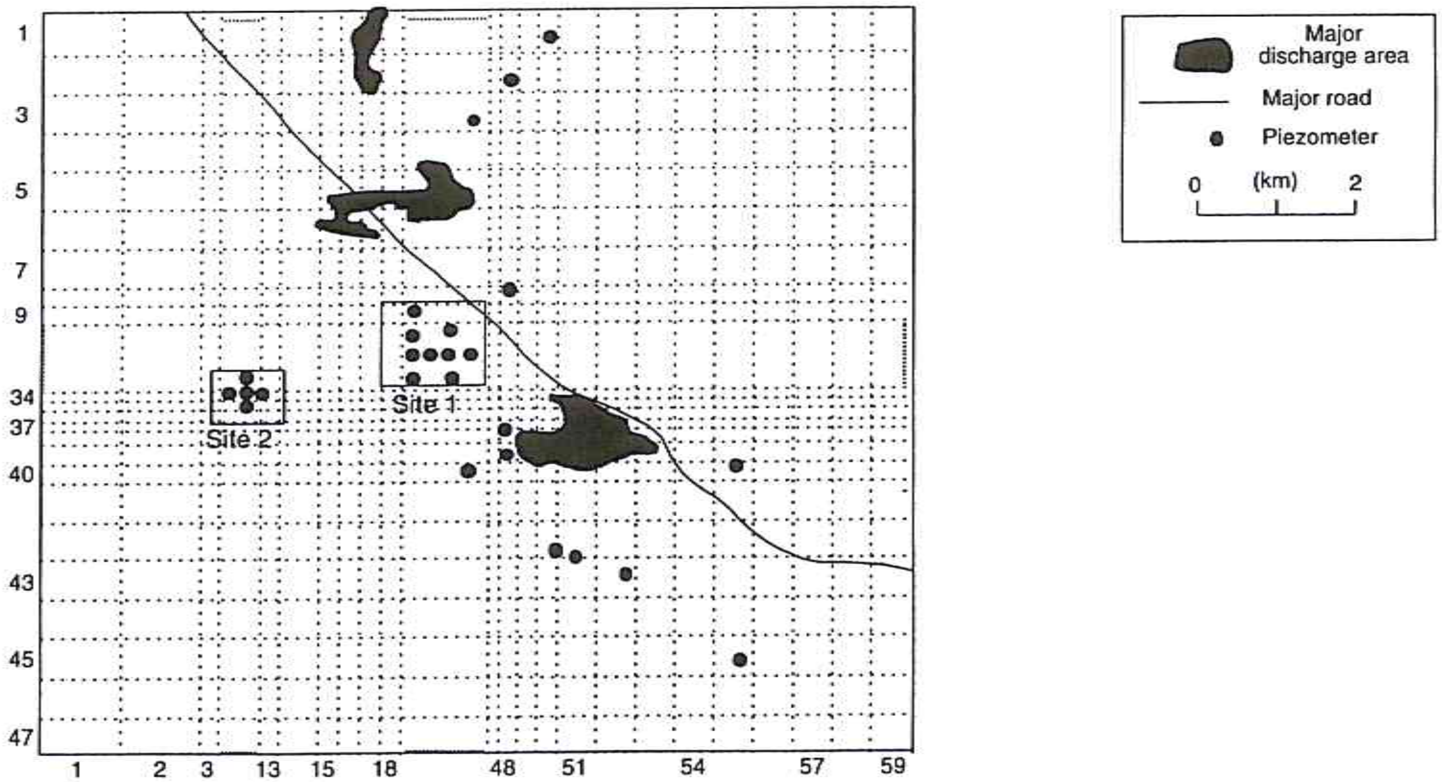
Figure 13: Finite difference grid for fine-mesh model



