TECHNICAL BASIS FOR THE PREDICTED IMPACTS OF RELOCATING REDGRAVE ABSTRACTION TO BOREHOLE B

1. INTRODUCTION

This technical note summarises the work carried out by Entec in Stage II of the relocation modelling study as follows:

- interpretation of results from the 50 day pumping test on Borehole B
- development of a regional groundwater flow model incorporating the concepts derived from this interpretation and from other work in Stage II.
- Calibration of the model against 20 years of historic data
- use of the model to predict the impacts of relocating to Borehole B.

Preliminary impact predictions based on this work have already been reported in our letter reference 15558C668 and are not repeated here. The aim of this note is to describe the work on which these predictions have been based to enable members of the Project Liaison Group to review the adequacy of the modelling tool used. As such it provides background information for those attending the review meeting in Ashbocking on 7 May 1996.

2. BOREHOLE B PUMPING TEST

2.1 Data Assessed

Data up to 28 April have been received and assessed. This includes all of the constant rate abstraction test comprising:

- rainfall
- abstraction and observation borehole water levels
- wellhead chemistry and analytical laboratory results
- abstraction rates
- surface water flows.

It also includes 31 days of water level recovery data and, following the preliminary interpretation reported to the Project Liaison Group in our letter 15558C627 (dated 1 April 1996), all of these data sets have been revisited.

Throughout the test, abstraction rates were held close to 42.3 l/sec.

2.2 Water Level Impacts

2.2.1 Data Presentation

In Figure 2.1 three cross-sections have been drawn through Borehole B towards Bressingham, Royden Fen and Great Fen respectively (section lines are shown on Figure 2.4). These sections illustrate the known geology from all available borehole logs and show Chalk and drift water levels in m AOD recorded before the start of the test and at the end, before switching off the pumps. The approximate stage elevations of the River Waveney are also shown.

Figures 2.2 and 2.3 shows changes in water level with time for all of the Chalk and drift observation boreholes monitored during the test with the exception of the sites of Fen Farm and Bier Lane for which digital data have not been received. The changes have been plotted relative to initial readings to enable all the data, for each unit to be included on one figure.

From this plot (and from hard copy plots of Fen Farm and Bier Lane) the boreholes impacted by the test have been identified on the basis of a clear response to both switching the pumps on and switching them off.

Regionally, Chalk water levels not impacted by pumping have shown a mixture of trends through the test period - some rising, some falling but most roughly stable. As no consistent trend has emerged, drawdowns have been simply calculated relative to the water level at the start of abstraction for those boreholes which were impacted.

Drawdowns thus derived in the Chalk after 1, 5, 43 and 50 days have been tabulated in Table 2.1 and contoured areally in Figures 2.4, 2.5, 2.6 and 2.7 respectively.

Finally, for conventional techniques of pumping test analysis the development of drawdown is shown against time for all impacted Chalk boreholes on a semilog plot in Figure 2.8 and against t/r^2 (time/radius squared) on a log-log plot in Figure 2.9. This latter plot is included as, if the aquifer were isotropic and of infinite extent, all the drawdown responses would be expected to plot into a single type curve.

The water level data presented on all above figures is interpreted in the following section.

2.2.2 Interpretation of Water Level Impacts

Several important statements can be made on the basis of the water level data presented.

- No drawdowns were observed north of the River Waveney.

  Although BH23 on Great Fen showed declining water levels before and during the first half of the test, these did not continue to fall and have not shown any recovery response to switching the pump off. It is concluded therefore that BH23 water levels did not respond to pumping. No other boreholes north of the river were seen to respond.

- Chalk drawdowns extended furthest towards the west.

  Clear drawdowns were recorded at Fen Farm, Bier Lane and Waveney Cottage whereas, at comparable distances to the north, south and east, no drawdowns were recorded.

- Chalk water levels over most of the Waveney Valley remained artesian.

  Between Wortham Ling and Redgrave Fen and including Borehole B, pre-test water levels in the Chalk were all in the range 25 to 26 m AOD. As ground levels over the floor of the valley are less than 25 m AOD, the chalk is artesian and, at least at Boreholes B7, near Bressingham, and 23 on Great Fen, levels remained artesian throughout the test (Figure 2.1). It follows that over most of the valley floor, there was no potential for leakage from the surface to the Chalk - any flow would be from the Chalk towards the drift.

- Drift water levels were impacted only on the valley flanks, close to Borehole B.

  The only drift borehole to respond to pumping was Borehole B6b near Wortham Manor where Chalk levels in B6a are confined but not artesian. Elsewhere on Great Fen at BH24 and BH B8, at BH B7b in Bressingham, at Royden and at Redgrave Fens, drift levels all rose during the test in response to rainfall (Figure 2.3).

  Any impacts at Hall Farm Meadow were masked by the rise due to the pumped discharge into the surrounding ditches.

- Chalk drawdown patterns clearly indicate the existence of contrasting zones of transmissivity.

Figures 2.4 to 2.7 show that drawdowns are far from radially symmetrical and suggest the existence of boundaries to the north and south of Borehole B, with a zone of higher transmissivity stretching westwards towards Fen Farm. Modelling work has confirmed that although drawdowns towards the Redgrave abstraction would be greater than if Redgrave were not pumping, this additional 'interference' effect is not sufficient to explain the responses at Fen Farm and Bier Lane. A zone of higher T has to be introduced.

Conventional analysis of the time drawdown data (which assumes an aquifer of infinite horizontal extent) shows it is not possible to fit the early (<1 day) and later (>1 day) data with the same type curve in any assumed aquifer state (confined, leaky, unconfined etc). Theis curve fits to early data from Borehole B or B1 suggest transmissivities in the order of 2000-3000 m^2/day whereas later data from all boreholes suggest apparent values around 400 m^2/day.

Drawdown responses thus indicate a zone of relatively high T around Borehole B with significant boundaries to the north and south.

2.2.3 Nature of Boundaries

The boundary to the south of Borehole B is almost certainly the area of low transmissivity Chalk which has been identified by pumping tests on Boreholes G and F and by the Stage I modelling.

Beneath the River Waveney there is also a boundary. Considering that there was and is no potential for downward flow over most of the valley area, this cannot be a recharge or 'fixed head' boundary. It is therefore concluded that there is also a significant reduction in Chalk transmissivity for lateral flows beneath the River Waveney to the north of Borehole B.

Even by the end of the test Chalk water levels were not approaching equilibrium. This offers further support for the concept of a barrier rather than a recharge boundary beneath the Waveney. Had Chalk drawdowns resulted in significant leakage from the drift along the Waveney valley some levelling off of water levels might have been expected by the end of the test.

