715	86	43	748	878	2.6	9.8	4.5	5.3	116
1995	976	120	96	692	909	2.6	11.8	11.9	-0.1	-1
1996	1098	101	122	679	901	2.6	27.7	28.8	-1.0	-4
1997	728	75	92	733	900	2.6	3.7	2.4	1.3	55
1998	897	99	124	639	861	2.6	4.9	4.5	0.4	8
1999	984	122	91	813	1026	2.6	8.8	13.2	-4.4	-33
2000	982	88	84	772	943	2.6	26.2	14.9	11.3	75
2001	507	63	71	585	719	2.6	0.0	0.0	0.0	0
Average	***902***	***100***	***108***	***712***	***920***	**2.6**	***12.7***	***12.7***	**0.1**	**0.06**

Evapotranspiration (ET) is a sum of interception, soil evaporation and transpiration.

(*) Negative values represent model underprediction.

5.3.1 Discussion

The model underestimated the peak annual streamflows in high-flow years, though as discussed in Section 5.2.1, this may not have been due to model inaccuracy alone. In particular, the modelling was highlighting the difficulties encountered when trying to estimate streamflow where it was such a small fraction of the overall water balance (< 2%). As discussed in Section 4.3.2, the parameter set used in this model was generic and derived from work on other catchments. If the model were being optimised for Yarragil 4X alone, the fit could be improved. For instance, the systematic underprediction of high flows and overprediction of low flows would probably be decreased by reducing the thickness of the near-surface soil layers in the valley floor. Future work could investigate the sensitivity to the concurrent optimisation of the soil and vegetation water-use parameters.

The model significantly overpredicted annual salinity for three years: 1997, 1998 and 1999. The primary reason for this overprediction may be related to the water and salt balance of six cells in the lower valley floor near the catchment outlet. These cells are where the groundwater contacted the surface during the high-flow periods of the 1980s and early 1990s. They were also major contributors of salt to stream salt load and salinity. These cells were still making a significant input of salt in the simulation period 1997–1999 while it is possible that their actual contribution may have stopped. An alteration in their layering, like that already discussed to improve flows, may remedy the situation.

The model suggested a reduction in soil water storage from both the saturated and unsaturated zones during the simulation period. Such a reduction in storage would affect the hydrology of the catchment and has implications for the streamflow response to management options such as forest thinning. The increase in available water caused by the reduction in ET through thinning would be partly absorbed by the soil water deficit, thus limiting the increases in stream yield. The simulated soil water deficit of 324 mm is significant given that the total observed yield for Yarragil 4X for the study period is two-thirds of this, 228 mm.

5.4 Sensitivity analysis

To demonstrate the sensitivity of the model to vegetation changes, two additional cases were considered: the constant LAI case and the single LAI case. In the constant LAI case, the initial LAI map derived from Landsat MSS data defined LAI prior to 1988; from 1988 onwards, the LAI map prepared from the February 1988 Landsat TM image was used for all years. The single LAI case applied only one LAI map, derived from the February 1988 Landsat TM scene, for the entire period of simulation.

Figure 17 shows how sensitive the model and streamflow generation processes are to changes in LAI. The constant LAI case is close to both the case which is using all the Landsat TM images (called 'Landsat TM LAI') in Figure 17 and the observed flows. However, when the 1988 Landsat TM image was used to derive a single LAI map applied to all years (the single LAI case) the flows in all years were underestimated. The underestimation was related to the depth to groundwater for model cells near the catchment outlet: Figure 18 shows a depth to water plot for one of these. The simulated depths to groundwater for the Landsat TM and constant LAI cases were similar and remained in the range 0-3 m; for the single LAI case the simulated depth increased to 6 m by 1988, a position from which it never recovered.