Note: small grids are not shown at this scale

Figure 14: Portion of finite difference grid for fine-mesh model at site 1

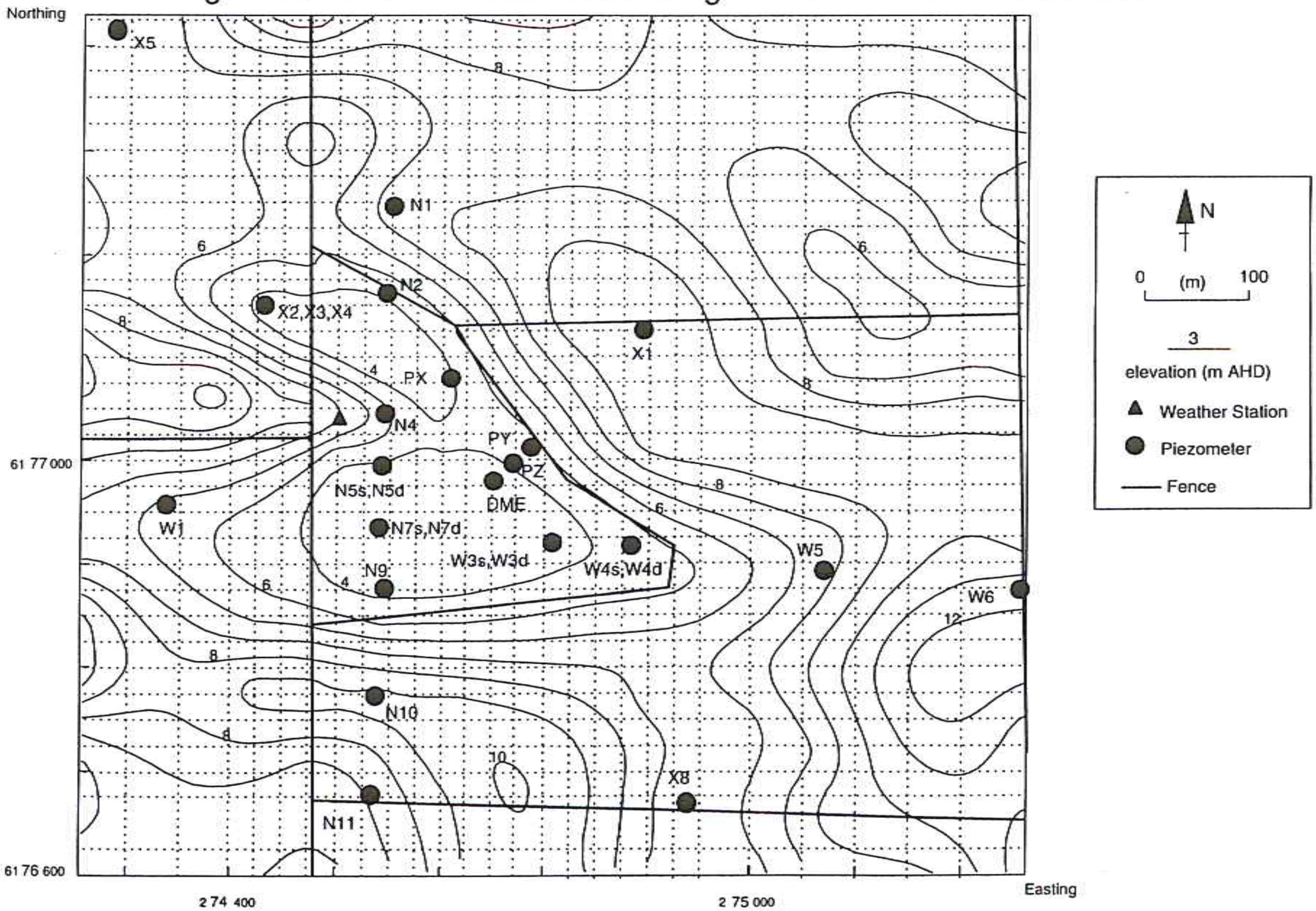


Figure 15: Portion of finite difference grid for fine-mesh model at site 2

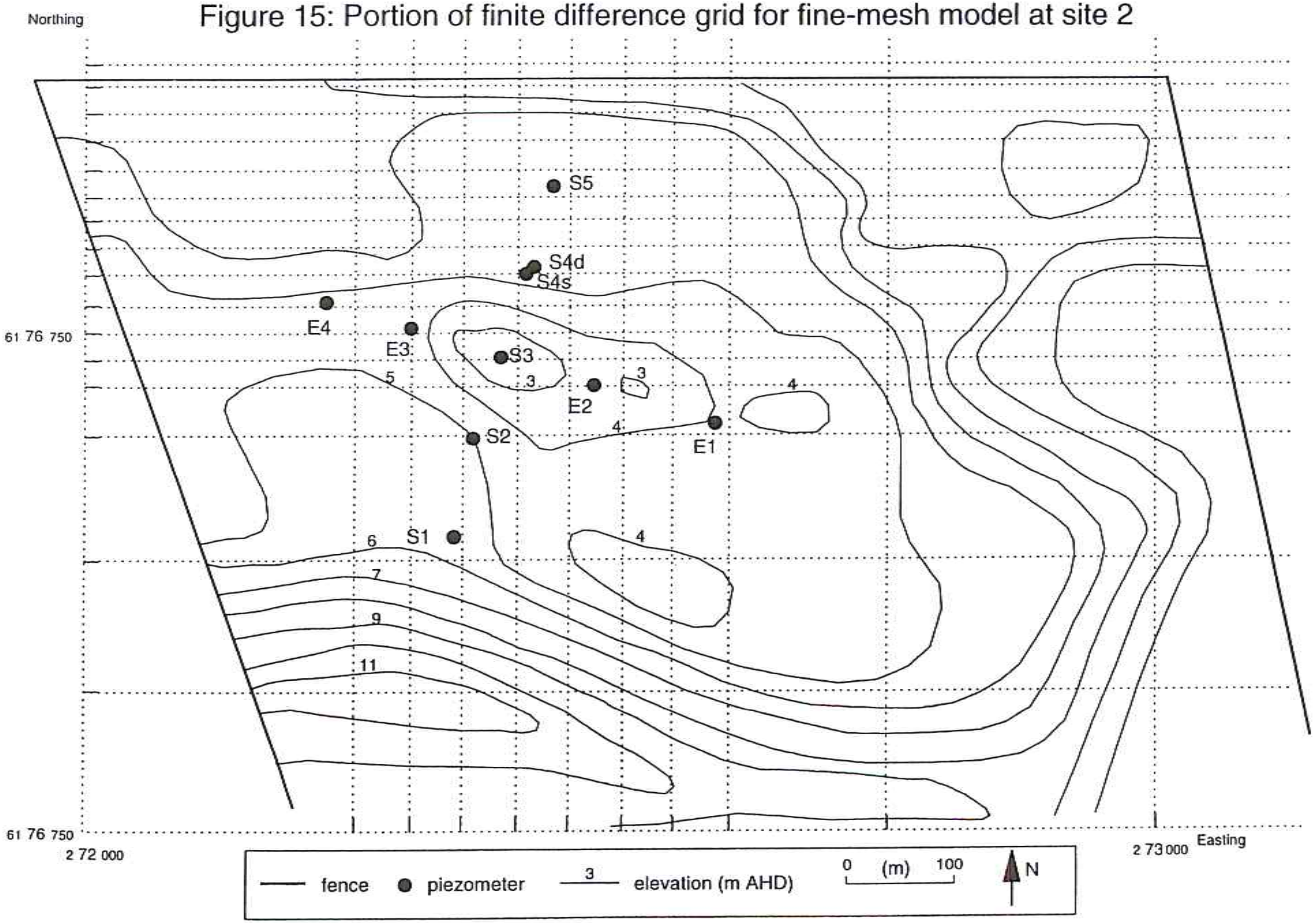


Fig.16:Comparison of steady state heads for broad-mesh and fine-mesh models

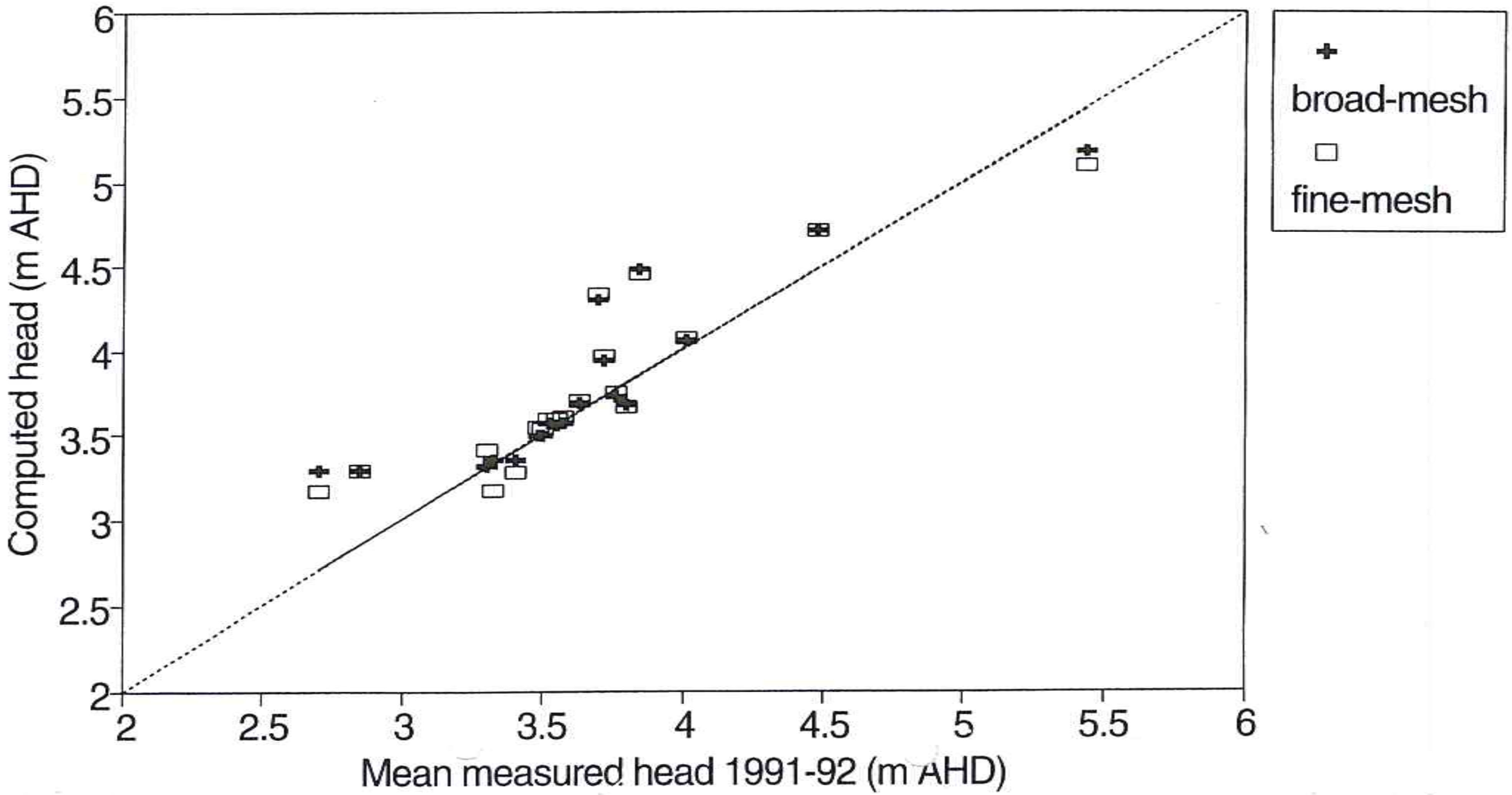
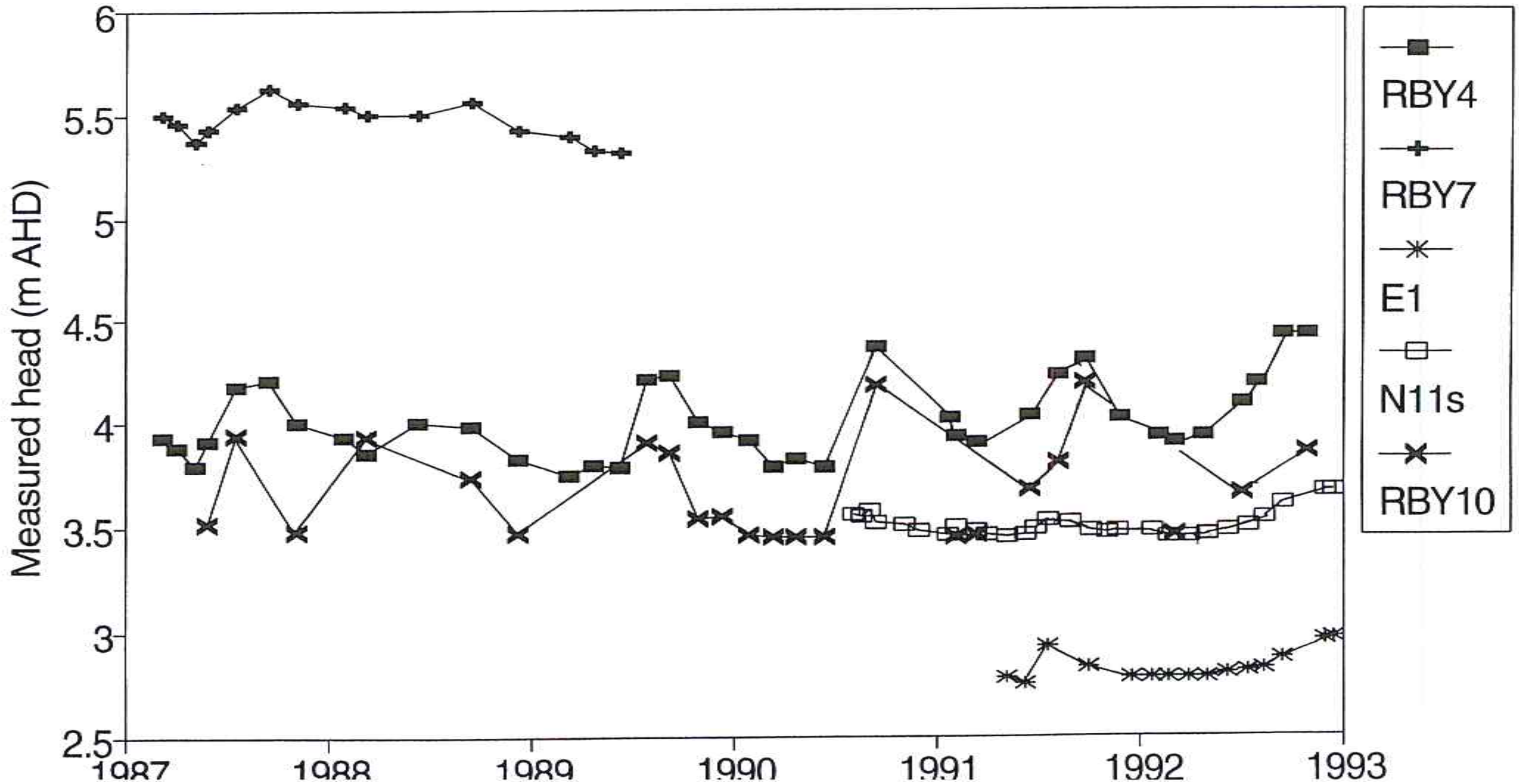


Figure 17: Measured heads at five sites within the model



Groundwater discharge was described by the soil evaporation function (rather than a specified flux as in the broad-mesh model), and potential evaporation rates for each year were given in Table 2. Due to the importance of discharge on the groundwater budget, and the degree of uncertainty in field determined extinction depth, this parameter was varied over the range of 0.5 to 2.0 metres.

A value of 0.05 was used for the specific yield throughout the model, as selected in the broad-mesh model.

A constant head was specified at the downgradient boundary, whilst a general head condition was specified at the upgradient boundary. In order to replicate conditions in 1987, the initial hydraulic head at the upgradient boundary was reduced by 0.3 m to 5.7 m AHD. The upgradient boundary head was increased at the rate of 0.05 m yr^{-1}, as observed (ie. from 5.7 to 5.95 over the calibration period). The downgradient boundary head was reduced to 2.2 m AHD (for reasons discussed later).

The calibration involved comparing the computed and measured heads based on the criteria outlined in Section 4.3. The parameters were selected to satisfy (to an appropriate degree) all of the criteria.

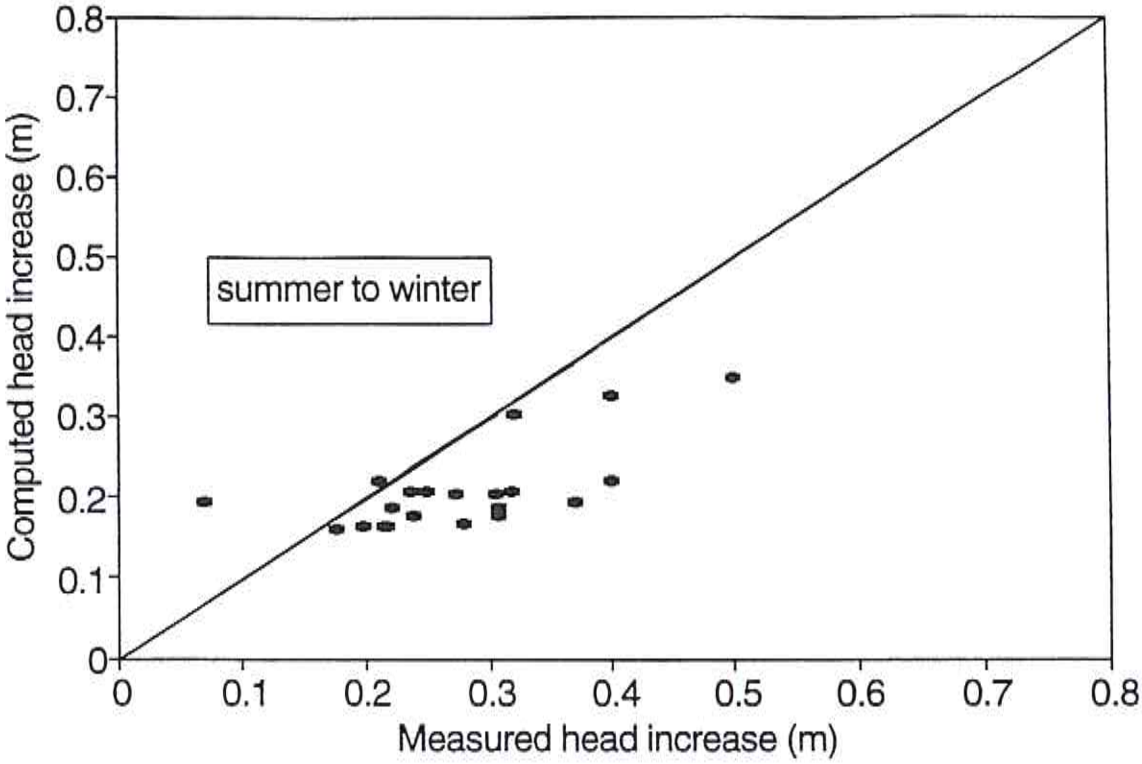
A mean recharge rate of 25 mm yr^{-1} was considered most appropriate, although 12.5 and 17 mm yr^{-1} were also tested. The value chosen was slightly higher, (but is considered more reliable) than that found from the broad-mesh model, but remained well within the range of measured values. Plotting the computed versus measured head increase between summer and winter 1992 gives an indication of the reliability of recharge rates (Fig. 18). Whilst computed heads are slightly less than measured heads, the trend throughout different areas of the model is evident. The option to increase recharge rates was disregarded on the basis of previous simulations (and measured data). A decrease in specific yield was tested, and although it improved this aspect of the model, the net effect was to increase the RMS error.

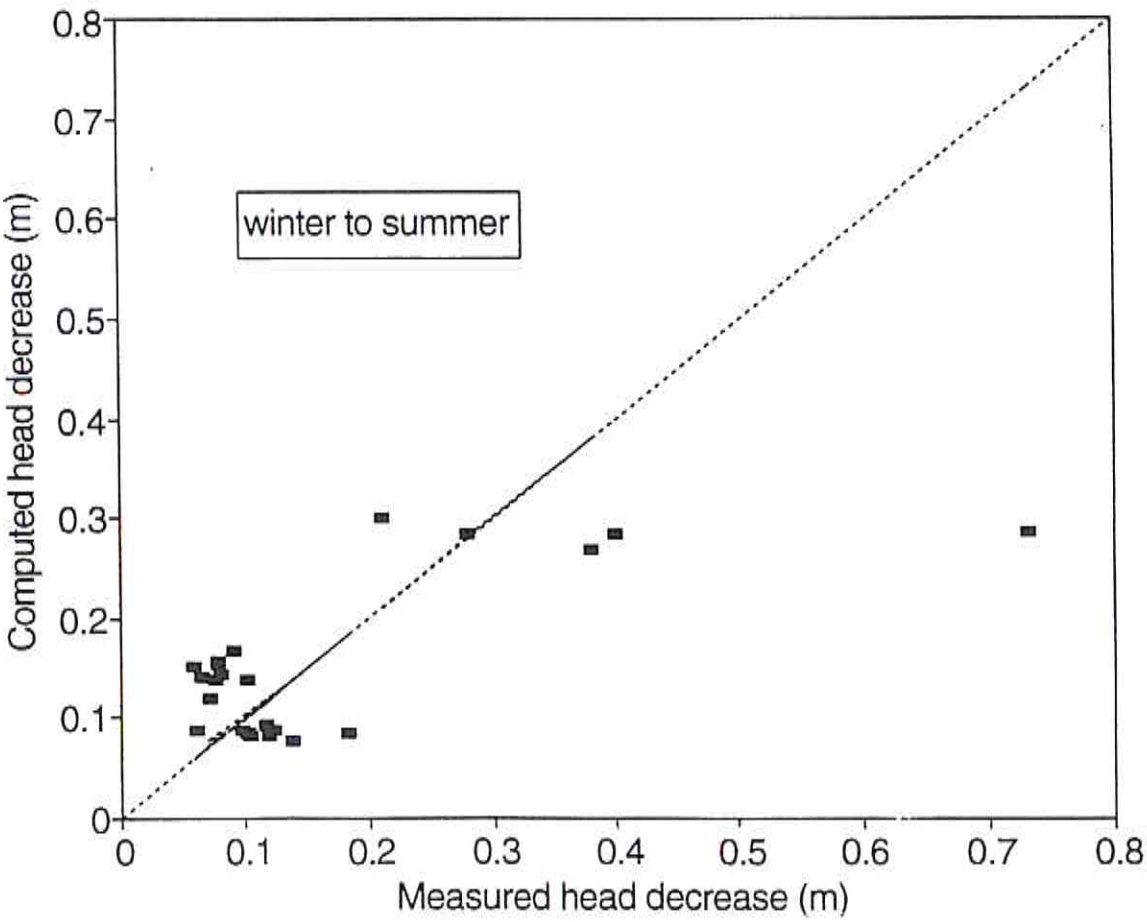
Extinction depth was varied from 0.5 to 2 metres. The effect of varying extinction depth results in a significant impact on the groundwater response in the vicinity of the older discharge areas, which is propagated throughout most of the model area. This was also made clear by altering discharge rates in the broad-mesh model. An extinction depth of 0.5 metres was found to be most appropriate. Figure 18 also shows the computed versus the measured head decline between winter and summer 1992. A reasonable agreement between measured and computed heads is evident, which would suggest that the model is handling discharge reasonably well.

Greater temporal response in piezometric levels is evident in the vicinity of discharge areas (eg. RBY10) where the superimposed effect of recharge as well as discharge is evident in the hydrographs (Fig. 17). The model simulations also showed similar responses in the discharge areas.