The barrier is probably related to the palaeovalley which most borehole and water level evidence suggests contains effectively confining thicknesses of clayey drift sediments. The pumping test results suggest that as well as limiting vertical flows between Chalk and valley floor, the palaeovalley sediments also act as an effective barrier to horizontal flows in the Chalk from one side of the valley to the other.

Further supporting evidence for the concept that the palaeovalley acts as a flow barrier is seen in the water levels sustained on the northern margins of Redgrave and Great Fens (Borehole TM08/500 and 23). These are around 25 to 26 m AOD and modelling work suggests that they are much less impacted by the Redgrave abstraction on the other side of the Fen than would be expected if the Chalk had an isotropic T of 1000 m^2/day as derived by Aspinwalls. The levels can only be reproduced in the model by introducing a zone of low T between the abstraction and observation wells.

The conceptual picture thus emerges of a zonation of chalk transmissivity running parallel to the palaeovalley and providing a strong east-west anisotropy in flows induced by the pumping test. This is consistent with the idea that the palaeovalley has removed high T chalk by erosion.

The drawdowns recorded at Fen Farm and Brier Lane also suggest that within the relatively high T zone to the south of the palaeovalley, flows may be drawn more easily from the west than the east.

2.3 River Flows

Flows in the River Waveney were not impacted by the 50 day pumping test. Against the backdrop of runoff dominated winter flows, any impacts would in any case be very difficult to detect.

2.4 Hydrochemistry

Having now examined the full set of hydrochemical data, conclusions remain unchanged from the preliminary interpretation letter of 1 April.

Water quality variation throughout the test was consistent with the progressive removal of acidified water from the aquifer following borehole acidification. The chemistry stabilised by the end of the test to a very good potable quality with manganese, iron and nitrate values all within Maximum Admissible Concentrations of the 1989 Water Supply Regulations.

Drilling around Borehole B where the Chalk is unconfined has shown that the generally clayey near surface till cover is fairly pervasive in the local vicinity. This is likely to provide useful protection for the abstraction so that the long term water quality prospects are unlikely to be subject to undue risk.

3. REGIONAL MODELLING IN STAGE II

The section summarises how the Stage II model has been formulated highlighting contrasts with the Stage I model as presented in Entec report ref 15558RR248i1 dated 23 June 1995. The changes made to this model are in line with the proposals sent to the EA and Essex and Suffolk Water in our letter 15558C488 of 23 October 1995. Calibration results are subsequently presented and the use of the model for impact prediction is referred to.

3.1 Model Formulation

3.1.1 New Data

Geological data from the new abstraction boreholes drilled around Borehole B have been incorporated into the Redgrave database. This updated database has then been used to contour Chalk rockhead, aquifer depths and, in association with BGS geological map information, to derive drift vertical conductance distributions based on lithology and thickness. These contoured distributions have formed the basis (with some manual edits related to the palaeovalley) of model geometry and recharge distribution.

3.1.2 Stage II Model Grid and Layer Distributions

Mesh intervals of the Stage II model have been changed to reflect the shift of focus from Borehole G to Borehole B by ensuring that Borehole B is surrounded by 200 m x 200 m cells (Figure 3.1).

As in Stage I the model has two layers. The lower layer (Layer 2) comprises the Chalk and any sands and gravels or Crag which directly overlie it. The upper layer (Layer 1) comprises the drift aquifers above the Chalk which, in the main valleys are saturated all year round and which are considered to be in hydraulic continuity with the wetlands. The flow of groundwater in superficial deposits elsewhere is managed in calculations of recharge and runoff, external to the groundwater model.

The extent of active layer 1 cells in the Stage II model is shown in Figure 3.1. These have been removed from the interfluves around Borehole G but have been extended in part to cover a wider swathe of the Waveney-Little Ouse Corridor, in response to comments by the EA.

The cell elevations of the ground surface and layer 1/2 interface have been derived from contoured data sets. The Waveney-Ouse palaeovalley has however, been manually edited into the contoured distributions as a continuous feature along the line interpreted in the BGS, 1:50 000 geology map (see Figure 3.2).

Layer 2 has been given a uniform 50 m thickness (unlike stage I in which the bottom of Layer 2 was fixed at -50 m AOD such that its thickness varied).

3.1.3 Recharge

At the end of Stage I, problems remained with the simulation of low summer flows in the River Waveney. This has resulted in a reconsideration of model recharge inputs.

In Stage 1, recharge inputs to the model were based on IoH baseflow separations of the gauged river flow data which suggested an average recharge of around 93 mm/a across both catchments. In Stage II rainfall-river flow transfer function modelling has been used to review recharge estimates. This has resulted in lower catchment averages in the model of 71 mm/a in the Little Ouse and only 39 mm/a in the Waveney. These values aggregated over both catchments are in fact much closer to the estimated 47 mm/a used by the EA in previous catchment water balance calculations.

The recharge has been distributed across the model in a similar manner to Stage I. A high percentage of the effective rainfall is applied to active layer 1 cells in the bottom of the valleys with recharge further enhanced at the margins of layer 1 to represent interflow. Where layer 2 only is active the recharge applied to it is proportional to the product of vertical drift permeability (K_v) and potential gradient, in line with Darcy's Law. Both K_v (in the range 0.0001 to 0.1 m/day) and vertical gradient are derived from contoured data sets.

The incorporation of the potential vertical gradient term (which was not used in Stage I) has proved to be important in that it reduces the recharge added to confined parts of Layer 2.

Using this approach, two areas of unconfined Chalk with little or no drift cover in the Little Ouse catchment emerge as the areas of greatest recharge to Layer 2 (Figure 3.3). In the Waveney Chalk interfluve recharge (i.e. to Layer 2) is only high around Borehole G where the borehole data suggests a permeable drift fill in a palaeovalley feature. Thus whilst the modelled catchment average recharge is 39 mm/a, many areas of interfluve chalk which are confined beneath thick and clayey till receive less than 10 mm/a.

In summary Stage II regional recharge estimates are similar to values previously used by the EA and distribution across the model based on Darcy's Law proportionately has resulted in contrasts between the two catchments. These factors have resulted in a much better simulation of river flows (see Section 3.2).

3.1.4 Layer 2 Transmissivities

The layer 2 (Chalk plus overlying sands or gravels) transmissivity distribution in the Stage II model (Figure 3.4) has been developed to reflect the concepts derived from the Borehole B test and Redgrave shutdown tests and to reproduce regional head distributions over the 20 year calibration period.