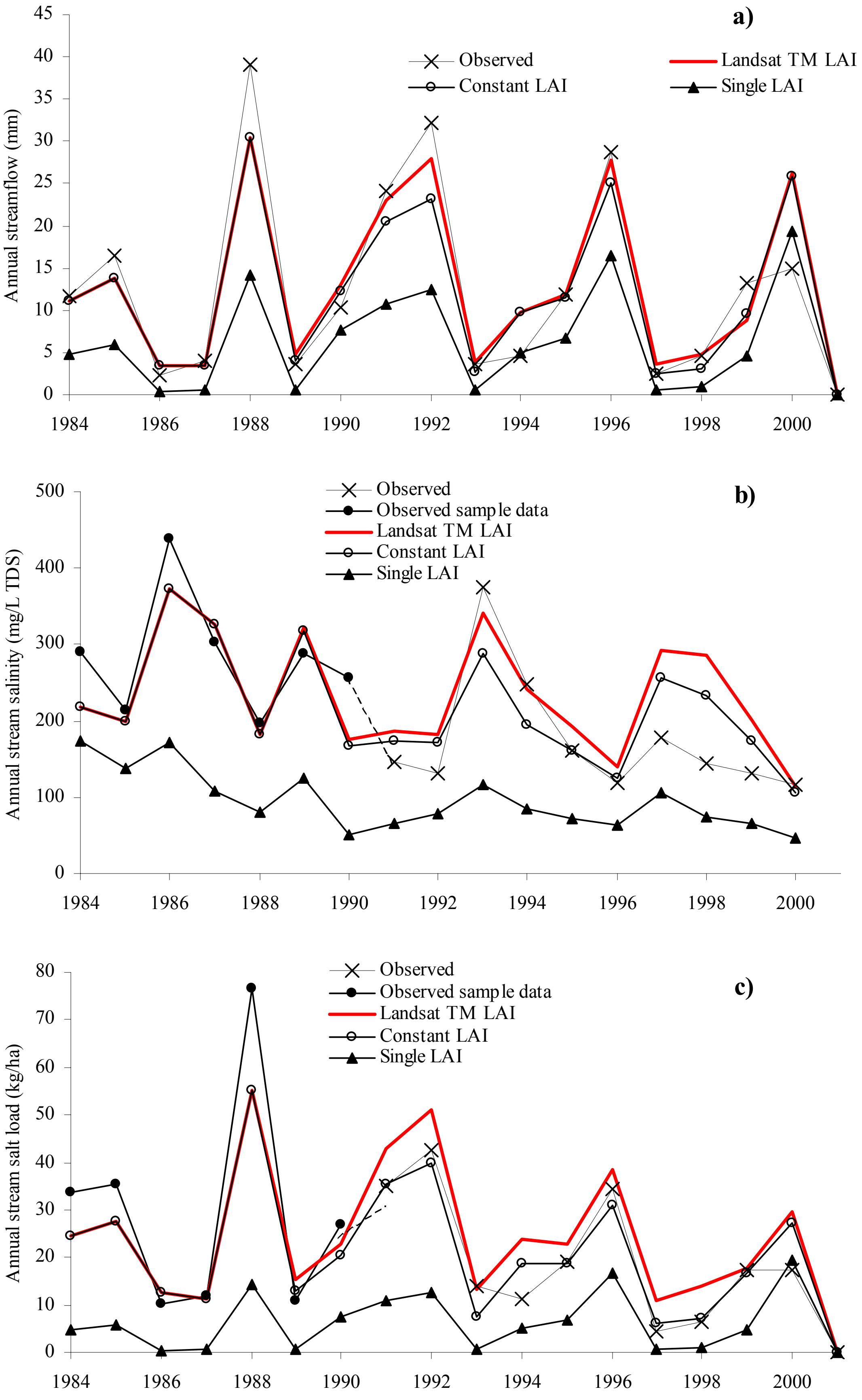

Figure 17a, b, c. Comparison between observed and simulated annual a) streamflow b) salinity and c) salt load, using three LAI cases

Figure 19 shows these three cases plotted as average LAI for the catchment. The initial LAI map (Appendix 1, Fig. 20) used to define the period 1980 to 1988 has markedly lower LAI values across the catchment than maps derived from Landsat TM (Appendix 1, Figs. 21 and 22). The Landsat MSS values were in the range 0.75 to 2.5, average 1.61; those from the 1988 Landsat TM scene ranged from 0.96 to 3.19, average 2.05.

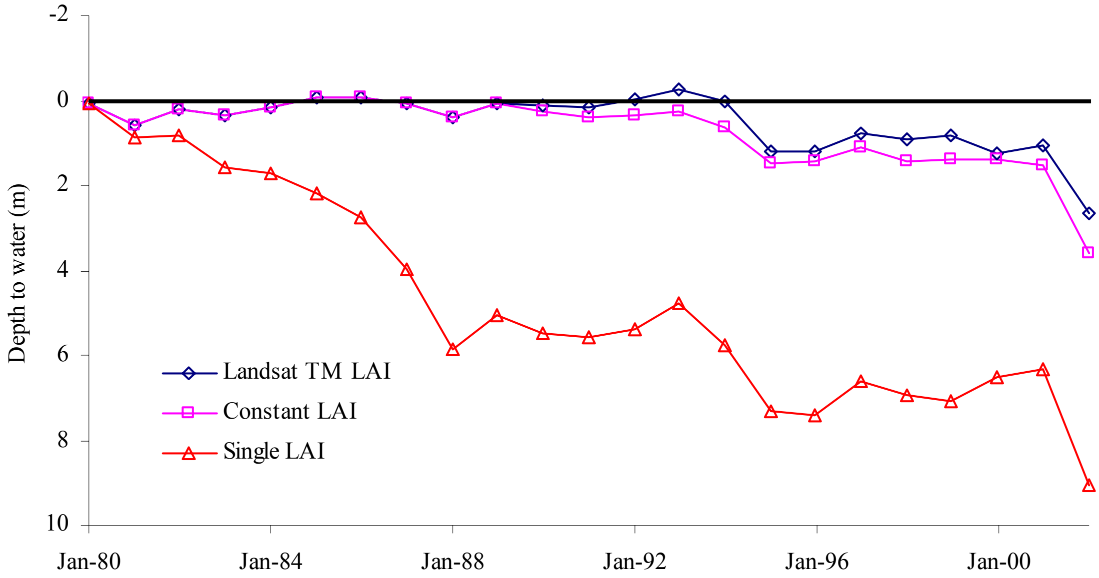

Figure 18. Plot of simulated depth to groundwater of a model cell near the catchment outlet for three LAI cases