With a satisfactory handling of recharge and discharge processes, the focus was then given to aquifer transmissivity, in order to adjust the mean levels computed to fit more closely the mean levels observed. It was considered appropriate that no more than about four zones of hydraulic conductivity be established due to the lack of hydraulic data in the study area. Areas which were targeted for investigation were the areas adjacent to the south-eastern and western boundaries of

Fig.18: Comparison between computed and measured head differences for 2 seasons





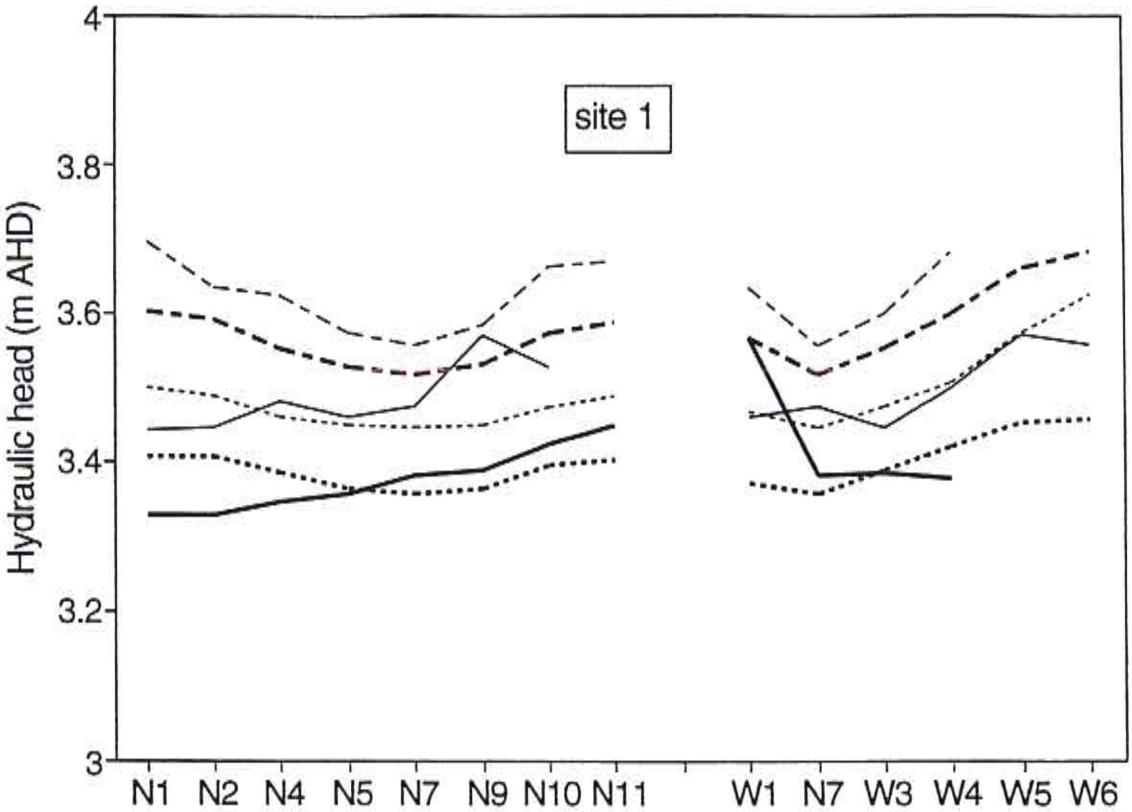
the model. The south-east corresponds to the area where the piezometric contours have been displaced approximately three kilometres to the west (Fig. 1). We suspect that this area has a low aquifer transmissivity (recharge estimation in this area suggests that enhanced recharge is not a probable cause of this anomaly). In the west the model underestimated the hydraulic gradient, which usually resulted in overestimating heads in the vicinity of site 2. The hydraulic head at the boundary was decreased to the lowest permissible value (2.2 m AHD).

Several configurations and values of hydraulic conductivity were tested, and ranges of 5 to 60 m day^{-1} were used. Modifying the distribution of hydraulic conductivity improved the fit with measured data of the groundwater flow pattern (particularly in the south-east), however the problem in the west proved difficult to constrain over the range tested. The eventual outcome resulted in heads at site 2 being overestimated by around 30 cm.

Figure 19 shows the measured and computed heads along perpendicular transects across study sites 1 and 2 for three time intervals corresponding to the ends of winter (September, 1991), summer (March, 1992) and following winter (December, 1992) with the eventual parameterisation chosen for the fine-mesh model. The degree of fit between measured ar computed heads is apparent from this figure, as is the problem with consistent differences in mean values at site 2 (although the trends appear to be good). Figure 20 shows a comparison between computed and measured heads for all available piezometers at time steps corresponding to those shown for the local transects (Fig. 19) near the end of the calibration period. The mean RMS error for the three time steps was 0.25 m for the model, whilst at site 1 it was considerably lower at 0.07 m, and higher at site 2 (0.35 m).

A summary of the parameters and boundary conditions chosen for the fine-mesh model is shown in Figure 21. These values were used in the subsequent predictive phase of the modelling.

Fig. 19: Comparison between measured and computed heads along transects



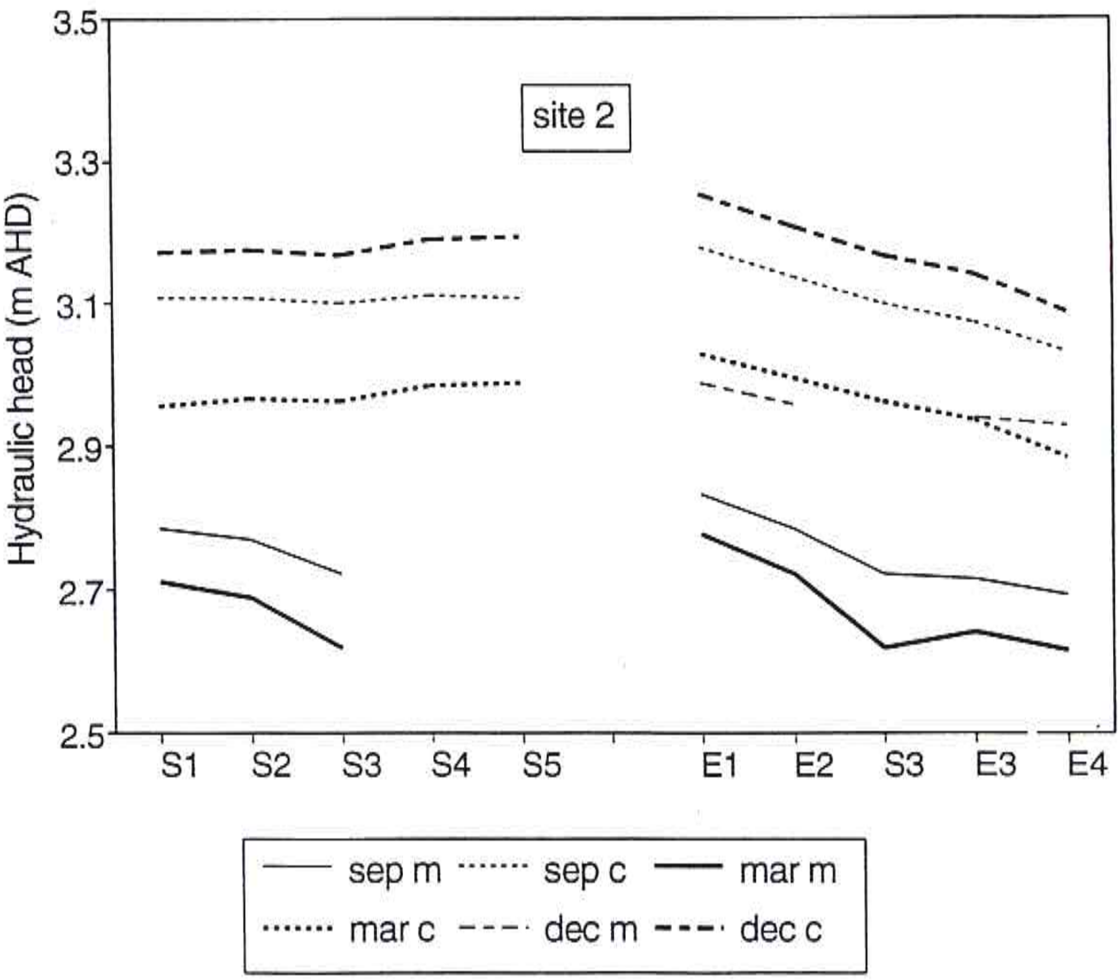


Fig. 20: Comparison between computed and measured heads for fine-mesh model

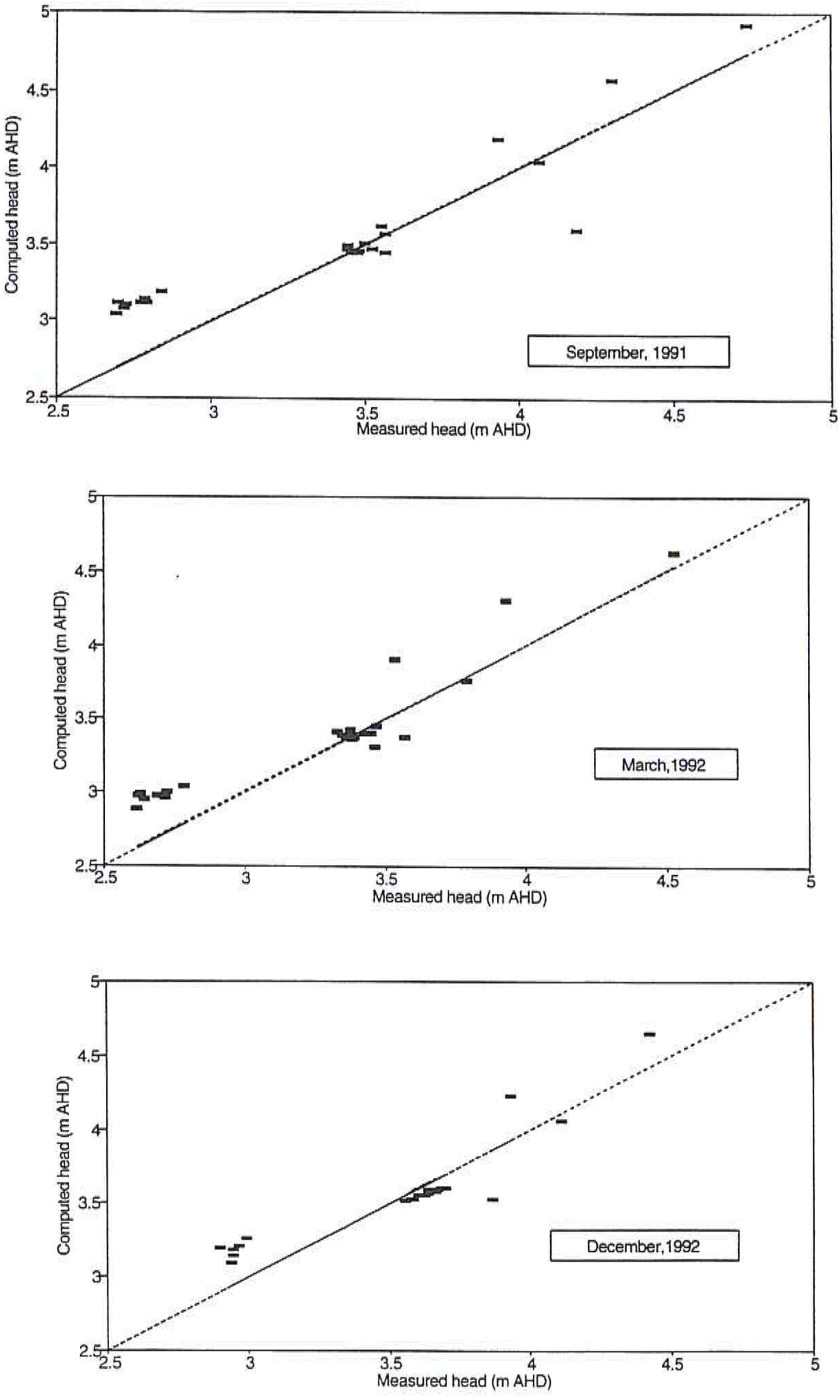
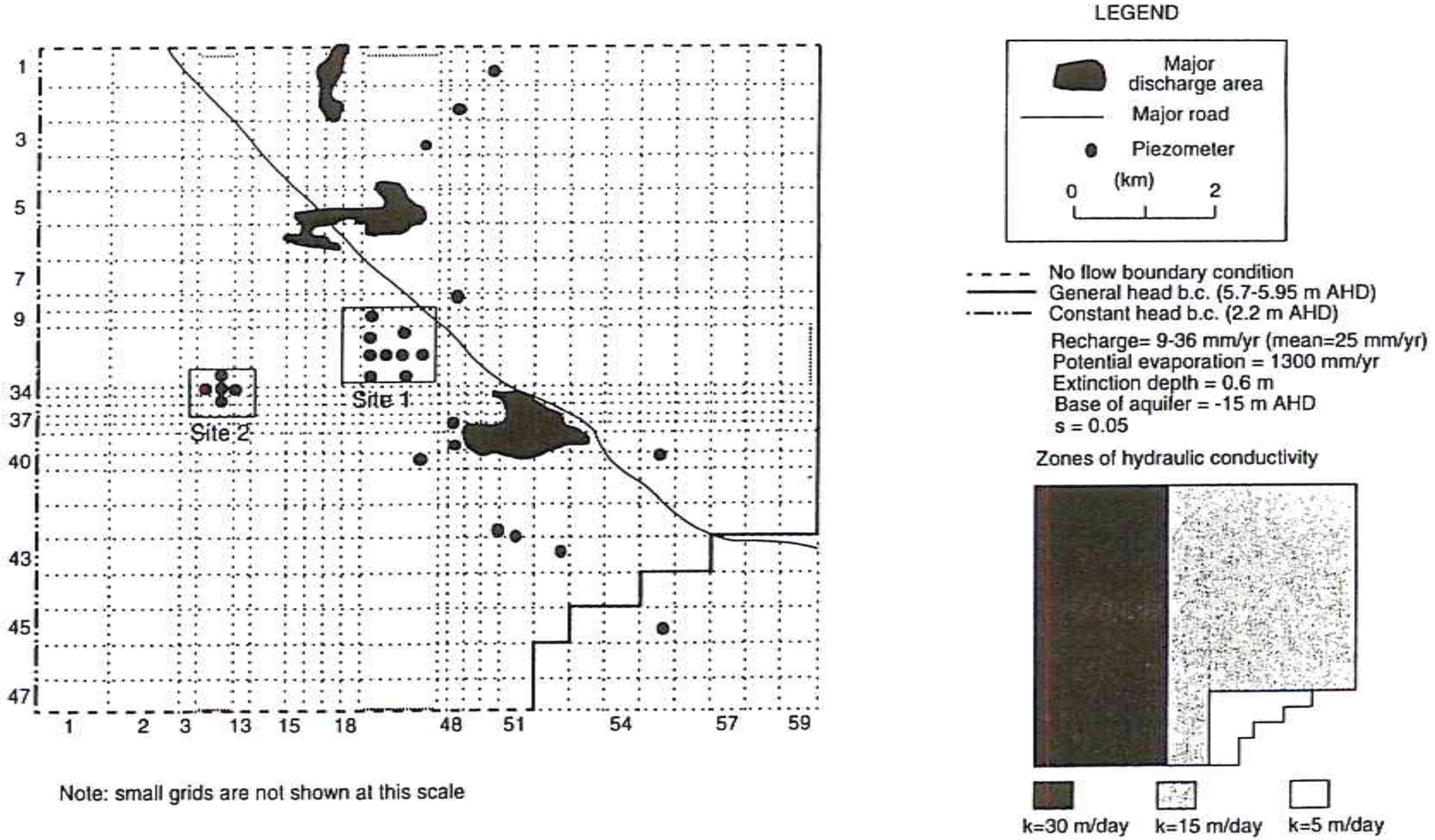