The highest transmissivities are thus in the Little Ouse catchment to produce the low observed gradients despite the relatively high recharge flux. However, on the basis of the pumping and shutdown tests, this zone of high T has been extended along the south of Redgrave Fen and eastward as far as Borehole B. In the Waveney valley to the east of Borehole B, model transmissivities are around 400 m^2/d (in line with the later time pumping test data) which are in turn much higher than those to the south around Borehole G (20 m^2/d) and to the north. Along the line of the palaeovalley, a zone of lower T (5 m^2/d) has been introduced as indicated by the pumping test interpretation.

3.1.5 Vertical Conductance Between Layers

The vertical hydraulic gradients between Chalk piezometric levels (artesian) and wetland levels observed over much of the Waveney valley floor can only be reproduced in the model by using fairly low interlayer conductances equivalent to hydraulic conductivities around 0.0003 to 0.0005 m/day. There is, however, evidence for locally enhanced connectivity between wetland and Chalk such as 'the sink' area near to the existing Redgrave borehole although even here a marked downward hydraulic gradient is maintained. The number and location of these areas of enhanced connection are very poorly controlled by data but, based on geological evidence, cells of higher vertical conductance (0.05 m/day) have been included at Hall Farm Meadow and Royden Fen, as well as at Redgrave.

3.2 Model Calibration Results

The Stage II model has been calibrated in steady state and transient operation using the same 20 year (1974 to 1994) effective rainfall and abstraction datasets as compiled for Stage I. This includes the

Redgrave borehole abstracting an average of 2.8 Ml/d (returns are lower than the licensed 3.6 Ml/d). The following figures illustrate the degree of 'fit' between modelled and observed heads and flows:

Figure 3.5	Regional head distributions
Figure 3.6-3.12	Groundwater hydrographs
Figures 3.13 and 3.14	River flows for the Waveney and Little Ouse.

Most of these are better than the Stage I model fits with a notable improvement in the River Waveney flows where summer low flows are now fairly closely matched. Winter 1991 and to a lesser extent Winter 1992, produces relatively poor fits to river flow data for both the Little Ouse and Waveney. These isolated poor fits, in a 20 year data run, are not considered to reflect fundamental problems in the groundwater model, but may indicate some problems with the soil moisture model during unusual sequences of meteorological conditions.

Absolute groundwater levels (in m AOD) are within 1 m of observed values over most of the Waveney-Little Ouse corridor. Boreholes TM08/500 and TM07/003 (Figures 3.8 and 3.12) are closest to Redgrave. Whilst head fits could certainly be further improved by further 'fine tuning' of transmissivities, Entec do not consider this to be worthwhile as impact prediction results are quoted as changes in water levels which are likely to be much more reliably modelled than absolute values.

3.3 Prediction of Relocation Impacts

After calibration against historical data sets, the model has been used to run the three future scenarios described in our letter (15558C688) of 1 May 1996. From these runs predicted impacts of relocating abstraction to Borehole B have been derived, as reported in that letter.

4. SUMMARY

This Technical Note has summarised the key findings of the Borehole B pumping test interpretation and has described the development of the Stage II groundwater model. This information has been provide to substantiate the impact predictions already reported as background for the Project Liaison Group review meeting to be held on 7 May 1996.

Author: Rob Soley

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Reviewer: John Heathcote

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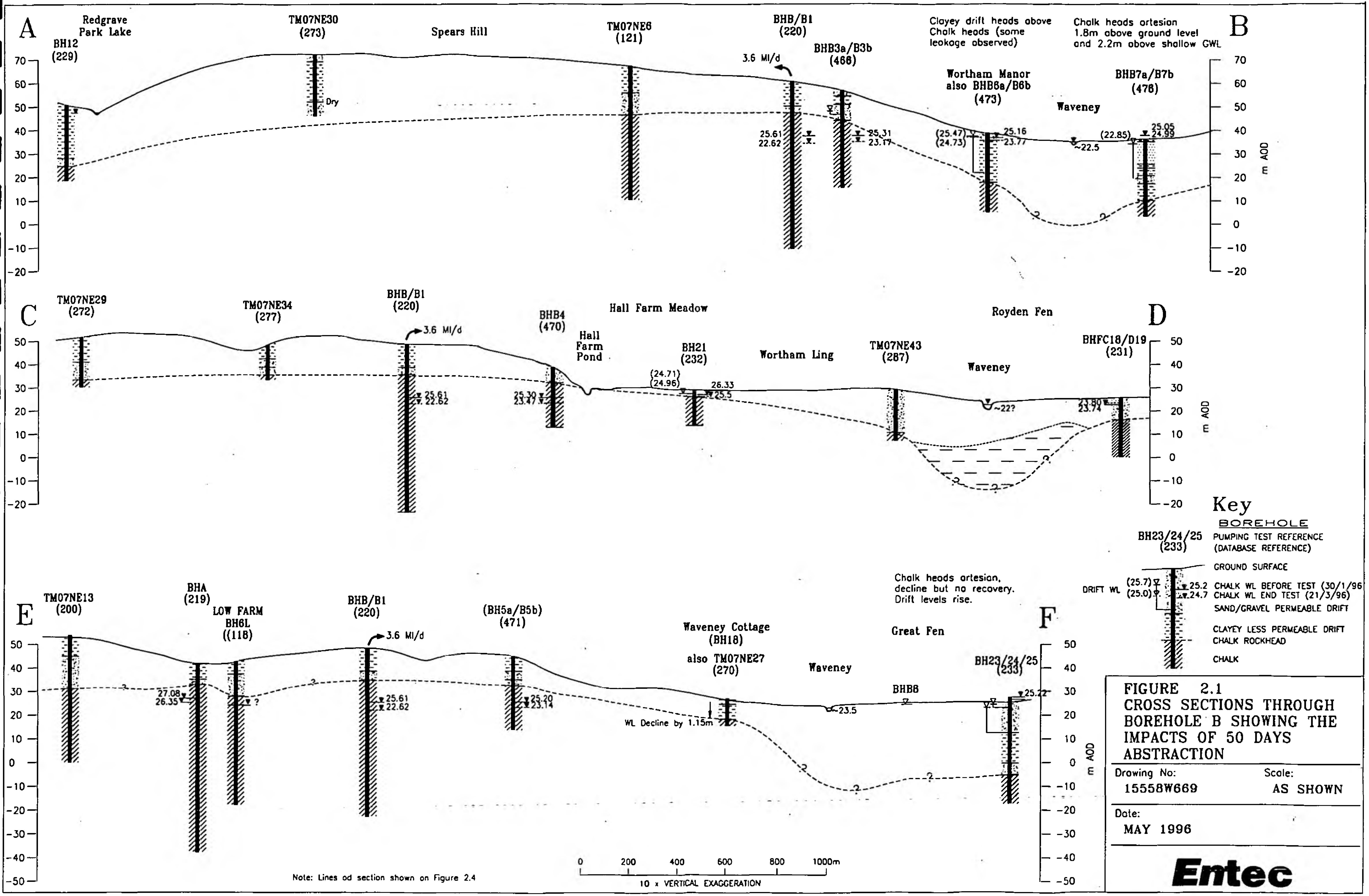