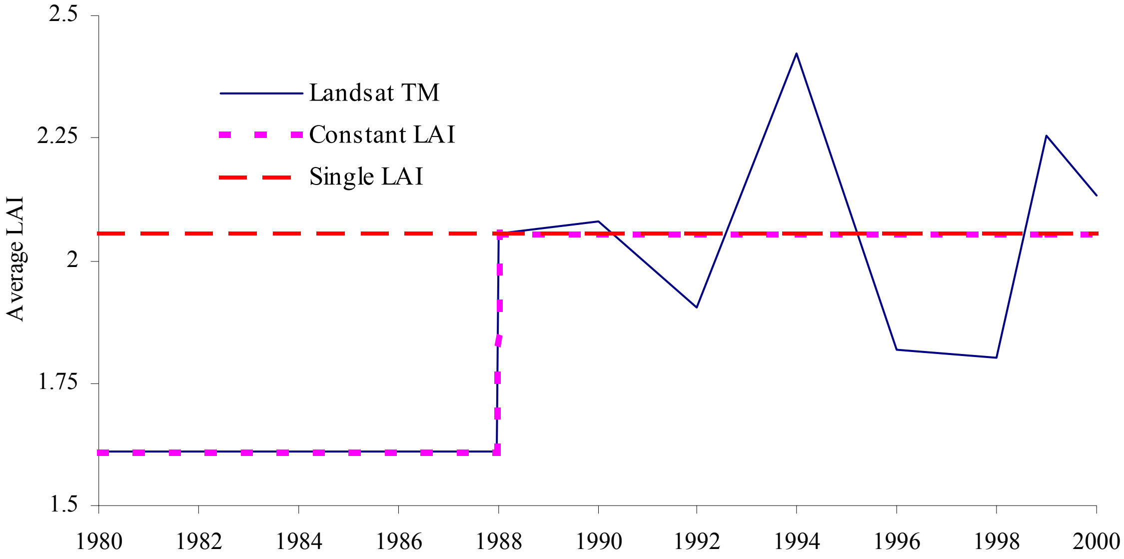

Figure 19. Comparison of the average catchment LAI for three LAI cases

A comparison of simulated annual water balances for the period 1984–2001 is shown in Table 4. In the constant and single LAI cases the model underestimated flow by 7 and 51% respectively. The underestimations were greater in the high-flow years (1988, 1992 and 1996) ranging from 13 to 28% for the constant LAI case and 42 to 64% for the single LAI case.

Table 4. Annual water balance components (in mm) for a) constant LAI case (Const.) and b) single LAI case (Single)

Year	*Rainfall*	*Interception*		*Soil evaporation*		*Transpiration*		*ET*		*Gw loss*	*Modelled flow*		*Observed flow*	*Error**		*Error %**	
	(mm)																
		Const.	*Single*	*Const.*	*Single*	*Const.*	*Single*	*Const.*	*Single*	*Const.&Single*	*Const.*	*Single*		*Const.*	*Single*	*Const.*	*Single*
1984	946	94	120	153	102	682	759	929	981	2.6	11.2	4.8	11.6	-0.4	-6.8	-3	-59
1985	921	90	115	153	103	692	769	935	988	2.6	13.9	5.8	16.4	-2.6	-10.6	-16	-64
1986	759	87	111	148	99	612	662	847	873	2.6	3.4	0.3	2.3	1.1	-2.0	47	-87
1987	730	75	95	135	89	584	642	793	827	2.6	3.4	0.7	4.0	-0.5	-3.3	-14	-83
1988	1184	114	114	110	109	728	691	953	914	2.6	30.5	14.2	39.1	-8.6	-25.0	-22	-64
1989	882	114	114	106	105	781	772	1001	991	2.6	4.1	0.6	3.7	0.4	-3.2	10	-85
1990	958	118	118	109	108	732	726	959	952	2.6	12.2	7.6	10.4	1.8	-2.8	17	-27
1991	1080	116	116	109	108	763	757	989	982	2.6	20.5	10.7	24.1	-3.6	-13.4	-15	-55
1992	1068	116	116	101	99	787	786	1004	1002	2.6	23.1	12.5	32.1	-9.0	-19.7	-28	-61
1993	829	116	116	111	110	748	750	975	977	2.6	2.6	0.6	3.7	-1.1	-3.1	-29	-83
1994	715	73	73	63	63	672	666	808	802	2.6	9.7	5.0	4.5	5.1	0.5	114	10
1995	976	116	116	107	106	688	676	911	898	2.6	11.5	6.7	11.9	-0.4	-5.3	-3	-44
1996	1098	114	114	102	101	742	734	958	949	2.6	25.1	16.5	28.8	-3.7	-12.2	-13	-42
1997	728	85	85	77	77	742	737	904	900	2.6	2.4	0.5	2.4	0.0	-1.9	0	-78
1998	897	113	113	101	101	679	673	893	887	2.6	3.1	0.9	4.5	-1.5	-3.6	-32	-81
1999	984	111	111	110	110	724	714	945	934	2.6	9.6	4.7	13.2	-3.6	-8.5	-27	-65
2000	982	84	84	81	80	766	759	931	923	2.6	25.9	19.4	14.9	10.9	4.4	73	30
2001	507	61	61	67	67	599	584	727	712	2.6	0.0	0.0	0.0	0.0	0.0	0	0
Average	***902***	***100***	***105***	***108***	***97***	***707***	***714***	***915***	***916***	***2.6***	***11.8***	***6.2***	***12.7***	**-16**	**-116**	**-7**	**-51**

Evapotranspiration (ET) is a sum of interception, soil evaporation and transpiration.
(*) Negative values represent model underprediction.