Figure 21: The model area, showing finite difference grid and calibrated model parameters



7. SIMULATIONS OF LAND MANAGEMENT OPTIONS

The predictive phase of the modelling involved a total of nine different scenario's which were selected to simulate a range of land management options. A time frame of 20 years (in addition to the initial 6 year calibration period) was considered a suitable time in which to determine the effectiveness of these options. The rainfall records for a 20 year period for 1967-1986 (see Fig. 5) were used to derive recharge rates. The scenario's included:

1. Do nothing: recharge rates remain at current levels
2. Do nothing: as for (1) however the sequence of recharge rates were in ascending order
3. Do nothing: as for (1) however the sequence of recharge rates were in descending order

4-6. Recharge reductions of 10, 50 and 90% of (1) throughout the entire area

7. Recharge reduction of 50% for an area of 78 ha for site 1
8. Discharge enhancement through pumping (20 m^3 day^{-1}) within the swale at site 1
9. Constant upgradient boundary condition (and 50% recharge reduction)

In the discussion that follows we refer primarily to the entire model area, however a subarea the model at site 1 is often used to demonstrate particular aspects of the model.

Hydraulic response across the model

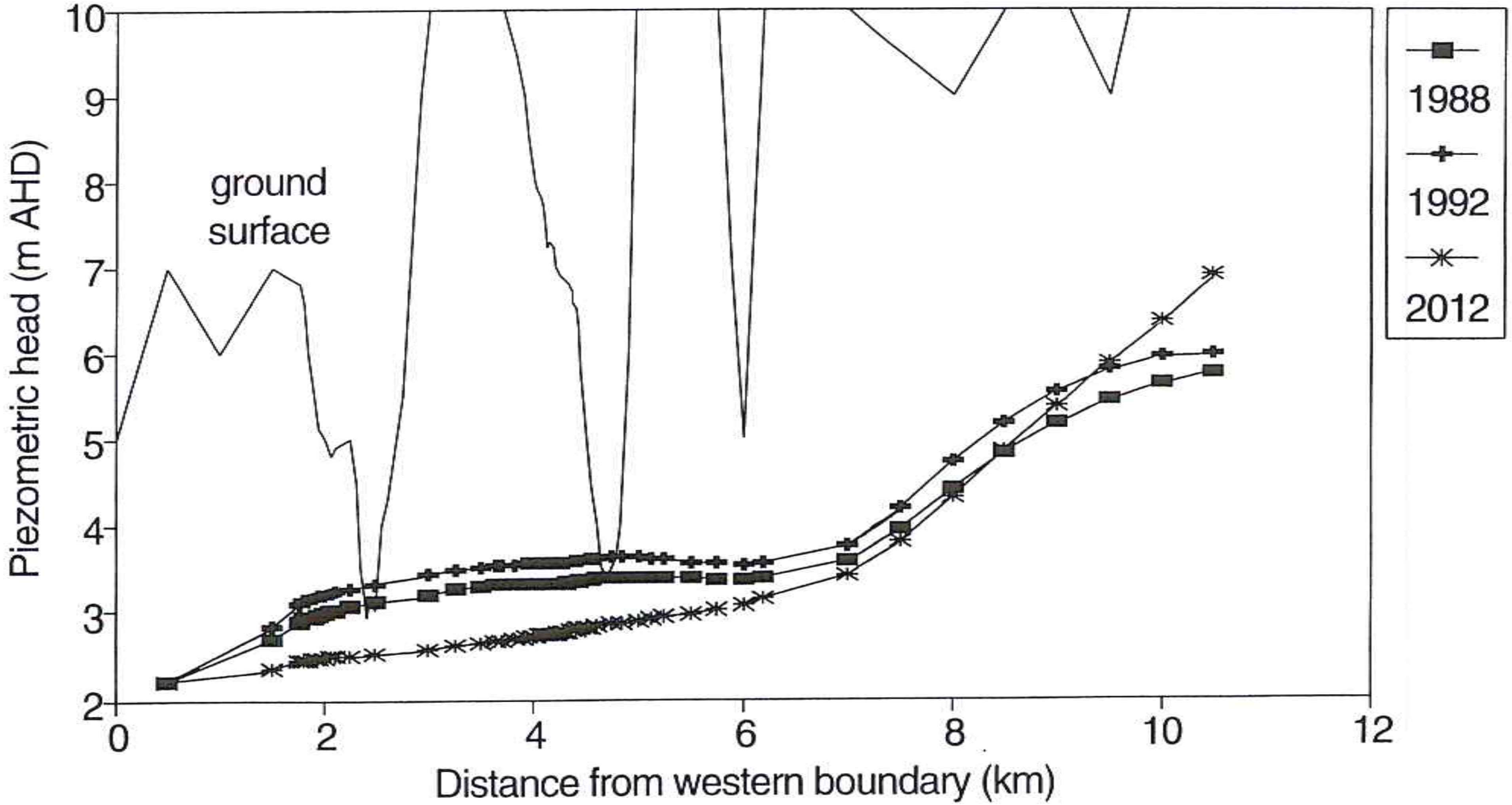
Calibration and sensitivity analysis has indicated that the hydraulic response of the model is spatially non-uniform, and is governed by processes within the model (ie. recharge-discharge areas) and also relationships at the model boundaries. Prior to giving a detailed description of the simulations, it is worthwhile to show the spatial response of the calibrated model. Figure 22 shows an East-West transect across the centre of the model at three times during a simulation (scenario 6; discussed later). The impact of the boundary conditions is clearly evident, as is the relationship between the land surface and the watertable, especially the old discharge areas and swales, which can be identified as depressions in the landscape.

The model predictions were undertaken with the assumption that all boundary conditions except for the upgradient remain unchanged in time. This may not necessarily be the case for the northern and southern (no-flow) boundaries if there is sufficient change in watertables within model to induce lateral inflow or outflow. Later results indicate that the effect of varying the eastern boundary condition between constant and rising head (scenario's 5 and 9) is not sufficiently large. Hence maintaining no-flow boundaries is not sufficiently large to suggest that they could be invalid.

Rainfall patterns (Scenario's 1,2,3)

The predictive phase of groundwater simulations presumes that rainfall patterns (and hence recharge) will behave in a particular fashion. The enigma is that one cannot forecast future rainfall with any degree of certainty, with established methods relying on historic records. The impact of the distribution of rainfall in time has been evaluated by distributing the rainfall in the natural, ascending and descending order using data from 1967 to 1986. In this way the upper and lower bounds of the influence of the rainfall sequence can be evaluated.

Fig. 22 :E-W transect across centre of model, showing the impact of scenario 6



Changing the sequence of rainfall alters piezometric heads at the end of the simulation, as well as the way in which heads are distributed in the time series. For example, these differences may be as much as 40 cm at site 1 (Fig. 23). Eventual levels for the ascending and descending sequences overestimate and underestimate by 10 and 30 cm respectively the level determined from the natural rainfall record.

These simulations show that piezometric heads are strongly influenced by rainfall, and that rainfall patterns in the future could influence the effectiveness of land management treatments which are implemented. For example, several dry years in succession can have a similar effect as a recharge reduction of 50% (discussed later) for the natural sequence of rainfall years.

Given that future uncertainties which exist in other aspects of the modelling (eg. upgradient boundary heads), it was considered unjustified to go through a rigorous stochastic modelling exercise based on rainfall sequences. Therefore the natural sequence (1967-1986) was chosen for all of the model simulations (except scenario's 2,3). This has the benefit of maintaining the natural correlation in rainfall from year to year.

Salinisation is defined here as occurring where the position of the watertable is within 0.6 metre of the ground surface at the end of September. This definition was chosen as it coincides with the maximum depth (at September) where there was a reduction in the yield of barley at Cooke Plains (Pavelic *et al.*, 1994).

Continue current practices (Scenario 1)

The model simulations suggest that maintaining current land management practices could result in a net water level rise in the order of 20 cm over 20 years within the low-lying and upland areas alike (Fig. 23). A further 50 ha of productive land would become salinised over the next 20 years, including a comparable proportion of land at site 1 (Fig. 24). The areas salinised after 20 years would be 390 ha for the model area and 3.3 ha for site 1. As already discussed, the predicted rise is dependent on rainfall patterns, (which influence recharge rates) and also on the extent of regional influences (which depend on upgradient landuses). The rate of growth of the area of salinised land will decline with time as the groundwater system approaches a new equilibrium.

Recharge reduction (Scenario's 1,4-6)

The impact of reductions in recharge of 10, 50 and 90% throughout the area is shown in Figure 25, for a location within a swale at site 1. A reduction in recharge of 10% has little impact on groundwater levels, whilst 50% reduces piezometric heads by 30 to 40 cm by the end of the simulation. Recharge reduction of 90% over the entire area produces declines of between 60 and 100 cm in some areas of the model. Larger watertable declines are associated with areas downgradient of the discharge areas (see Fig. 22).

Seasonal fluctuations become damped as recharge rates decline and are almost undetectable at a 90% reduction. Time spans in the order of 5 to 10 years are required for watertables to stabilise when a quasi-steady state is established.

Figure 23: The impact of rainfall sequence on water levels at site 1 (W3)