FIGURE 2.1
CROSS SECTIONS THROUGH BOREHOLE B SHOWING THE IMPACTS OF 50 DAYS ABSTRACTION

Drawing No: 15558W669

Scale: AS SHOWN

Date: MAY 1996

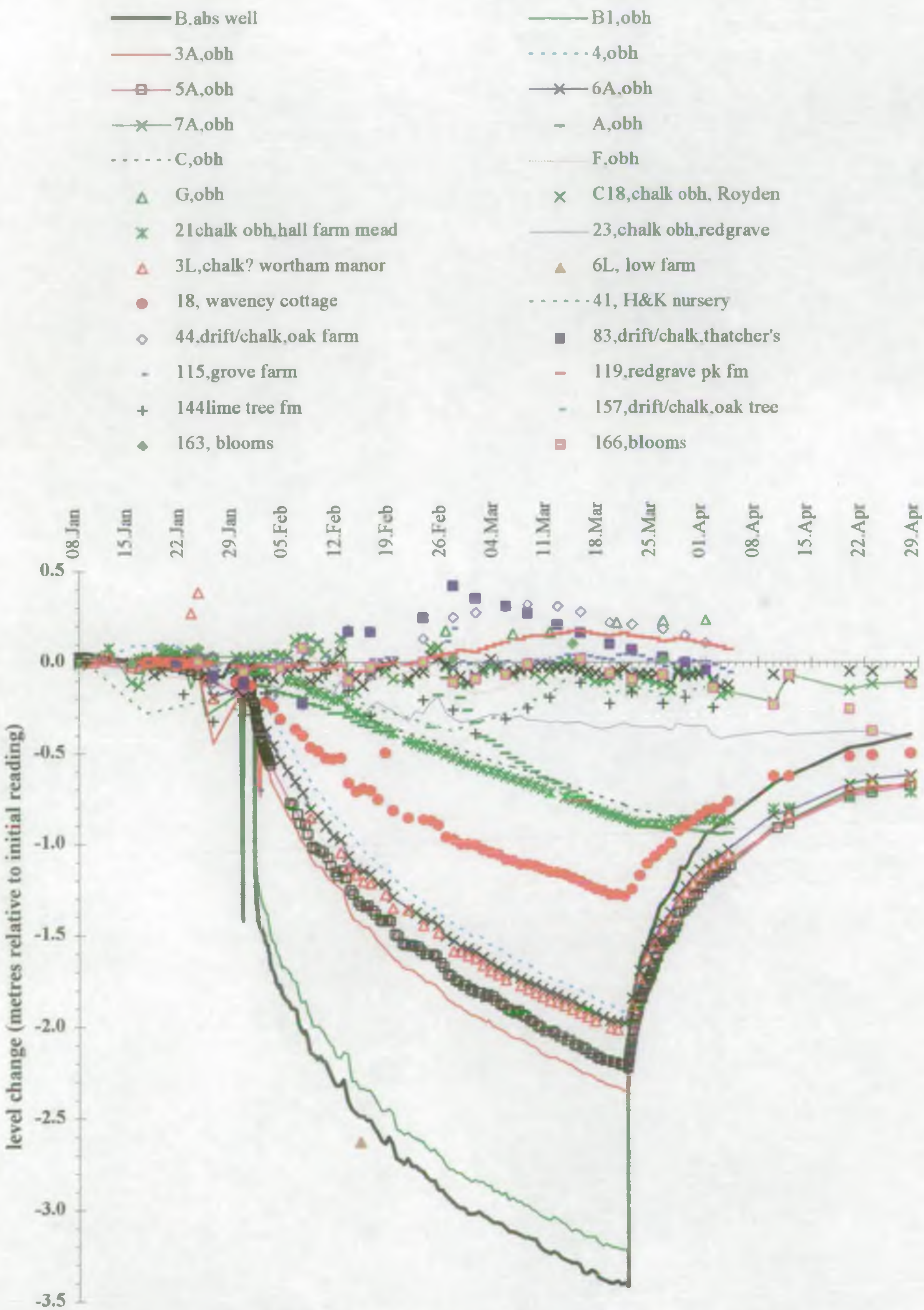

FIGURE 2.2 **CHALK WATER LEVEL CHANGES**