5.4.1 Discussion

The initial LAI map, derived from Landsat MSS data, has noticeably lower values across the catchment than the LAI map developed from the February 1988 Landsat TM image. The reasons for this large difference are not apparent, and, while its use as an initial LAI map created a better history match, this cannot be the sole justification for its use.

The model is sensitive to the description of vegetation cover, the level of sensitivity dependent on whether LAI differences will trigger a change in hydrological state in the catchment. For instance, using low LAI values at the beginning of simulation (Landsat TM LAI and constant LAI cases) increased the groundwater contribution to streamflow and changed the catchment hydrological regime. In the single LAI case, when denser vegetation cover was assumed in the pre-1988 period, the change in the hydrological state was not apparent.

It is therefore simplistic to view changes in model vegetation, that is the model parameters and data defining vegetation, in isolation from other variables such as rainfall and initial conditions. Had the rainfall during the 1980s been higher, it is possible all three cases would have had groundwater levels at or near the soil surface in the valley floor. The differences in streamflow between them would therefore have been much less than reported. It is also highly likely that changes in initial soil water conditions would have a marked effect on simulated stream yields and sensitivity to pre-1988 LAI values. For instance, presently used initial groundwater levels are the best guess based on limited information; raising these could largely negate the need to have lower pre-1988 LAI values to achieve a history match. Before the effects of such factors can be clearly understood, more detailed sensitivity studies are required.

6 Conclusions

The most important conclusion from the study was that the generic parameter set used (first developed for the Cameron catchments) created a reasonable history match to stream yields for the Yarragil 4X catchment. This result gives some confidence in using this generic parameter set for the initial applications of the WEC-C model to other catchments within the Intermediate Rainfall Zone (IRZ) of the Northern Jarrah Forest. This parameter set was considered to be suboptimal for the Yarragil 4X catchment: if a specific parameter set were developed for this catchment the history match should be superior to that obtained to date.

The study found the model's predictive ability highly dependent on LAI estimation. The LAI values used were derived from Landsat MSS and TM data with the initial map defining vegetation up to 1988 markedly different from those maps that followed. A different map for the initial LAI would probably result in a different parameterisation of the model to the catchment.

Despite the above concerns of the final model's accuracy, its development improved knowledge of catchment response to vegetation cover changes and confirmed the suitability of the generic parameter set to Darling Plateau catchments. However, there are uncertainties in the present model and they make it preliminary. Implementation of the recommendations (Section 7) would be expected to transform the model into a reliable tool for prediction of the impacts of forest management.

7 Recommendations

- Apply aerial photographs to define early LAI estimates, particularly those for the 1980s, and revise the present LAI maps. The model was considered preliminary, primarily due to uncertainties with the accuracy of LAI estimates (particularly those for the 1980s). Other studies (Croton 2004) have successfully used aerial photographs to define early LAI.

- Apply the WEC-C model to the Yarragil 6C catchment and create a single parameter set which achieves the best history match for both the Yarragil 4X and Yarragil 6C catchments. (CALM has funded a proposal to apply the WEC-C model to the Yarragil 6C catchment and this study is underway.) Such replication would probably help resolve the issues of LAI estimation as well as create a more accurate parameter set.

- Investigate the poor match of observed and simulated flows in the years 1988, 1994, 1999 and 2000. For 1988 and 1994 the mismatch may be fire-related; however, there is no obvious explanation for 1999 and 2000.

References

Bari, MA & Croton, JT 2000, 'Predicting the impacts of land use changes on streamflow and salinity by a fully distributed catchment model', in: *Hydro 2000, Third International Hydrology and Water resources Symposium*, The Institution of Engineers Australia.

Beverly, CR & Croton, JT 2002, 'Formulation and application of the unsaturated/saturated catchment models SUSCAT and WEC-C', *Hydrological Processes,* vol. 16, pp. 2369–94.

Campbell, GS 1974, 'A simple method for determining unsaturated conductivity from moisture retention data', *Journal of Soil Science*, vol. 117, pp. 311–314.

Clark, CJ, George, RJ, Bennett, DL & Bell, RW 2000 'Geologically related variations in saturated hydraulic conductivity in regolith of the western wheatbelt of Western Australia and it implications for the development of dryland salinity' *Australian Journal of Soil Research*, vol 38, pp. 555–568.

Croton, JT 2004, *Simulation of the hydrologic response of the Del Park catchment to bauxite mining*, Alcoa Research Bulletin No. 32.

Croton, JT & Bari, MA 2001, 'Using WEC-C, a fully distributed, deterministic catchment model, to simulate hydrologic responses to agricultural clearing', *Environmental Modelling and Software,* vol. 16, pp. 601–614.