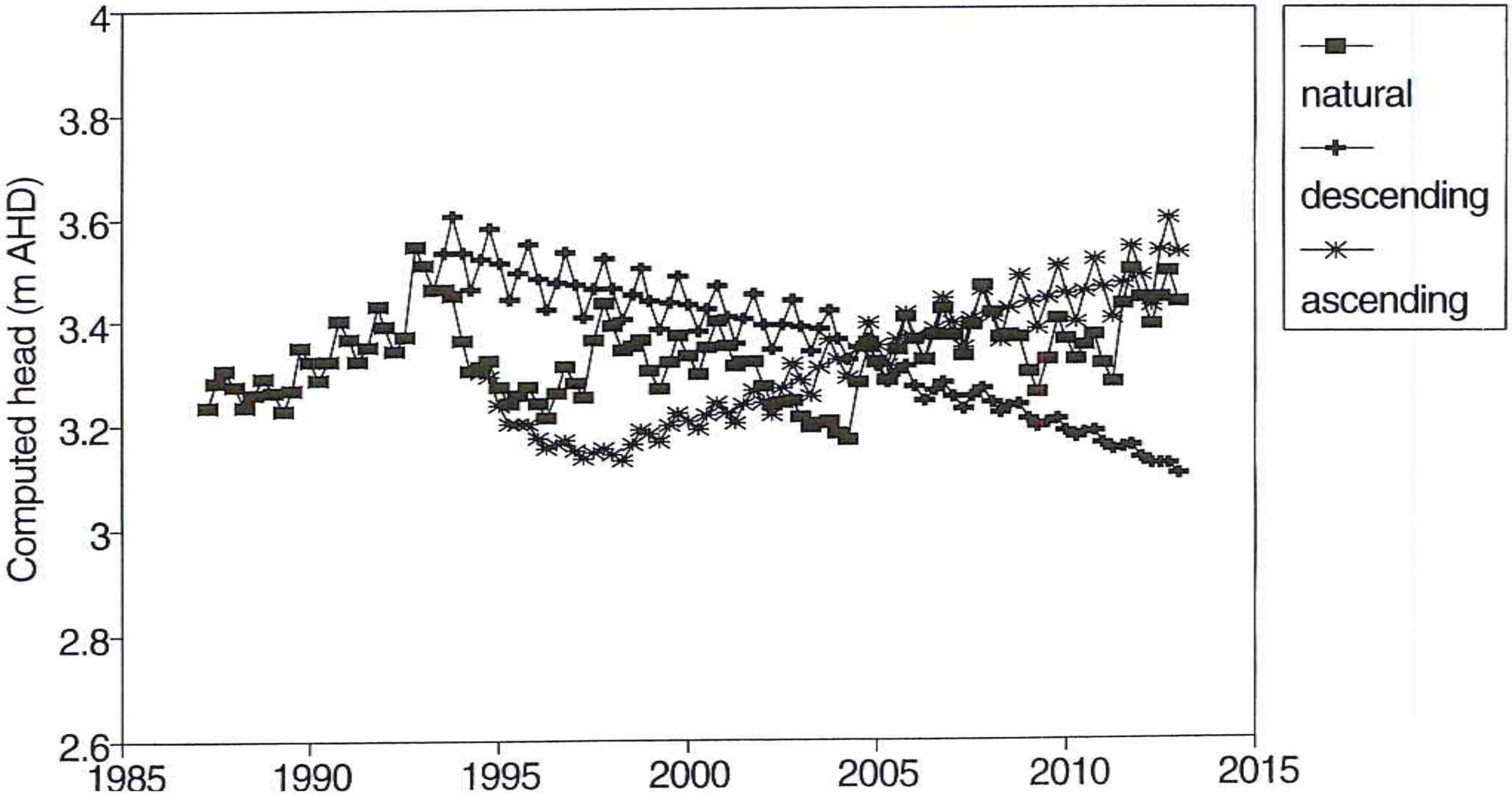


Figure 24: Areas salinised for various proportions of recharge reduction

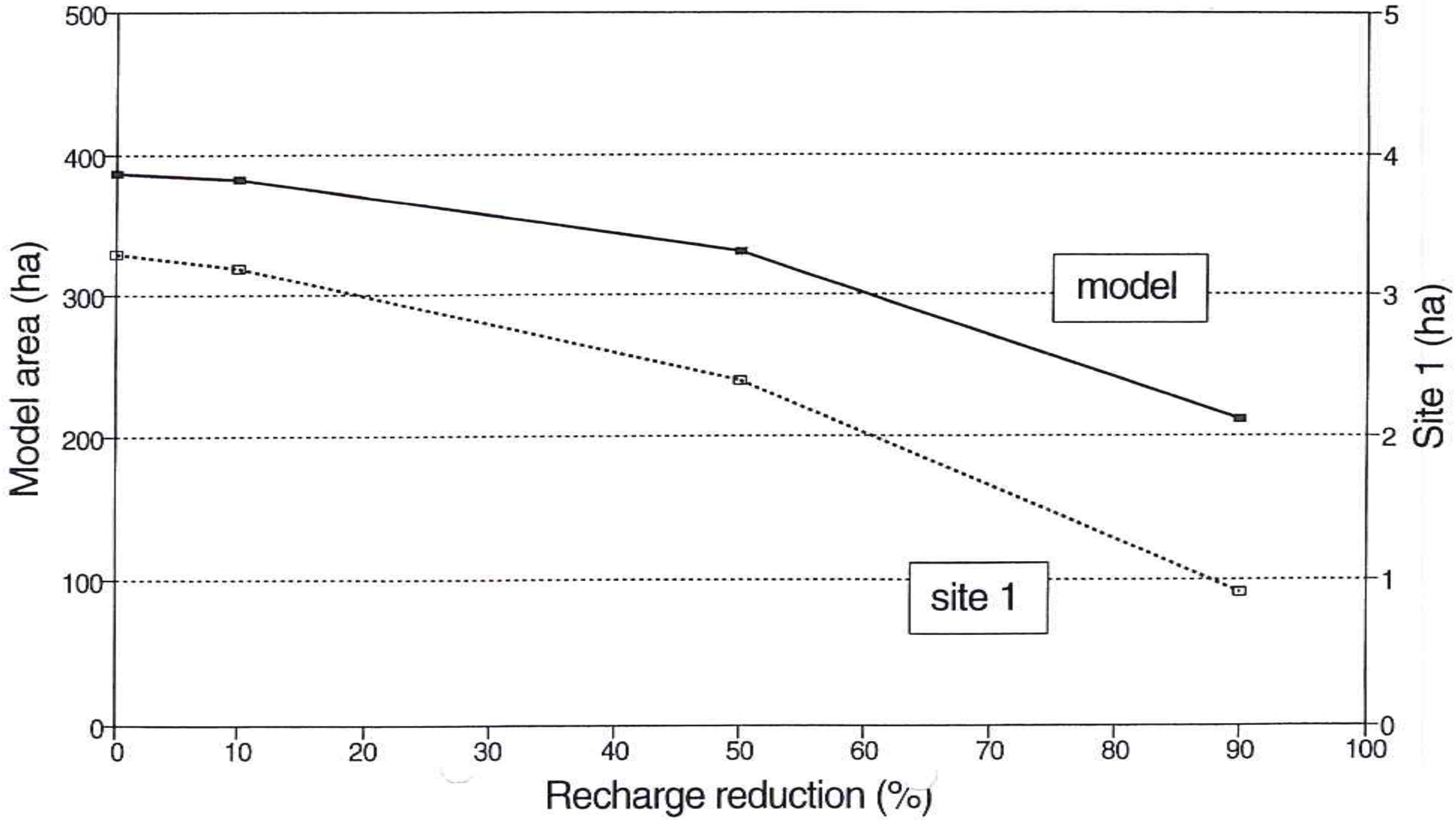
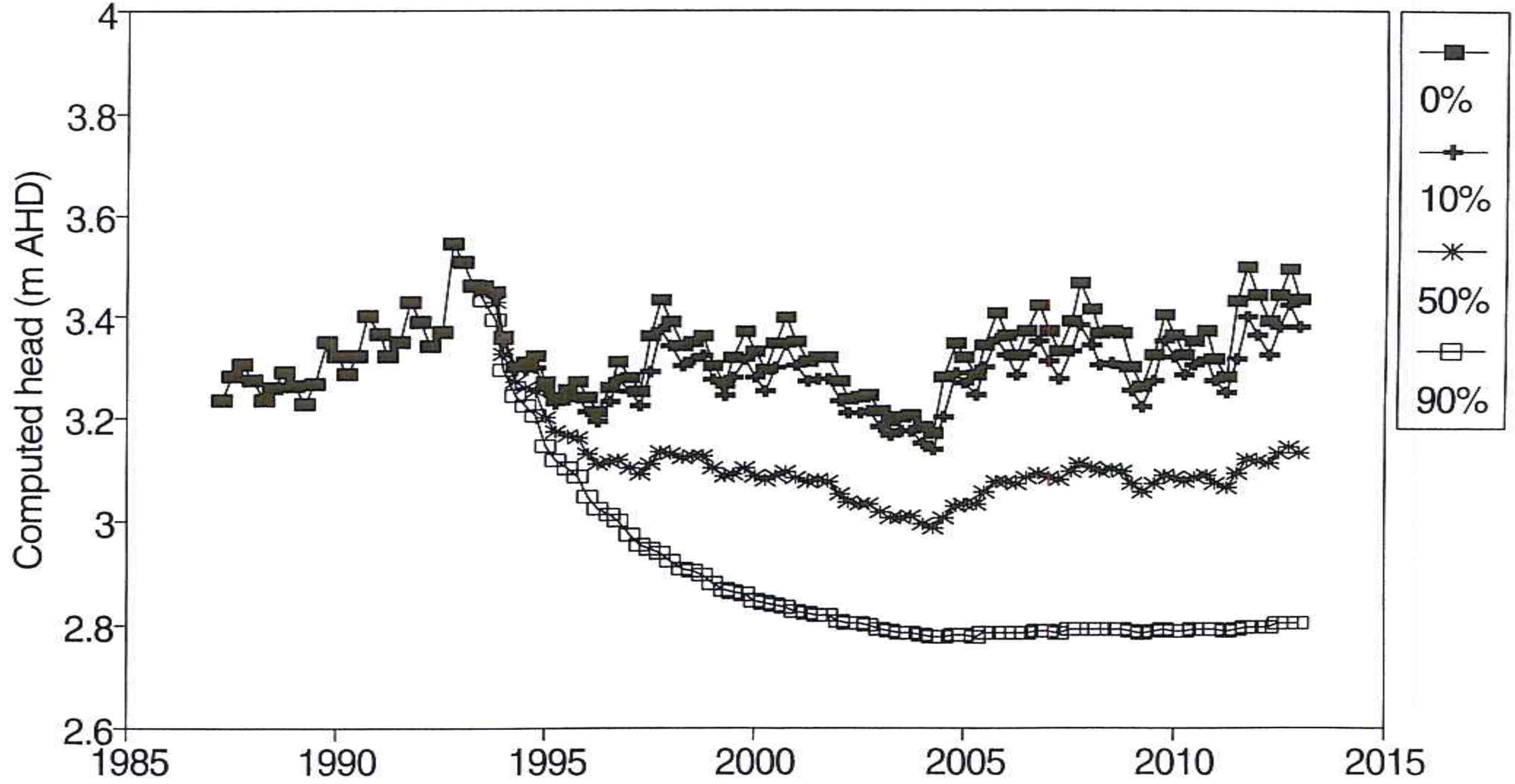


Figure 25: The impact of recharge reduction on water levels at site 1(W3)



From Figure 24 the area salinised will increase from its current 340 ha to 390 ha if recharge is not reduced, and will decline to 380, 330, and 210 ha for recharge rate declines of 10, 50 and 90% respectively. For site 1 the change in salinised area is proportional to that for the model area.

Local recharge reduction at farm-scale (Scenario 7)

The impact of small scale agronomic treatments are shown in Figure 26, where an area of 78 ha (effectively the area shown in Fig. 15) has a 50% recharge reduction, whilst recharge rates were unchanged in the remaining areas. There is no significant influence on groundwater levels in the vicinity of site 1 due to the predominating influence of higher rates of recharge in surrounding areas. There was virtually no difference in the areas salinised between scenario's 1 and 7. This result has important implications for management. In particular, individual farmers are unlikely to have the impact which could be produced by working cooperatively.

Discharge enhancement (Scenario 8)

The use of windmills to extract groundwater via pumping assumes that all waters are disposed of off-site (say into discharge lakes), and that none of this water is returned to the aquifer. The specified discharge rate of 20 m^3 day^{-1} was chosen, which is typical for windmills, and identical to that selected by Salama *et al.*, (1993*a*).

As in the case of local recharge reduction groundwater pumping at such low discharge rates within the swale at site 1 has negligible impact on heads (Fig. 27). This is attributed to the relatively high transmissivity and specific yield of the aquifer which restricts piezometric declines. This supports our hypothesis on the effectiveness of discharge enhancement based on the measured hydraulic properties of the aquifer. Drawdowns after 20 years were in the order of 5 cm at a radial distance of 40 metres, and undetectable at 200 metres.

Regional recharge reduction upgradient of the study area (Scenario 9)

The impact of local as opposed to regional (upgradient) effects within the study area were evaluated by varying the upgradient boundary condition. Modelling has been undertaken on the assumption that the upgradient boundary condition was increasing at the rate of 0.05 m yr^{-1}, as observed, although a constant boundary condition (fixed at the current level) was also tested. This allowed a comparison between regional and local groundwater impacts within the study area. Scenario 9 is akin to areas upgradient of the study area also participating in some degree of recharge reduction.

The simulation suggests that lateral groundwater inflow from upgradient areas is to some degree detrimental to the efforts of landholders within the model area, particularly in areas situated closest to the upgradient boundary. Figure 28 shows a comparison between fixed and rising boundary conditions at two sites within the study area. One is situated near the eastern (upgradient) boundary whilst the other is situated near the western boundary (site 1). Declining heads are attributable to the 50% recharge reduction specified in both simulations. Near the eastern boundary the declining watertables due to recharge reduction are hampered by the effect of the monotonically rising heads. The increasing difference between the rising and constant boundary condition may result in differences up to 100 cm after 20 years in the east, whilst to

Figure 26:The impact of local treatment on groundwater levels at site 1 (W3)

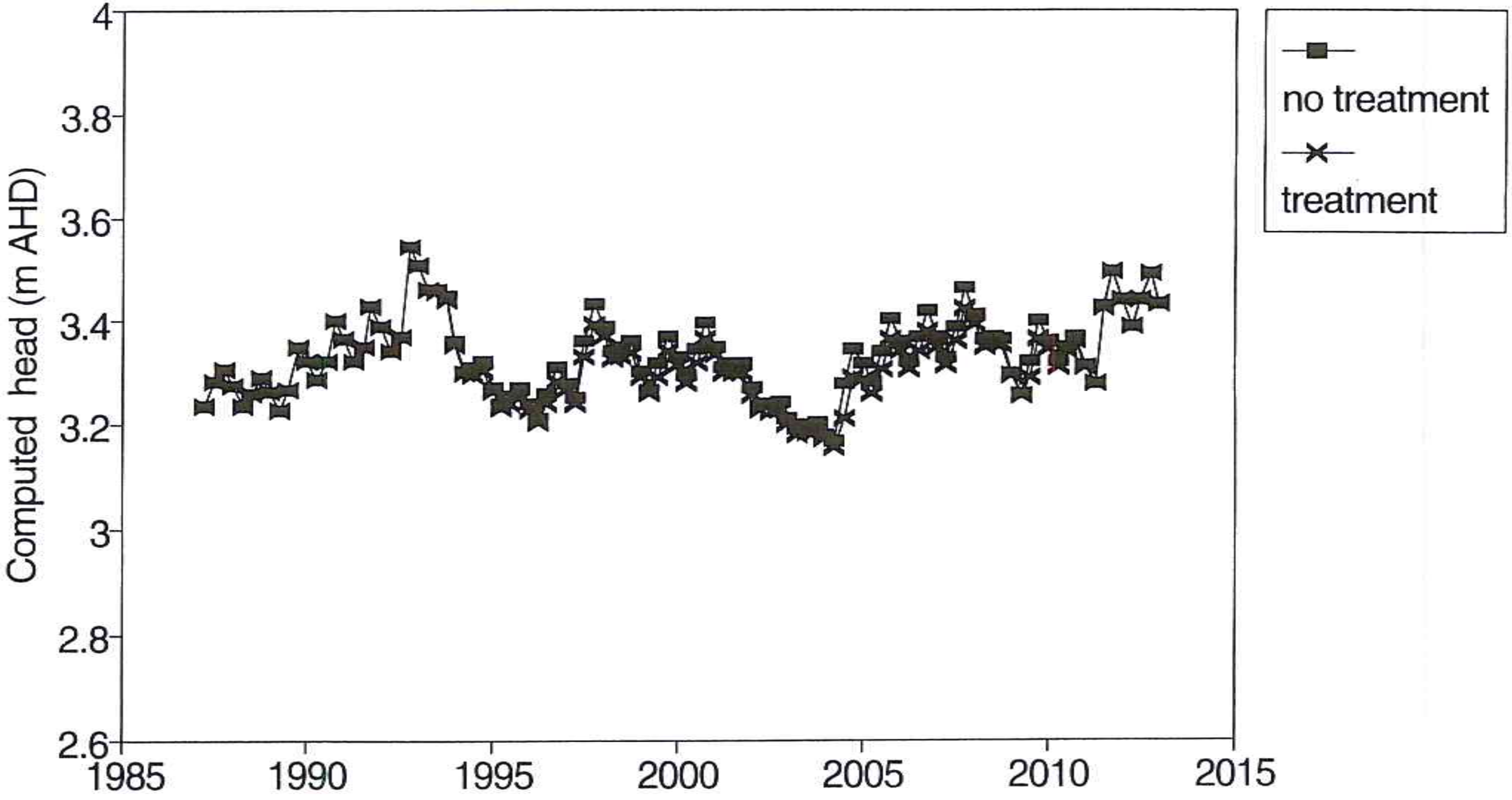


Figure 27: The impact of a windmill on groundwater levels at 40 metres (N4)