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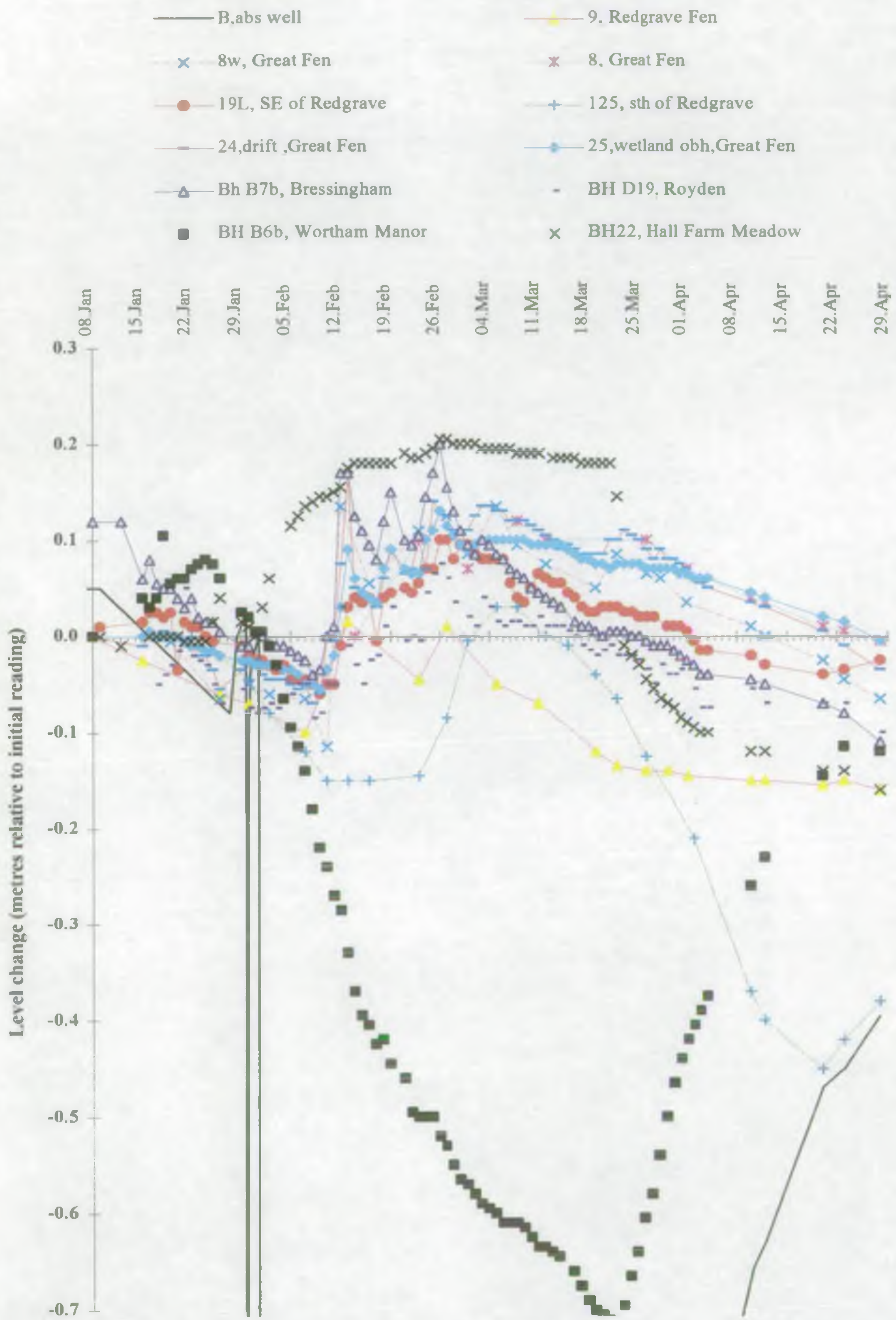

FIGURE 2.3 DRIFT WATER LEVEL CHANGES

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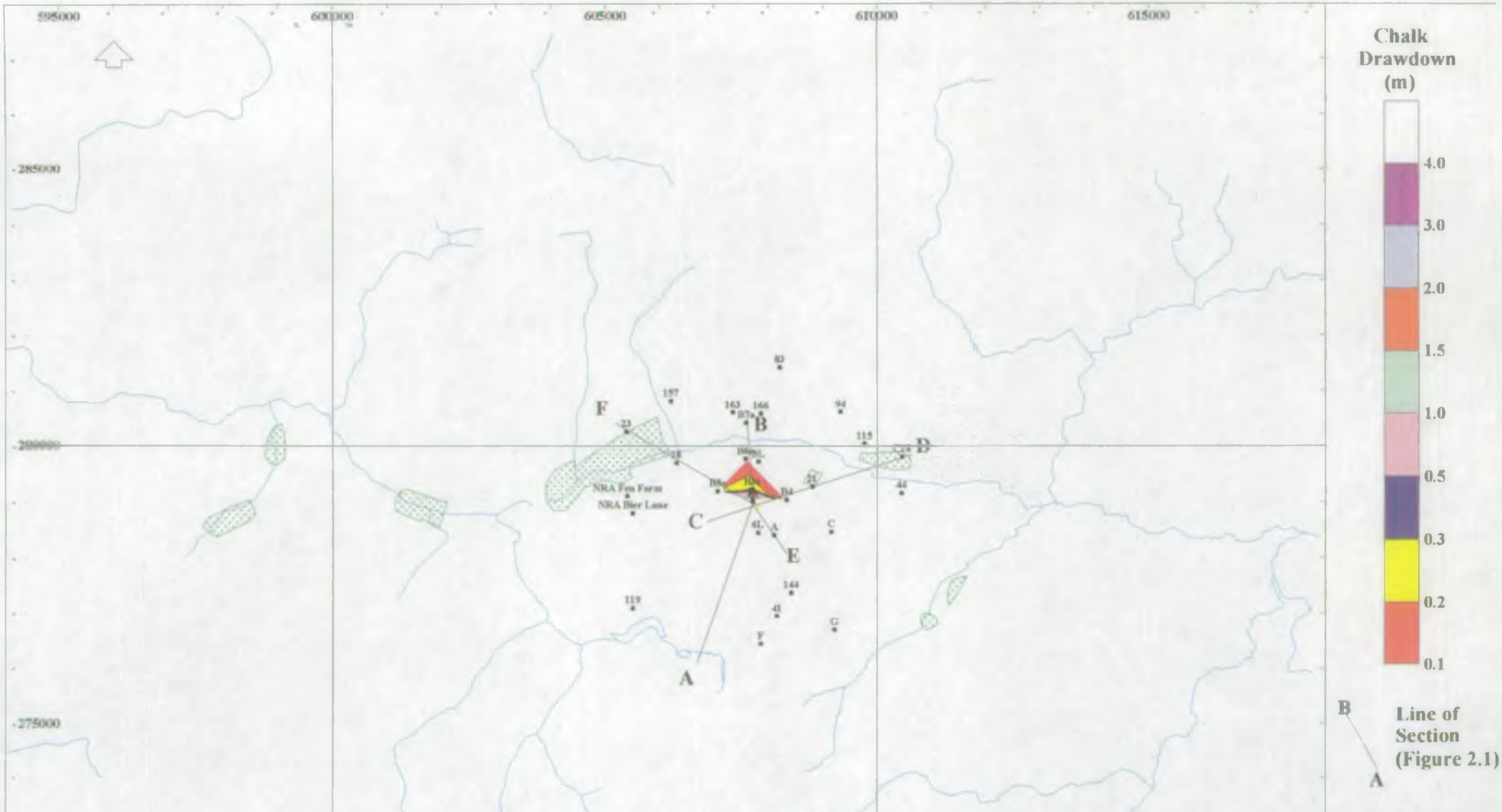

FIGURE 2.4
CHALK DRAWDOWN (m)
AFTER 1 DAY
(triangulated contours)