Croton, JT & Barry, DA 2001, 'WEC-C: A distributed, deterministic catchment model — theory, formulation and testing', *Environmental Modelling and Software*, vol. 16, pp. 583–599.

Croton, JT, Norton, SMG & Dalton JA 1997, *Simulation of the hydrological impact of mining in the Cameron area on the Serpentine Reservoir,* Water and Environmental Consultants report to Alcoa of Australia Limited, November 1997.

Department of Conservation and Environment 1983, *The Darling system—System 6, Part II: Recommendations for specific localities*, Report 13, October 1983.

Herbert, EJ, Shea, SR & Hatch, AB 1978, *Salt content of lateritic profiles in the Yarragil catchment, Western Australia*, Forest Department of Western Australia, Research Paper 32.

Hingston, FJ & Gailitis, V 1976, 'The geographic variation of salt precipitated over Western Australia', *Australian Journal of Soil Research,* vol. 14, pp. 319–335.

Hutson, JL & Cass, A 1987, 'A retentivity function for use in soil water simulation models', *Journal of Soil Science,* vol. 38, pp. 105–113.

Luke, GJ, Burke, KL & O'Brien, TM 1988, *Evaporation data for Western Australia,* Western Australian Department of Agriculture Technical Report 65.

Martin, MW 1984, *Analysis of pumping test from the Darling Range, eastern Collie area, Western Australia*, Geological Survey of WA, Published Record 1988/32.

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

Mauger, GW, Day, JE & Croton, JT (eds) 1998, *Hydrological and associated research related to bauxite mining in the Darling Range of Western Australia—1997 review,* Water and Rivers Commission, Water Resource Technical Series No. WRT 26.

Moulds, BD, Bari, MA & Boyd, DW 1994, *Effects of forest thinning on streamflow and salinity at Yarragil catchment in the Intermediate Rainfall Zone of Western Australia,* Water Authority of Western Australia, Report No. WS 140.

Ovington, JD & Pryor, LD 1983, 'Temperate broad-leaved evergreen forests of Australia', in: JD Ovington (Editor), *Ecosystems of the World*, *vol. 10, Temperate Broad-Leaved Evergreen Forests*, Elsevier, Amsterdam, pp.73–101.

Raper, GP & Croton, JT 1996, *Hydraulic properties of Darling Range soils*, Water & Environmental Consultants Report to Alcoa of Australia Ltd, 98p.

Ruprecht, JK & Schofield, NJ 1990a, 'Seasonal soil water dynamics in the jarrah forest, Western Australia', I: 'Results from a hillslope transect with coarse-textured soil profiles', *Hydrological Process,* vol. 4, pp. 241–258.

Ruprecht, JK & Schofield, NJ 1990b, 'Seasonal soil water dynamics in the jarrah forest, Western Australia', II: 'Results from a site with fine-textured soil profiles', *Hydrological Process,* vol. 4, pp. 259–267.

Schofield, NJ, Stoneman, GL & Loh, IC 1989, 'Hydrology of the jarrah forest', in: Dell, B, Havel, JJ & Malajczuk, N (Eds), *The jarrah forest: a complex Mediterranean ecosystem*, Kluwer Academic Publishers, Dordrecht, pp. 179–201.

Shea, SR, Hatch, AB, Havel, J & Ritson, P 1975, 'The effect of changes in forest structure and composition on water quality and yield from the Northern Jarrah Forest', in: Managing Terrestrial Ecosystems, vol. 9, Proceedings of the Ecological Society of Australia Symposium (J. Kikkawa and H.A. Nix, eds.), Symposium, Brisbane, pp. 58–73.

Steering Committee for Research on Land Use and Water Supply 1987, *Forest management to increase water yield in the Northern Jarrah Forest*, Water Authority of Western Australia, Report No. WS 3, 23p.

Stoneman, GL 1993, 'Hydrological response to thinning a small jarrah (*Eucalyptus marginata*) forest catchment*',* *Journal of Hydrology*, vol. 150, pp. 393–407.

Stoneman, GL & Schofield, NJ 1989, 'Silviculture for water production in the jarrah forest of Western Australia: An evaluation', *Forest Ecology and Management*, vol. 27, pp. 273–293.

Water & Environmental Consultants 1997, *Data for modelling the Cameron West and Central catchments*, Report to Alcoa of Australia Limited, September 1997.

Water and Rivers Commission Regional Services Division 1996, *Catalogue of water resources information 1996*, Volume 1: the South West Drainage Division, ISBN 0 7309 7240 2, Perth.