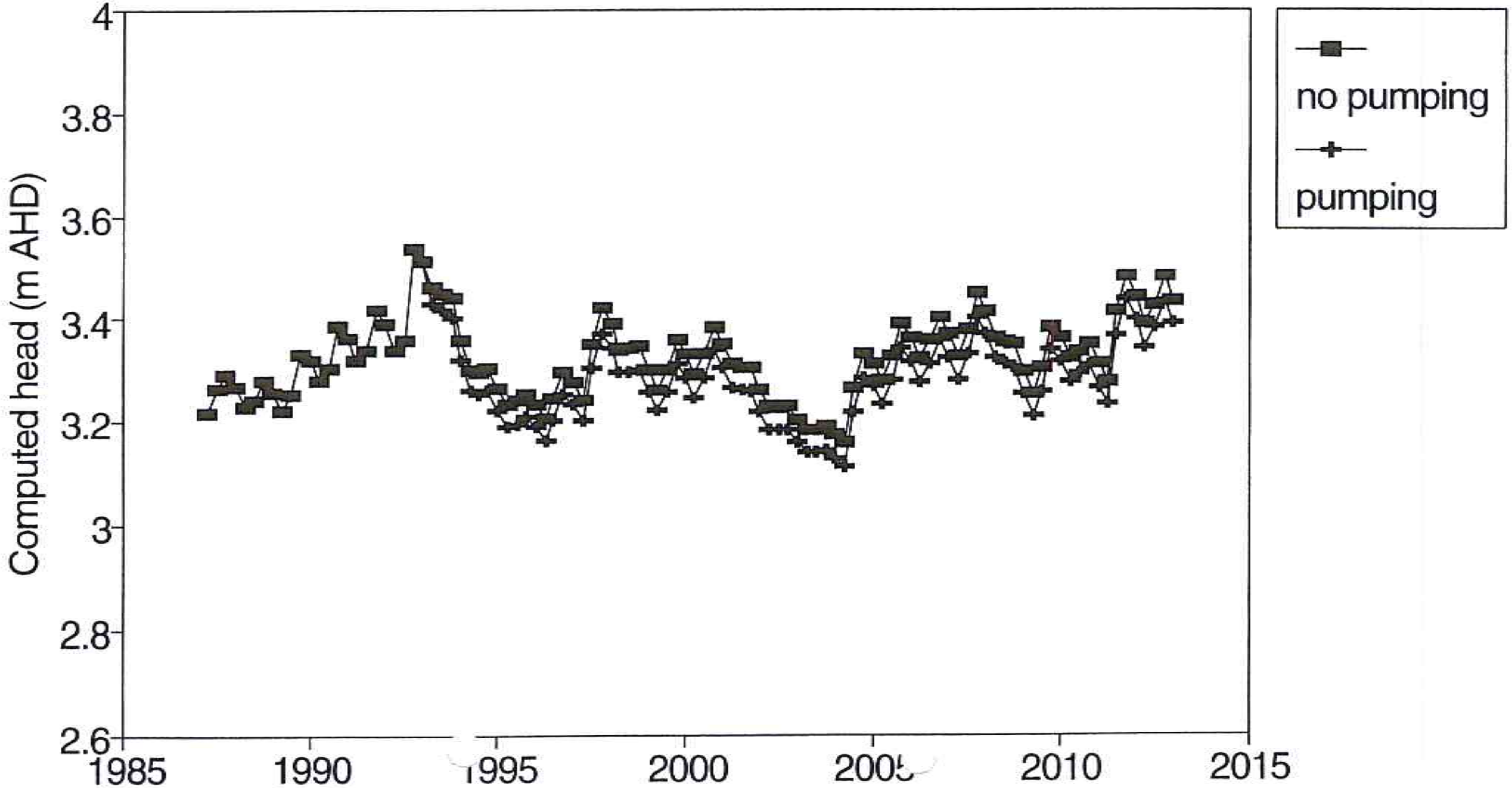
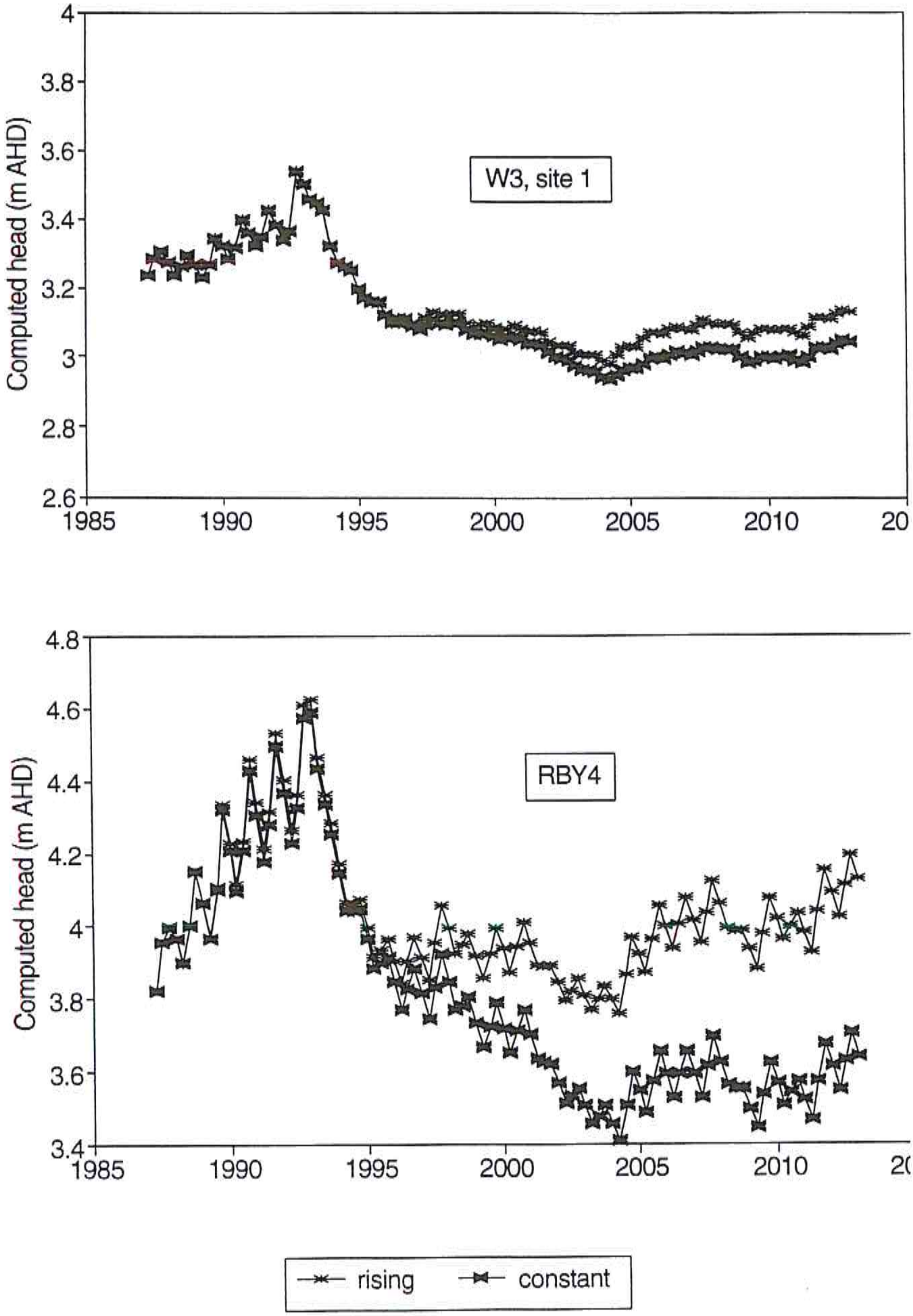


Figure 28: The impact of upgradient boundary condition on waterlevels



the west there is no effect, due partially to the fixed boundary condition in the west, and due partially to the short circuiting effect on groundwater flow to the lakes.

Based on Figure 28 it appears that recharge reduction measures will be effective west of the lakes even if land holders upgradient of the study area do not participate in reducing recharge.

8. CONCLUSIONS

Groundwater flow modelling was undertaken for an area of 105 km^2 situated within a regional groundwater flow system near Cooke Plains in SA. Our initial approach was to develop a broad-mesh model to test our conceptual model, and also for sensitivity analysis of model parameters and boundary conditions.

A subsequent fine-mesh model (for the same area) was shown to be capable of adequately simulating local and large scale processes. Steady state and transient simulations involving modifications in recharge, discharge, hydraulic conductivity, specific yield and boundary conditions were varied over ranges identified from field studies until a satisfactory agreement between computed and measured hydraulic heads was obtained. The calibrated model was used to predict hydraulic heads for the next 20 years for various land management options.

The predictive phase of the modelling has shown that:

Continuing current land management practices (crop/pasture rotation) will result in groundwater level rises of the order of 20 cm, and increased land salinisation of 50 ha over the study area in the next 20 years (based on historical rainfall patterns). This represents 13% of the area currently salinised or 0.5% of the model area.

Recharge reduction (such as by establishing lucerne) has the potential to reduce groundwater levels and allow the re-establishment of crops on 180 ha of saline land. However this would require the reduction in recharge of up to 90% which would need more than 90% of the land to be re-established in lucerne. Watertable responses would occur rapidly, and heads would stabilise within 5 to 10 years of recharge reduction.

Recharge reductions of 10% will have negligible impacts on salinity but 50% reductions would reclaim 50 ha of salt affected land over 20 years.

Small scale land management will have virtually no impact on groundwater levels due to the overriding influence of surrounding higher recharge areas. The simulations show that expanding the area of farmland where recharge reduction is undertaken, will result in larger declines in groundwater levels.

Discharge enhancement through the use of windmills has little impact on groundwater levels due to the high transmissivity and specific yield of the aquifer.

The impacts of land treatment in the study area are diminished to some degree especially east of the old discharge areas the effects of continuing high recharge rates in upgradient areas. However, the modelling shows that under current hydrological conditions, local processes dominate, and therefore efforts to reverse salinisation through recharge reduction by landholders in the study area are viable.

9. ACKNOWLEDGMENTS

The authors are grateful to the members of the Coomandook Landcare Group for their co-operation and assistance over the course of this study. We are particularly indebted to Ian Wilson and Peter Ifould who generously allowed and supported the field studies which were undertaken on their properties. Steve Barnett (DME) and Andrew Hansen (Landcare Group) provided groundwater level data for the model calibration. Steve Barnett, Don Armstrong (consulting hydrogeologist) and David Williamson (CSIRO Division of Water Resources, Perth) provided helpful advice during the calibration of the model. Steve and Don also reviewed an earlier version of the manuscript. The production of the maps was greatly enhanced through digitisation by Anne McKenzie (CSIRO Division of Water Resources, Perth).

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APPENDIX 1: PIEZOMETRIC LEVEL DATA

SITE I

	N1	N2	N4	N5s	N5d	N7s	N7d	N9	N10	N11s	N11d	W1
Ground level	7.387	4.080	5.457	3.775	3.837	3.500	3.476	3.785	9.199	7.058	7.058	5.693
Base elevation	-0.7	-2.4	0.7	2.6	-8.0	2.5	-13.1	1.8	0.8	-4.9		-4.4
02 Aug 90	3.453	3.293	3.539	3.522	3.635	3.539	3.522		3.554	3.553		3.526
15-Aug 90	3.491	3.418	3.605	3.667		3.537			3.584	3.551		3.542
31-Aug 90	3.489	3.433	3.577	3.560	3.656	3.546	3.483		3.595	3.586		3.557
09 Oct 90	3.365	3.383	3.430	3.430	3.488	3.416	3.422		3.508	3.523		3.439
31-Oct-90	3.493	3.364	3.443	3.531	3.560	3.445	3.422		3.492	3.511		3.392
28-Nov 90	3.439	3.332	3.415	3.412	3.400	3.396	3.370		3.458	3.479		3.398
15-Jan-91	3.413	3.306	3.397	3.374	3.478	3.330	3.341		3.445	3.464		3.397
31-Jan-91	3.402	3.317	3.398	3.432	3.538	3.379	3.343		3.443	3.503		3.400
06-Mar 91	3.411	3.318	3.411	3.395	3.518	3.426	3.373		3.464	3.483		3.418
28-Mar 91	3.382	3.327	3.395	3.389	3.484	3.367	3.314		3.448	3.463		3.466
02-May 91	3.387	3.332	3.415	3.430	3.492	3.393	3.373		3.447	3.450		3.438
07-Jun 91	3.409	3.347	3.471	3.473	3.602	3.495	3.458		3.484	3.463		3.416
21-Jun 91	3.422	3.357	3.501	3.458	3.586	3.490	3.451		3.507	3.493		3.443
16-Jul 91	3.452	3.387	3.534	3.508	3.626	3.530	3.488		3.554	3.526		3.483
23 Aug 91	3.442	3.382	3.527	3.513	3.486	3.486	3.487		3.534	3.521		3.456
27 Sep 91	3.442	3.444	3.482	3.458	3.468	3.476	3.439	3.569	3.528			3.458
03-Oct-91	3.362		3.354	3.328	3.336	3.325	3.328	3.357		3.478	2.287	
31-Oct 91	3.357	3.340	3.354	3.325	3.330	3.321	3.325	3.352	3.445	3.473	2.284	
19 Nov 91	3.387	3.377	3.392	3.368	3.366	3.285	3.346	3.382	3.456	3.480	2.367	
04 Dec-91												
[illegible]	3.369	3.354	3.369	3.356	3.341	3.330	3.336	3.379	3.457			
22-Jan 92	3.364	3.359	3.374	3.368	3.331	3.370	3.351	3.397	3.453	3.476	2.474	
24-Jan 92												3.588
06-Feb 92												
19-Feb-92	3.347	3.345	3.361	3.368	3.350	3.389	3.338	3.387	3.442	3.458	2.507	3.588
26-Mar-92	3.327	3.327	3.344	3.356	3.336	3.380	3.328	3.387	3.425	3.448	2.542	3.568
28-Apr-92								3.448		3.466	2.589	3.593
05-Jun-92	3.363	3.363	3.402	3.417	3.383	3.397	3.367	3.435	3.469	3.485	-0.221	3.494
10-Jul-92	3.402	3.412	3.459	3.448	3.436	3.475	3.423	3.472	3.482	3.498	-0.058	3.513
10-Aug 92	3.437	3.483	3.548	3.518	3.514	3.529	3.510	3.549	3.537	3.538	-1.551	3.506
11-Sep-92	3.510	3.531	3.584	3.547	3.544	3.565	3.543	3.587	3.609	3.605		3.593
20-Oct-92												
27-Nov-92	3.687	3.645	3.640	3.593	3.587	3.600	3.593	3.600	3.673	3.669	-0.664	
13-Dec-92	3.696	3.636	3.623	3.573	3.566	3.556	3.578	3.585	3.664	3.669	-0.555	3.681
03-Feb-93	3.669	3.610	3.565	3.552	3.528	3.537	3.548	3.585	3.651	3.680		3.668
08 Mar-93			3.550									
05 Apr-93				3.540	3.505	3.503	3.521			3.625		