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Scale: 1:100 000

Date: MAY 1996

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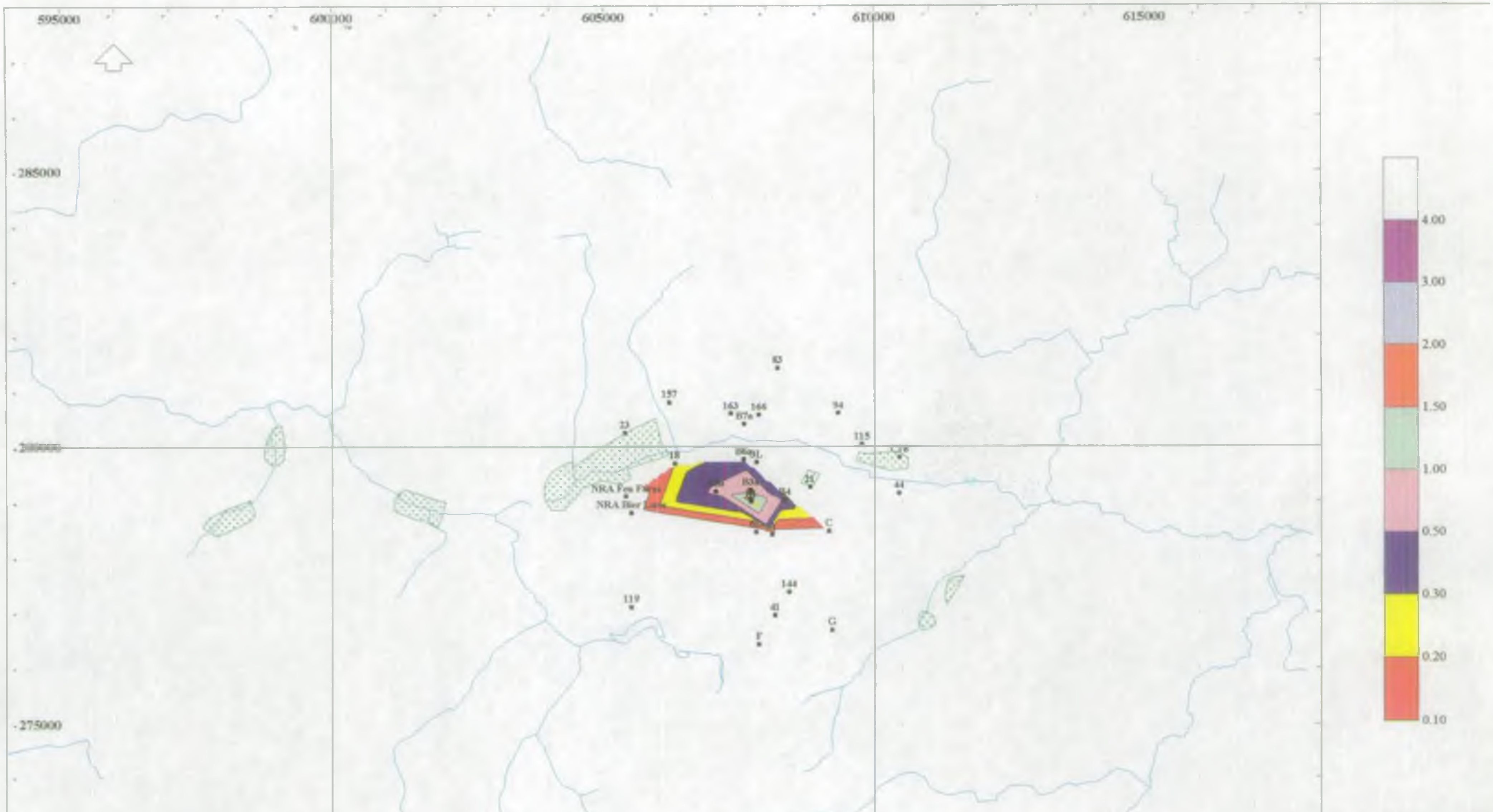

FIGURE 2.5
CHALK DRAWDOWN (m)
AFTER 5 DAYS
(triangulated contours)

Drawing No: 15558W684
Scale: 1:100 000
Date: MAY 1996

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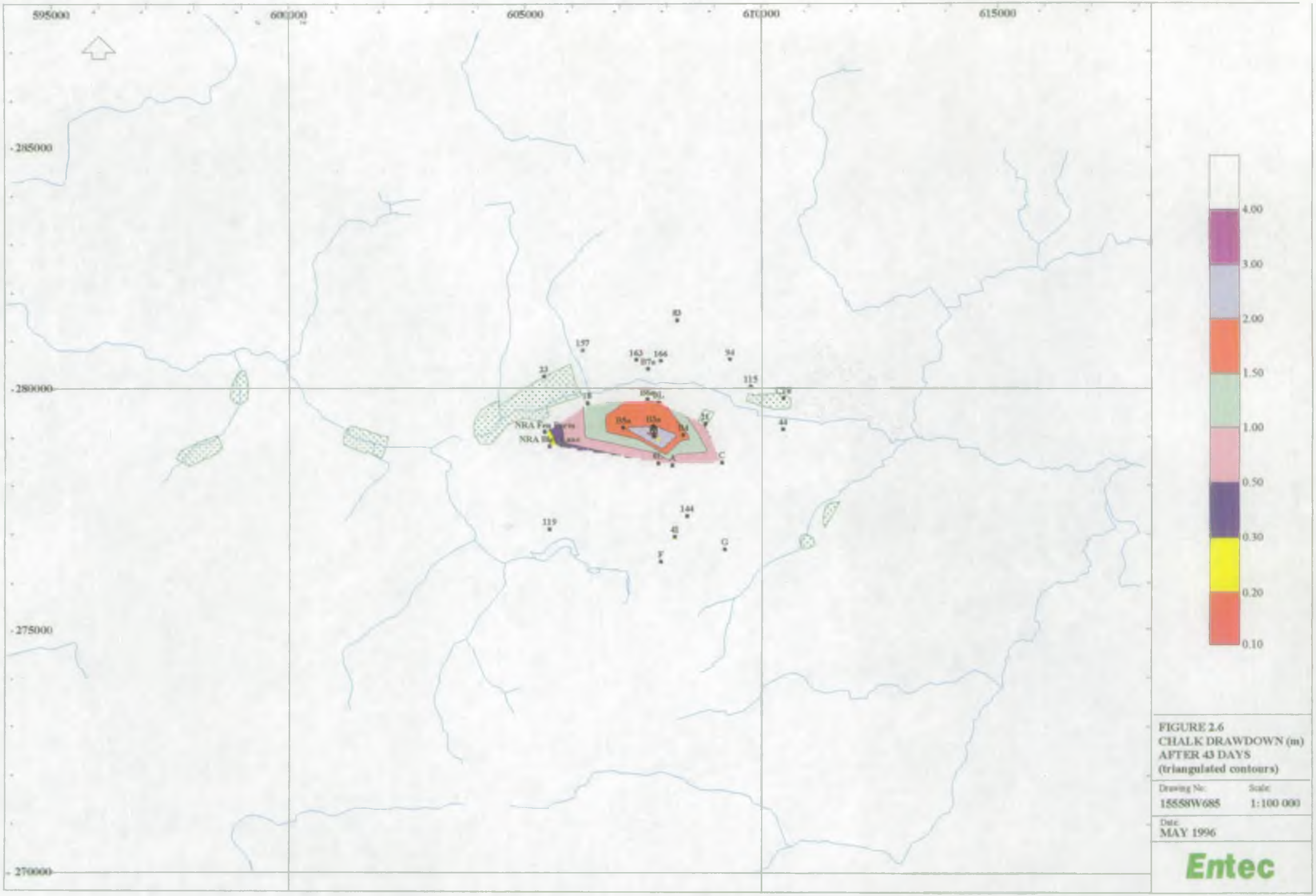