Appendix 1
LAI maps used in modelling

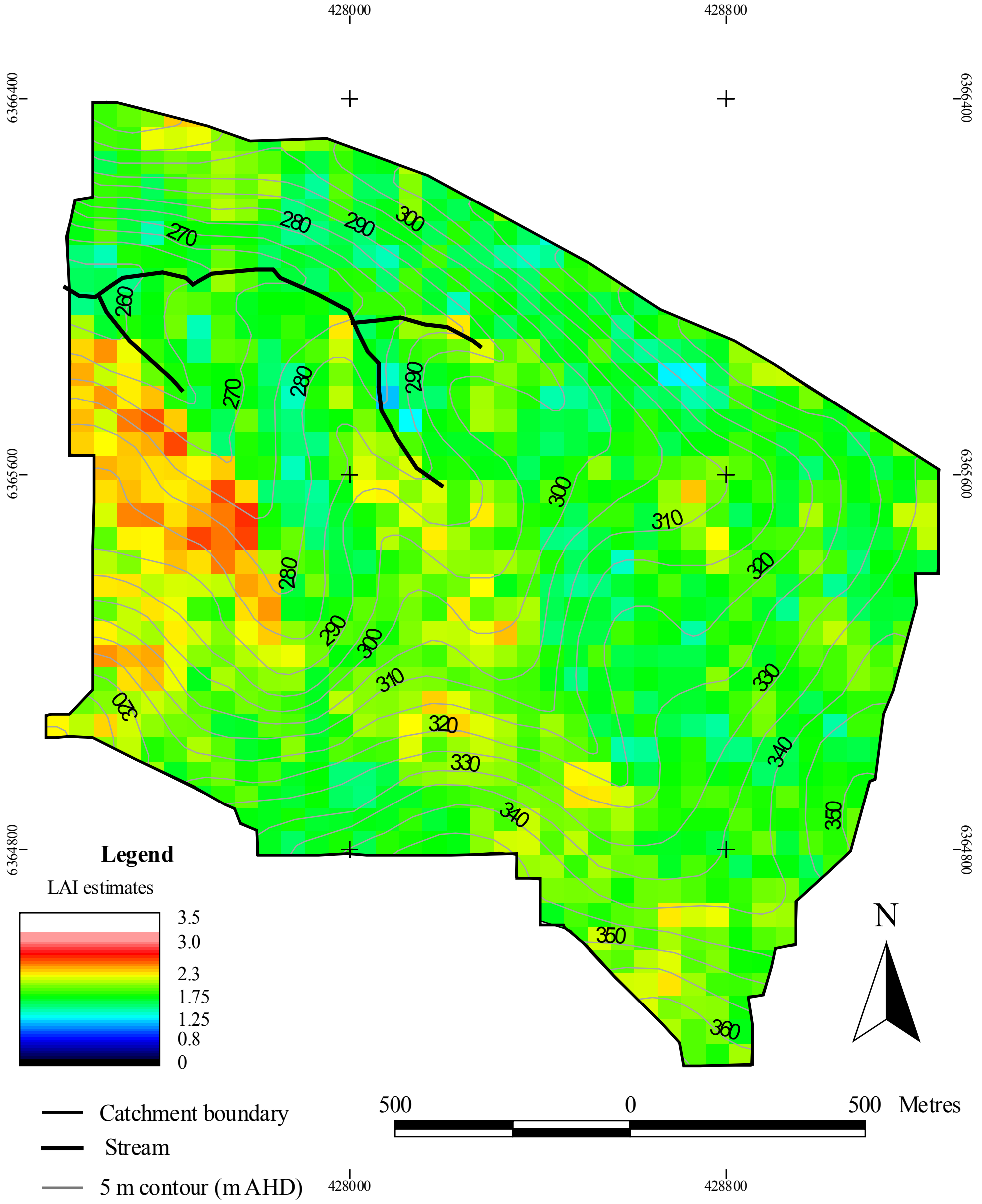

Figure 20. Initial LAI map derived from historical CALM data and Landsat MSS

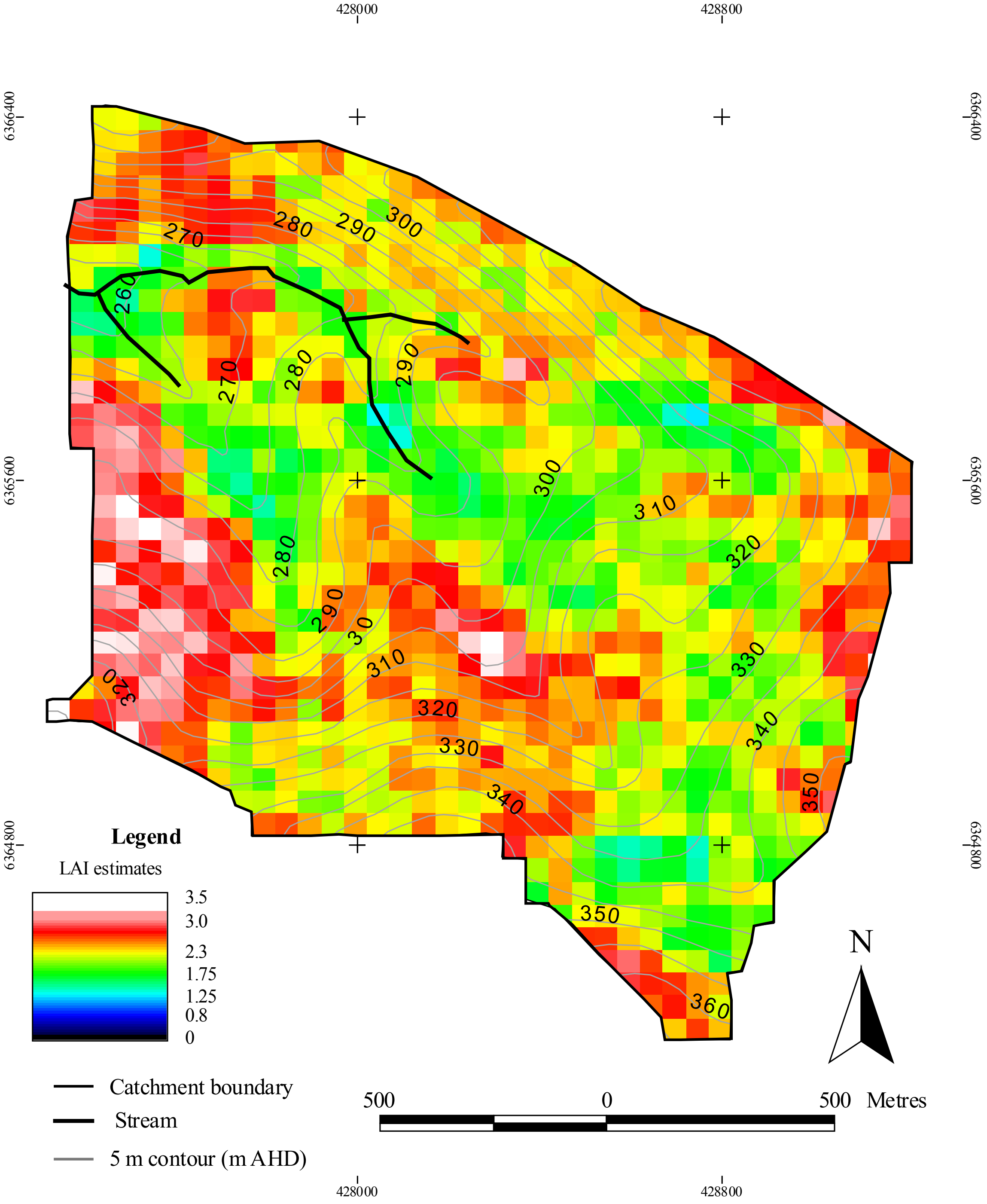