	W3s	W3d	W4s	W4d	W5	W6	PX	PY	PZ	X1	X2	X3	X4	X5	X8	X6	X7
Ground level	3.752	3.737	4.343	4.292	7.600	11.515	3.865	4.671	3.816	9.748	3.864	3.779	3.798	8.277	6.657	3.677	3.638
Base elevation	2.7	-2.7	2.4	-19.9	0.5	0.1				-7.4	-0.7	-5.0			-4.9	0.8	-2.8
02 Aug 90	3.400	3.492	3.530	3.640	3.548	3.530											
15-Aug 90	3.546		3.584		3.557	3.573											
31-Aug 90	3.478	3.504	3.563	3.848	3.587	3.576											
09 Oct 90	3.436	3.455	3.488	3.851	3.600	3.615											
31-Oct-90	3.538	3.543	3.482	3.799	3.595	3.616											
28-Nov 90	3.415	3.426	3.446	3.764	3.567	3.586											
15-Jan-91	3.407	3.356	3.431	3.746	3.540	3.548											
31-Jan-91	3.375	3.373	3.432	3.733	3.531	3.546											
06-Mar 91	3.313	3.420	3.441	3.715	3.527	3.526											
28-Mar 91	3.361	3.382	3.418	3.699	3.501	3.518											
02-May 91	3.418	3.389	3.415	3.693	3.477	3.474											
07-Jun 91		3.459	3.476	3.710	3.480	3.481											
21-Jun 91		3.448	3.484	3.727	3.502	3.481											
16-Jul 91		3.495	3.541	3.778	3.535	3.512											
23 Aug 91		3.532	3.511	3.764	3.557	3.556											
27 Sep 91		3.444	3.499		3.569	3.556											
03-Oct-91		3.352	3.401	3.700	9.075		3.497	3.302	3.389								
31-Oct 91		3.352	3.401	3.700			3.492	3.390	3.383								
19 Nov 91		3.397	3.433	3.710			3.534	3.408	3.399								
04 Dec-91			3.421	3.710													
[illegible]			3.409				3.512	3.382	3.009								
22-Jan 92			3.410	3.665			3.511	3.384	3.381								
24-Jan 92																	
06-Feb 92										3.353					3.502	2.907	3.050
19-Feb-92			3.396	3.652			3.504	3.364	3.377	3.379	3.350	3.457	3.336	3.062	3.502	2.838	3.022
26-Mar-92	3.385		3.375	3.630		3.466	3.485	3.347	3.364	3.351	3.313	3.496	3.178	3.233	3.475		3.077
28-Apr-92	3.432		3.458	3.085		3.464				3.390	3.373	3.424	3.388	3.229	3.485		3.357
05-Jun-92	3.425		3.419	3.563		3.495	3.487	3.399	3.390	3.388	3.347	3.359	3.360	3.227	3.489		3.305
10-Jul-92	3.426						3.537			3.393	3.363	3.359	3.383	3.222	3.492		3.425
10-Aug 92	3.530		3.536	3.634			3.585	3.546	3.569	3.443	3.443	3.444	3.433	3.240	3.545		3.602
11-Sep-92			3.576	3.700			3.627	3.575	3.600	3.522	3.501	3.505	3.498	3.292	3.599	3.235	3.619
20-Oct-92													3.613				3.685
27-Nov-92			3.640	3.808			3.708	3.642	3.619	3.672	3.636	3.641	3.648		3.705	3.557	3.646
13-Dec-92			3.636	3.809			3.708	3.635	3.608	3.683	3.628	3.630	3.647	3.628	3.710		
03-Feb-93	3.581	3.564	3.621	3.802			3.668	3.598	3.580	3.682	3.504	3.604	3.608	3.639	3.732		3.330
08 Mar-93											3.576	3.579	3.581			3.076	3.212
05 Apr-93														3.544	3.646	3.002	3.160

SITE II

	S1	S2	S3	S4s	S4d (m AHD)	S5	E1	E2	E3	E4
Ground level	5.059	5.147	2.957	5.236	5.388	5.547	4.126	3.382	4.336	4.660
02-May-91	2.740	2.719	2.674	2.980		2.659	2.789	2.739	2.665	2.643
07-Jun-91	2.741	2.717	2.750	2.988		2.652	2.747	2.967	2.685	2.658
18-Jul-91	2.864	2.849	2.800	3.110		2.778	2.935	2.886	2.776	2.755
27-Sep-91	2.788	2.769	2.722	3.028		2.698	2.837	2.787	2.716	2.693
16-Dec-91	2.727	2.699	2.640	2.967		2.638	2.782	2.732	2.653	2.635
23-Dec-91	2.719	2.709	2.645	2.965	2.720	2.628	2.782	2.747	2.653	2.625
21-Jan-92	2.729	2.704	2.645	2.960	2.720	2.633	2.787	2.732	2.653	2.630
19-Feb-92	2.721	2.696	2.633	2.957	2.720	2.626	2.782	2.727	2.645	2.623
26-Mar-92				2.955	2.707	2.626	2.780	2.722	2.638	2.615
28-Apr-92				2.964	2.730	2.620	2.798	2.746	2.637	2.610
05-Jun-92				2.982	2.653	2.643	2.808	2.746	2.662	2.638
10-Jul-92				2.985	2.690	2.643	2.822		2.678	
10-Aug-92				3.056	2.680	2.703	2.869	2.849	2.733	2.705
11-Sep-92				3.175	2.826	2.823	2.959	2.949	2.862	2.839
20-Oct-92										
27-Nov-92		2.989	2.875	3.220	2.980	2.883	2.967	2.947	2.941	2.928
13-Dec-92				3.228	3.056	2.898	2.990	2.959	2.944	2.933
03-Feb-93	2.967		2.843	3.185	2.918	2.880	2.956	2.895	2.888	2.877
08-Mar-93	2.895		2.835							
05-Apr-93	2.874		2.832	3.114	2.670		2.918	2.854	2.793	2.771

REMAINING PIEZOMETERS

		RBY4	RBY5	RBY7
04/03/87	1.915	3.933	4.027	5.494
01/04/87	1.960	3.888	3.997	5.459
04/05/87	2.050	3.798	3.962	5.379
26/05/87	1.930	3.918	4.037	5.434
14/07/87	1.665	4.183	4.282	5.539
13/09/87	1.635	4.213	4.317	5.619
03/11/87	1.850	3.998	4.127	5.559
01/02/88	1.911	3.937	4.027	5.539
09/03/88	2.000	3.848	3.937	5.499
08/06/88	1.840	4.008	4.097	5.499
13/09/88	1.870	3.978		5.559
06/12/88	2.020	3.828	3.957	5.419
06/03/89	2.100	3.748	3.887	5.389
20/04/89	2.050	3.798	3.887	5.329
06/06/89	2.060	3.788	3.877	5.309
25/07/89	1.640	4.208	4.267	
05/09/89	1.620	4.228	4.297	
25/10/89	1.840	4.008	4.087	
07/12/89	1.900	3.948	4.037	
25/01/90	1.930	3.918	4.007	
08/03/90	2.060	3.788	3.937	
20/ 4/90	2.020	3.828	3.947	
8/ 6/90	2.060	3.788	3.897	
13/ 9/90	1.480	4.368	4.457	
22/ 1/91	1.830	4.018	4.077	
4/ 2/91	1.910	3.938	4.067	
7/ 3/91	1.940	3.908	3.997	
13/ 6/91	1.820	4.028	4.137	
1/ 8/91	1.620	4.228	4.277	
19/ 9/91	1.540	4.308		
22/11/91	1.830	4.018	4.077	
30/ 1/92	1.920	3.928	3.977	
2/ 3/92	1.950	3.898	3.957	
23/ 4/92	1.920	3.928	3.977	
30/ 6/92	1.760	4.088		
24/ 7/92	1.660	4.188	4.277	
11/ 9/92	1.420	4.428	4.497	
27/10/92	1.420	4.428	4.467	

	RBY10
26/05/87	3.519
14/07/87	3.942
03/11/87	3.475
08/07/88	3.93
13/09/88	3.74
06/12/88	3.47
25/07/89	3.91
05/09/89	3.85
25/10/89	3.54
07/12/89	3.55
25/01/90	3.46
08/03/90	3.45
20/ 4/90	3.45
4/ 6/90	3.45
13/ 9/90	4.18
4/ 2/91	3.45
7/ 3/91	3.46
13/ 6/91	3.68
1/ 8/91	3.81
19/ 9/91	4.19
2/ 3/92	3.46
30/ 6/92	3.66
27/10/92	3.86

	RBY12
14/07/87	4.451
08/07/88	4.481
13/09/88	4.281
25/07/89	4.621
05/09/89	4.641
25/10/89	4.241
25/01/90	4.241
13/ 9/90	4.701
1/ 8/91	4.351
19/ 9/91	4.431
24/ 7/92	4.501
11/ 9/92	4.741
27/10/92	4.531
20/ 4/91	dry
4/ 2/91	dry
13/ 6/91	dry
30/ 6/92	dry

	RBY2	RBY3
		3.645
01/04/87	3.63	3.69
04/05/87	3.835	3.7
26/05/87	3.75	3.842
14/07/87	3.955	3.825
13/09/87	3.705	3.76
03/11/87	3.62	3.732
01/02/88	3.609	3.68
09/03/88	3.59	3.82
08/06/88	3.98	3.76
13/09/88	3.79	3.63
06/12/88	3.55	3.57
06/03/89	3.49	3.56
20/04/89	3.51	3.62
06/06/89	3.53	3.79
25/07/89	3.82	3.89
05/09/89	3.91	3.79
25/10/89	3.75	3.73
07/12/89	3.68	3.69
25/01/90	3.59	3.64
08/03/90	3.58	3.68
20/ 4/90	3.85	3.54
8/ 6/90	3.58	3.95
13/ 9/90	4.06	3.72
22/ 1/91	3.66	3.59
4/ 2/91	3.63	3.63
7/ 3/91	3.57	3.74
13/ 6/91	3.96	3.78
1/ 8/91	3.85	3.87
19/ 9/91	4.07	3.72
22/11/91	3.66	3.62
30/ 1/92	3.6	3.68
2/ 3/92	3.96	3.63
23/ 4/92	3.79	3.68
30/ 6/92	3.76	3.82
24/ 7/92	4.03	3.91
11/ 9/92	4.06	4.03
27/10/92	4.11	

	RBY 6	RBY 9
04/05/87	3.513	
26/05/87	3.583	[illegible]
14/07/87	3.843	[illegible]
13/09/87	3.818	
03/11/87	3.613	[illegible]
01/02/88	3.578	
09/03/88	3.503	
08/06/88	3.693	[illegible]
13/09/88	3.643	[illegible]
06/12/88	3.523	[illegible]
06/03/89	3.463	
20/04/89	3.443	
06/06/89	3.433	
25/07/89	3.833	[illegible]
05/09/89	3.903	[illegible]
25/10/89	3.673	[illegible]
07/12/89	3.623	[illegible]
25/01/90	3.563	[illegible]
08/03/90	3.503	
20/ 4/90	3.463	
8/ 6/90	3.343	
13/ 9/90	3.973	[illegible]
22/ 1/91	3.623	
4/ 2/91	3.483	
7/ 3/91	3.343	[illegible]
13/ 6/91	3.603	[illegible]
1/ 8/91	3.793	[illegible]
19/ 9/91	3.933	[illegible]
22/11/91	3.623	
30/ 1/92	3.523	
2/ 3/92	3.533	[illegible]
23/ 4/92	3.553	
30/ 6/92	3.693	[illegible]
24/ 7/92	3.813	
11/ 9/92	3.813	
27/10/92	3.933	[illegible]

	LC(luc)	LC(con)
23/ 3/91	3.871	3.729
22/ 4/91	3.881	3.719
22/ 5/91	3.901	3.719
26/ 6/91	4.121	3.854
28/ 7/91	4.331	3.969
8/91	4.081	3.724
21/ 8/91	4.291	3.999
11/ 9/91		
29/ 9/91	4.311	4.049
24/10/91	4.161	3.974
6/11/91	3.481	3.864
27/11/91	3.681	3.794
29/11/91		
16/12/91	3.511	3.394
1/92	3.401	3.314
3/92	3.441	3.264
4/93	3.361	3.254
6/92	3.601	3.564
7/92	3.691	3.464
8/92	3.821	3.554

Appendix 2: Conceptual Model and Groundwater Budget

The groundwater budget described is based on the studies of Barnett, (1992) and Walker *et al.*, (1992*b*). Field measurements in conjunction with simple analytical models have been used to estimate fluxes. The conceptual model was based on the groundwater budget presented here in conjunction with piezometric data and hydrogeological information. It forms the framework for the development of the groundwater model(s). The model domain, its discretisation in space and time, as well as the range of input parameter values used to provide a model calibration rely on the conceptual understanding of the groundwater system.