FIGURE 2.6
CHALK DRAWDOWN (m)
AFTER 43 DAYS
(triangulated contours)

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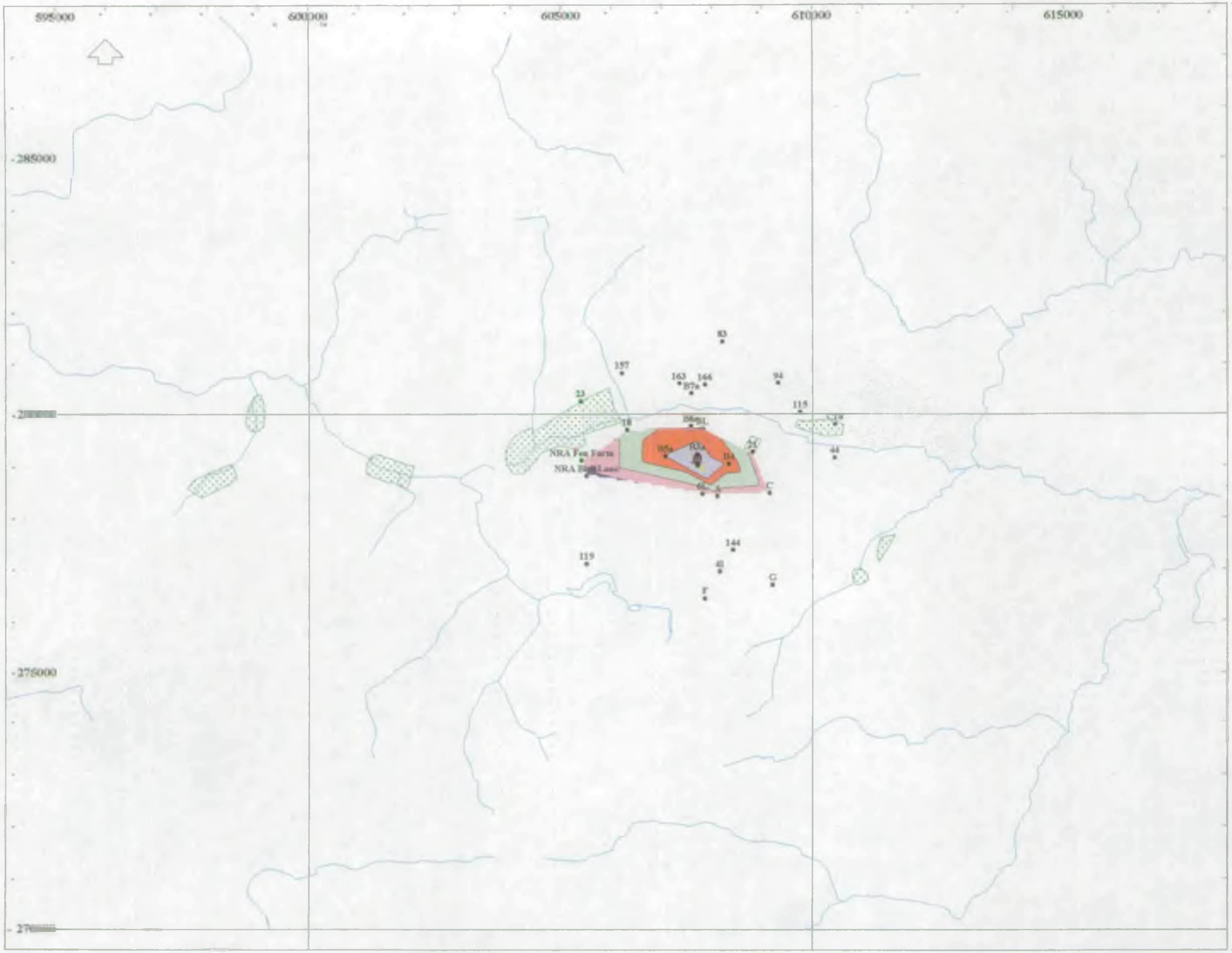

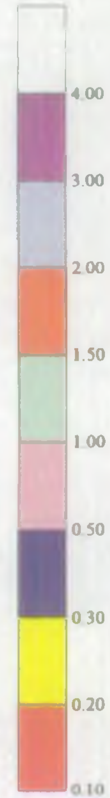

FIGURE 2.7
CHALK DRAWDOWN (m)
AFTER 50 DAYS
(triangulated contours)