Figure 21. LAI map derived from the Landsat TM scene for February 1988

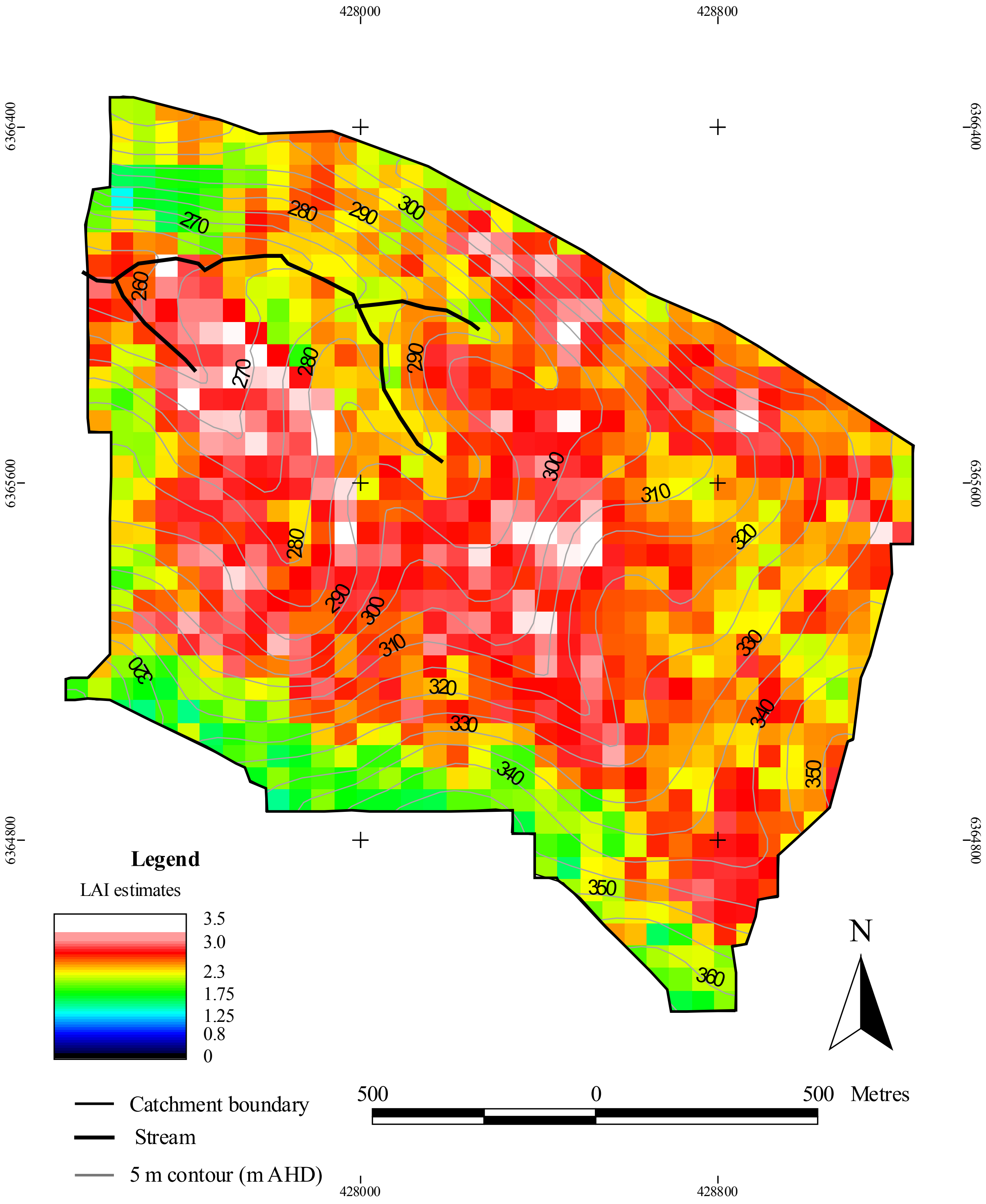

Figure 22. LAI map derived from the Landsat TM scene for January 1999

Appendix 2
Soil salt storage data