GROUNDWATER BUDGET

For a defined region over a given period of time, the inflow minus the outflow is the change in storage. The groundwater budget (which describes this balance) may be expressed as:

$$R_g - I_g = ET_g + O_g \pm \Delta S_g \qquad \text{(A1)}$$

where R_g = local groundwater recharge
I_g = lateral groundwater inflow
ET_g = groundwater evapotranspiration
O_g = lateral groundwater outflow
ΔS_g = change in groundwater storage

An estimate is made of each component of equation (A1), in addition to the total groundwater storage and groundwater velocity.

TOTAL GROUNDWATER STORAGE

The total volume of groundwater in storage, V is given by:

$$V = Ad\varepsilon \qquad \text{(A2)}$$

where A = surface area of study site (10^8 m^2)
d = saturated thickness of aquifer (20 m)
ε = aquifer porosity (0.3)

Therefore it follows that V = 600.000 ML
this is equivalent to 6000 mm of water over the study area

ANNUAL INCREASE IN STORAGE

The average long term increase in groundwater levels provides the best approach for estimating the additional increase in groundwater storage as a result of increased recharge rates.

Assuming a rise of 0.10 m yr^{-1} and a specific yield of 0.05 gives a net increase of 5 mm yr^{-1} (500 ML over the study area).

LATERAL GROUNDWATER FLOW

Flow net analysis is based on piezometric levels for March, 1992 (however similar gradients are evident for other times of the year). Flow rate calculations (per unit width) are based on the Dupuit equation:

$$q=\frac{k(h_1^2-h_2^2)}{2l} \quad (A3)$$

where q = groundwater flow rate (per unit width)
k = hydraulic conductivity of aquifer
h_1 = hydraulic head (upslope), measured from base of aquifer
h_2 = hydraulic head (downslope) measured from base of aquifer
l = distance between h_1 and h_2

To determine the total groundwater flow, Q into a given area, we multiply q by the length over which flow occurs.

Therefore

$$Q=\frac{k(h_1^2-h_2^2)L}{2l} \quad (A4)$$

INFLOW

Using the following values to determine groundwater inflow from the eastern boundary of the study area:

k=20 m day^{-1}; d=20 m: h_1=21 m; h_2=20 m; l=1430 m; L=9,500 m

from equation A4 we obtain:

$Q = 990$ ML yr^{-1}
this is equivalent to 10 mm yr^{-1} for the study area

OUTFLOW

Using the following values to determine groundwater outflow through the western boundary of the study area:

$k=20$ m day^{-1}; $d=20$ m; $h_1=17.5$ m; $h_2=17$ m; $l=1670$ m; $L=9.500$ m

once again from equation 4 we obtain:

$Q = 360$ ML yr^{-1}
this is equivalent to 4 mm yr^{-1} for the study area

GROUNDWATER VELOCITY

The "Darcy" groundwater velocity is given as:

$$v=\frac{k}{\varepsilon}\frac{\partial h}{\partial x} \qquad \text{(A5)}$$

where

v = groundwater velocity
$k = dh/dx$ = hydraulic gradient across study area
ε = porosity of aquifer

Using values of hydraulic conductivity of 20 m day^{-1}, gradient of 5×10^{-4} and porosity of 0.3 gives a velocity of 12 m yr^{-1}. This indicates the travel time for groundwater across the study area (11 km) is approximately 900 years.

DISCHARGE RATES

Field measurements (based on a time series solute profiles in the unsaturated zone) in the salinised swales suggest a mean annual discharge of approximately 100 mm yr^{-1}. Flow net analysis of an older discharge area suggests a flux in the order of 500 mm yr^{-1}.

RECHARGE RATES

The mean annual post cleared recharge rate is estimated to be approximately 20 mm yr^{-1} from field measurements. Hydrograph analysis indicates that recharge may range between around 10 to 40 mm yr^{-1} between wet and dry years.

GROUNDWATER BUDGET

Substituting the components of the groundwater budget already calculated (in ML) into equation A1 gives another method for calculating recharge:

$$R_g + 990 = 1410 + 360 + 500$$

$$R_g = 1280 \text{ ML}$$

This is equivalent to 13 mm over the study area, and is within the range of 10 to 40 mm determined independently.

APPENDIX 3: Summary of model simulations

BROAD-MESH MODEL

RUN NUMBE	GRID SIZE	RECHAR (mm/yr)	DISCHARGE antecedent (mm/yr)	DISCHARGE recent	T (m2/day)	S	TIME OF MODEL SIMULATION years	TIME OF MODEL SIMULATION stresses	BOUNDARY CONDITION west (m)	BOUNDARY CONDITION east	PIEZOMETERS USED FOR RMS	RMS error (m)	COMMENTS
	STEADY STATE												
1	21x24	0	500	100	680-840	-	1	-	2.5	6		0.49	
2	24x25	10	500	100	680-840	-	10	-	2.5	6		-	
3	24x25	10	500	100	680-840	-	10	-	2.5	6		0.35	
4	24x25	5	500	100	680-840	-	10	-	2.5	6	RBY2/3	0.36	
5	24x25	5	4	100	680-840	-	10	-	2.5	6	RBY4	1.05	
6	24x25	10	500	100	340-420	-	10	-	2.5	6	RBY6	0.6	
7	24x25	20	500	100	340-420	-	10	-	2.5	6	RBY7	0.38	
8	24x25	15	500	100	340-420	-	10	-	2.5	6	RBY9	0.39	
9	24x25	15	500	100	680-840	-	10	-	2.5	6	RBY10	0.41	
10	24x25	15	500 800	0	340-420	-	10	-	2.5	6	RBY12	0.98	500 (large)/800 (small)
11	24x25	15	500	50	340-420	-	10	-	2.5	6	LC(luc)	0.39	
12	24x25	15	500	100	340-420	-	10	-	2.5	6	LC(con)	0.43	discharge in cell [18,22] = 300 mm/yr
13	24x25	15	500	100	340-420	-	10	-	2.5	6	X1	0.43	constant head for cell [22,22]
14	24x25	15	500	100	340-420	-	10		2.2	6	X5	0.5	
15	24x25	15	500	100	340-420	-	10	-	2.5	6	X6	0.46	constant head for cell [21,23]
16	24x25	15	500	100	340-420	-	10	-	2.5	6	X7	0.4	
17	24x25	15	500	100	340-420	-	10	-	2.5	6	X8	0.7	
18	24x25	15	500	100	320-240	-	10	-	2.5	6	W1	0.3	
22	24x25	30	1000	100	500-340	-	10	-	2.5	6	W6	0.87	varying basement depth (-19 east to -15 m AHD west)
23	24x25	30	500	100	340-420	-	10	-	2.5	6	N11	-	
24	24x25	20	700	100	340-420	-	10	-	2.5	6	E1	-	
25	24x25	20	600	100	340-420	-	10	-	2.5	6	E4	-	
34	24x25	15	400	100	340-420	-	10	-	2.5	6		0.38	
35	24x25	15	600	100	340-420	-	10	-	2.5	6		0.68	
36	24x25	15	500	200	340-420	-	10	-	2.5	6		0.41	
42	24x25	15	500	100	340-420	-	10	-	2.5	6			position of south-eastern boundary aletered
43	24x25	30	500	100	340-420	-	10	-	2.5	6			(ie. cells [22,22] and [23,21] added)
44	24x25	20	500	100	340-420	-	10	-	2.5	6			
45	24x25	5	500	100	340-420	-	10	-	2.5	6			
	TRANSIENT												
19	24x25	15	0	0	340-420	0.05	0.5	1	2.5	6			
20	24x25	30	0	0	340-420	0.05	0.5	1	2.5	6			
21	24x25	15	500	100	340-420	0.05	1	4	2.5	6			sensitivity of time steps and time step multiplier
26	24x25	15	500	100	340-420	0.05	6	24	2.5	6			sensitivity of time steps and time step multiplier
27	24x25	15	500	100	340-420	0.05	6	24	2.5	6	As		(calculate)
28	24x25	10-20	500	100	340-420	0.05	6	24	2.5	6	above		recharge of 15 mm/yr in years 1,3,5,6, 10 mm/yr in year 2 and 20 mm/yr in year 4
29	24x25	15	500	100	340-420	0.05	5.75	23	2.5	6			first time interval ommitted
30	24x25	20	500	100	340-420	0.1	5.75	23	2.5	6			"
31	24x25	20	500	100	340-420	0.02	5.75	23	2.5	6			"
32	24x25	20	500	100	340-420	0.02	17.75	71	2.5	6			first run beyond 6 years
33	24x25	20	500	100	340-420	0.05	5.75	23	2.5	6			
37	24x25	20	500	100	340-420	0.05	18	72	2.5	6			
38	24x25	20-2	500	100	340-420	0.05	18	72	2.5	6			20 mm/yr for first 6 years, then 2 mm/yr for years 7 to 18
39	24x25	20-2	500-200	100	340-420	0.05	18	72	2.5	6			step change in recharge (as in run38), discharge declines from years 7 to 12
40	24x25	20	500	100	340-420	0.05	18	72	2.5	6-6.85			general head boundary condition (upgradient)
41	24x25	20	500	100	340-420	0.05	18	72	2.5	6			

APPENDIX 3: Summary of model simulations

FINE-MESH MODEL

RUN NUMBE	GRID SIZE	RECHAR (mm/yr)	DISCHARGE antecedent (mm/yr)	DISCHARGE recent	T (m2/day)	S	TIME OF MODEL SIMULATION years	TIME OF MODEL SIMULATION stresses	BOUNDARY CONDITIONS west (m)	BOUNDARY CONDITIONS east (m)	RMS error (m)	COMMENTS
		STEADY STATE										
50	46x46	15	500	100	340-420	-	10	-	2.5	6	0.78	grid found to have errors
51	46x46	15	500	100	340-420	-	10	-	2.5	6	0.75	
52	46x47	15	500	100	340-420	-	10	-	2.5	6	0.74	
53	47x59	15	800	100	340-420	-	10	-	2.5	6	0.45	final mesh change
54	47x59	20	500	100	340-420	-	10	-	2.5	6	0.35	
58	47x59	20	500	100	340-420	-	10	-	2.5	5.6	0.34	
62	47x59	20	500	100	340-420	-	10	-	2.5	5.6	0.39	change in position of boundary in southeastern corner of model
66	47x59	20	500	100	340-420	-	10	-	2.5	5.7		position of south-eastern boundary aletered
67	47x59	20	500	100	340-420	-	10	-	2.5	6		ie. cells [22,22] and [23,21] added
		TRANSIENT										
55	47x59	15	500	100	340-420	0.05	6	24	2.5	6-6.25	0.39	
56	47x59	20	500	100	340-420	0.05	6	24	2.5	6-6.25	0.29	
57	47x59	variable	ET depth =	1.3 m	340-420	0.05	6	24	2.5	6-6.25	0.35	first use of exteinction depth and variable recharge based on rainfall
59	47x59	variable		1.3	340-420	0.05	6	24	2.5	5.6-5.85	0.33	upgradient boundary heads reduced
60	47x59	variable		5	340-420	0.05	6	24	2.5	5.6-5.85	1.32	
61	47x59	variable		2	340-420	0.05	6	24	2.5	5.6-5.85	0.47	
63	47x59	variable		1.3	340-420	0.05	6	24	2.5	5.6-5.85	0.49	
64	47x59	variable		0.5	340-420	0.05	6	24	2.5	5.6-5.85	0.54	
65	47x59	variable		1.3	170-205	0.05	6	24	2.5	5.6-5.85	0.58	
68	47x59	17 (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		
69	47x59	17 (avg)		0.5	170-205	0.05	6	24	2.5	5.7-5.95		
70	47x59	25 (avg)		0.5	170-205	0.05	6	24	2.5	5.7-5.95		
71	47x59	17 (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		elevation of second lake =3.5 m AHD
72	47x59	12.5 (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		
73	47x59	17* (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		recharge of 34 mm/yr in areas where watertable less than one metre
74	47x59	25 (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		
75	47x59	17 (avg)		1.3	170-205	0.05	6	24	2.5	5.7-5.95		
76	47x59	25* (avg)		1.3	170-205	0.05	6	24	2.2	5.7-5.95		
77	47x59	25* (avg)		1.3	170-205	0.05	6	24	2.2	5.7-5.95		elevation for [14,6] amd [15,6] raised from 3.5 to 10 (Conductance = 840 for rows 43-46)
78	47x59	25* (avg)		1.3	340-410	0.05	6	24	2.2	5.7-5.95		
79	47x59	25* (avg)		1.3		0.05	6	24	2.2	5.7-5.95		conductance = 420 throughout
80	47x59	25* (avg)		1.3	340-410	0.05	6	24	2.2	5.7-5.95		varying conductance
81	47x59	25* (avg)		1.3		0.05	6	24	2.2	5.7-5.95		varying conductance
82	47x59	25* (avg)		1.3		0.05	6	24	2.2	5.7-5.95		varying conductance
83	47x59	25* (avg)		1.3		0.05	6	24	2.2	5.7-5.95		varying conductance
84	47x59	25* (avg)		1.3		0.05	6	24	2.2	5.7-5.95		varying conductance
85	47x59	25* (avg)		0.5		0.05	6	24	2.2	5.7-5.95		
86	47x59	25 (avg)		0.5		0.05	6	24	2.2	5.7-5.95		
87	47x59	25 (avg)		0.6		0.05	6	24	2.2	5.7-5.95		
88	47x59	25 (avg)		0.6		0.02	6	24	2.2	5.7-5.95		reduced specific yield