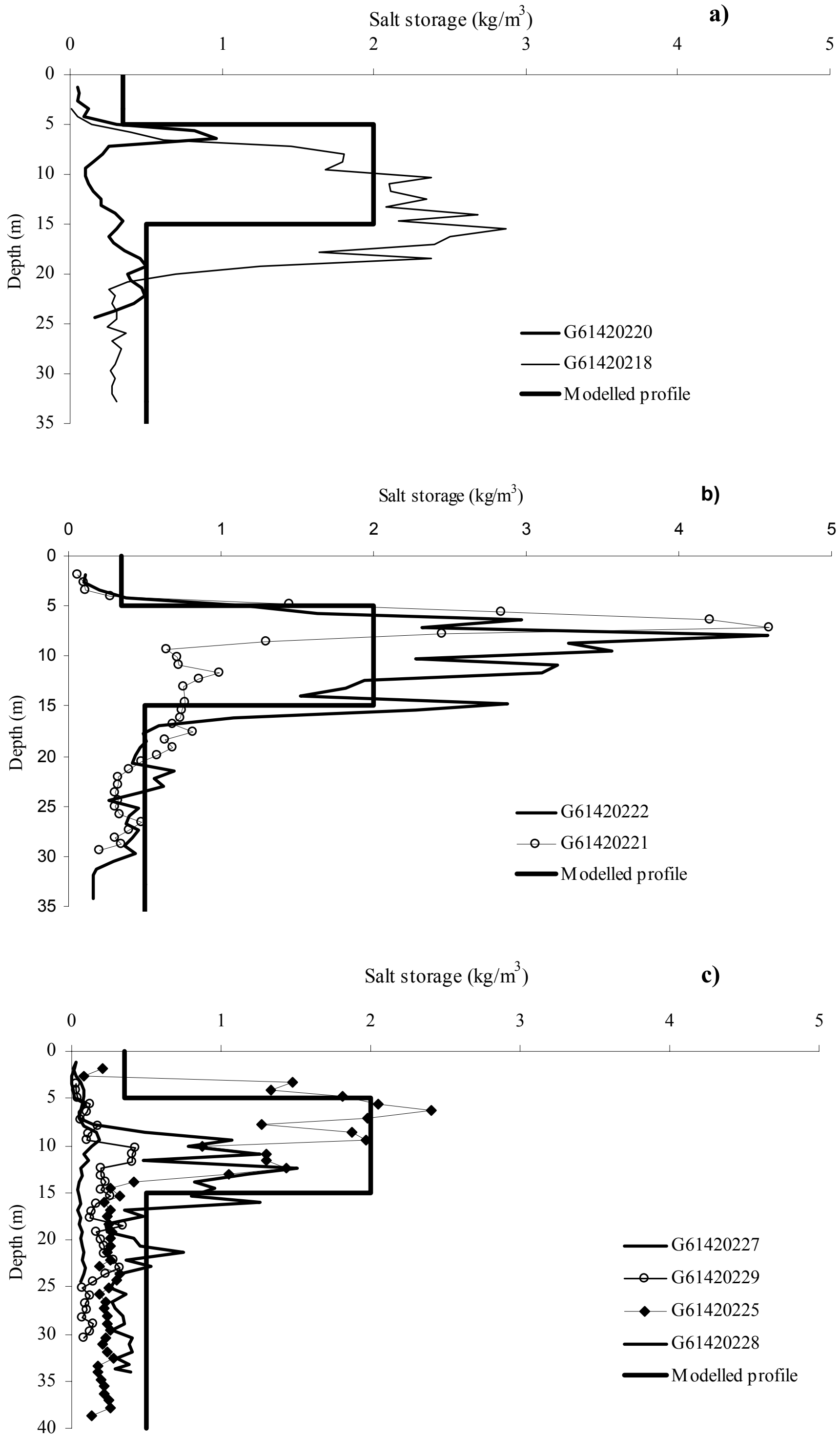

Figure 23. Soil salt storage profiles for catchment bores: a) streamzone b) midslope and c) upslope

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