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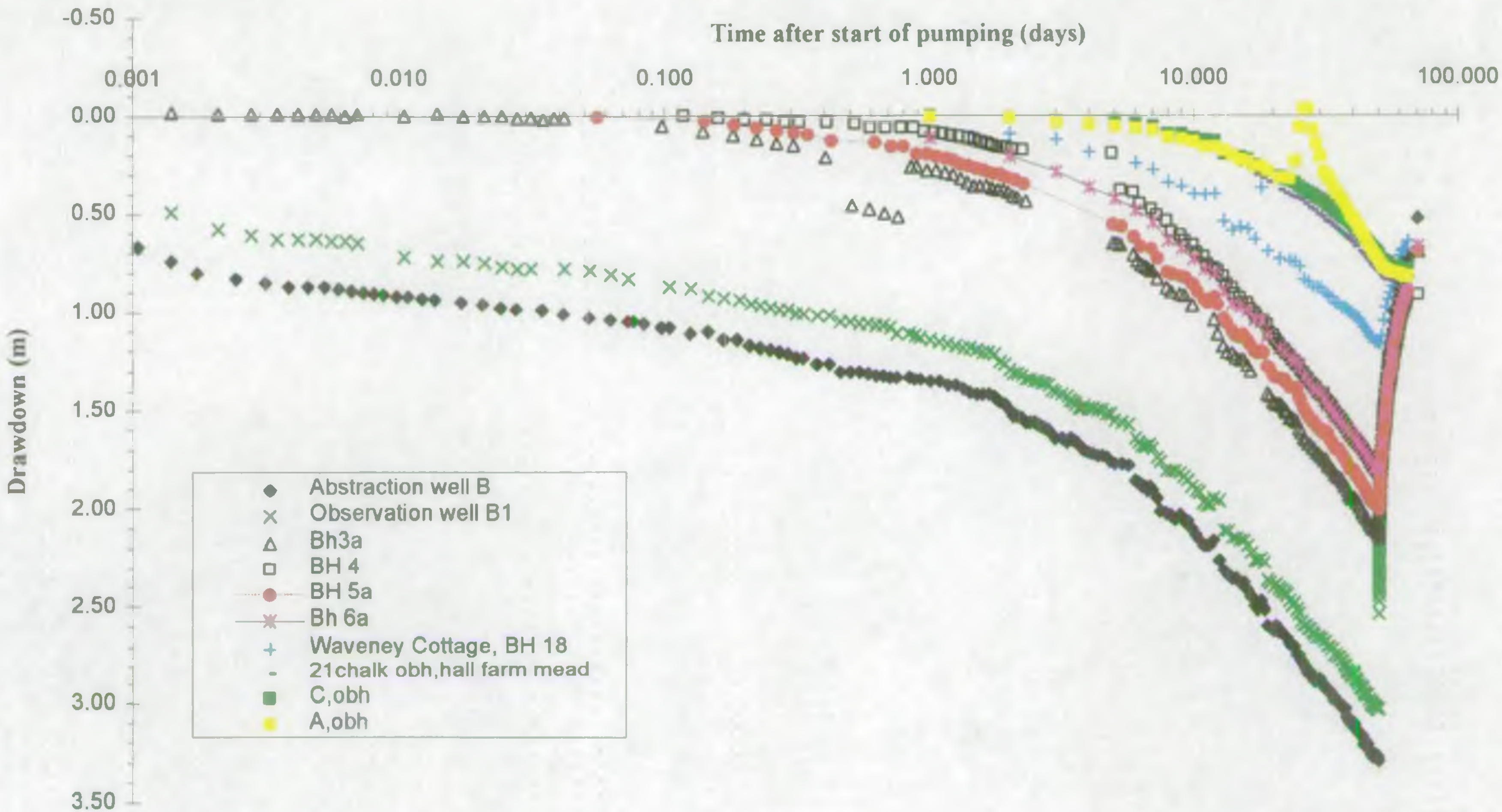

FIGURE 2.8 SEMI-LOG PLOT OF DRAWDOWN VS TIME

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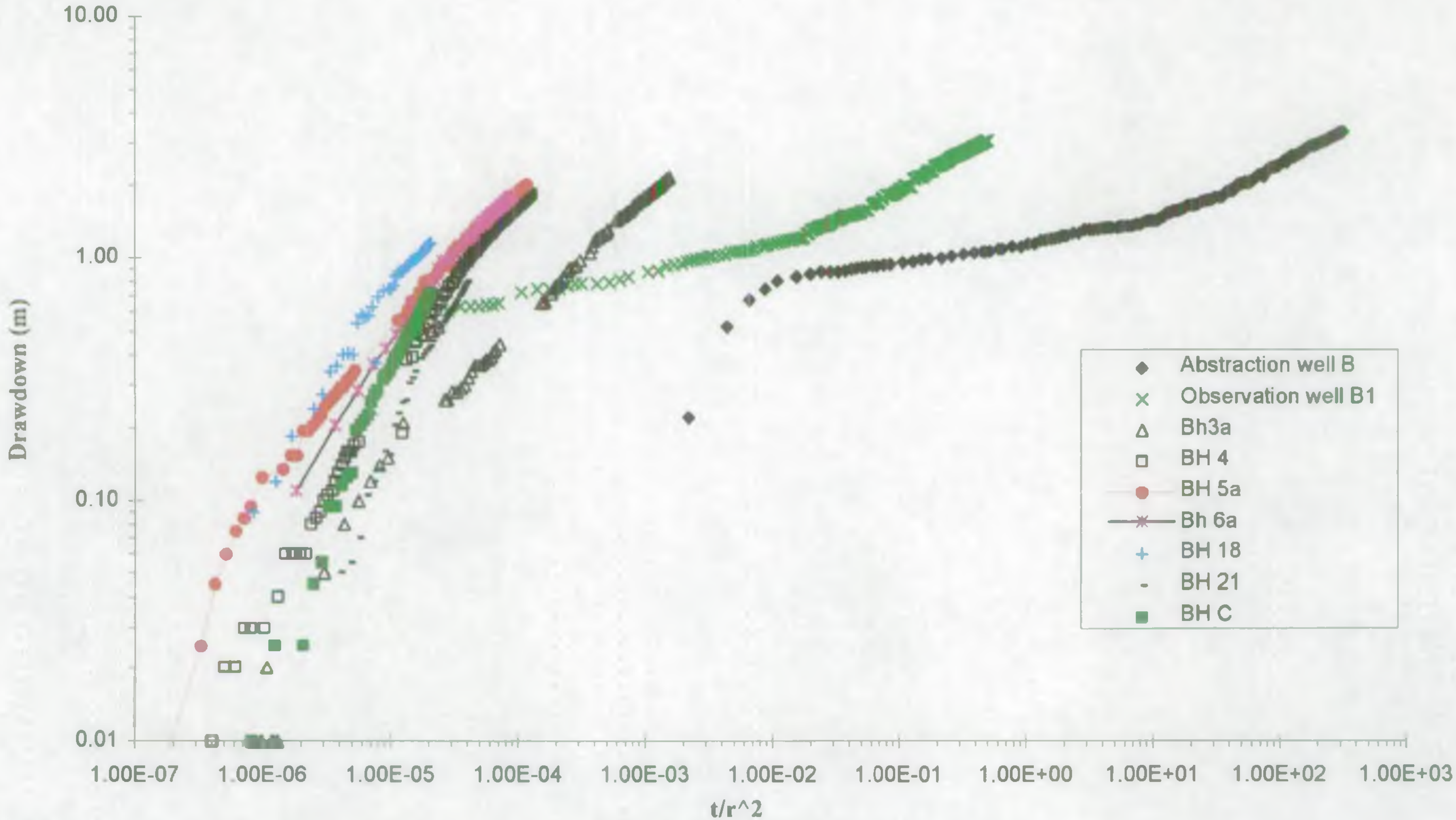

FIGURE 2.9 LOG-LOG PLOT OF DRAWDOWN VS t/r^2

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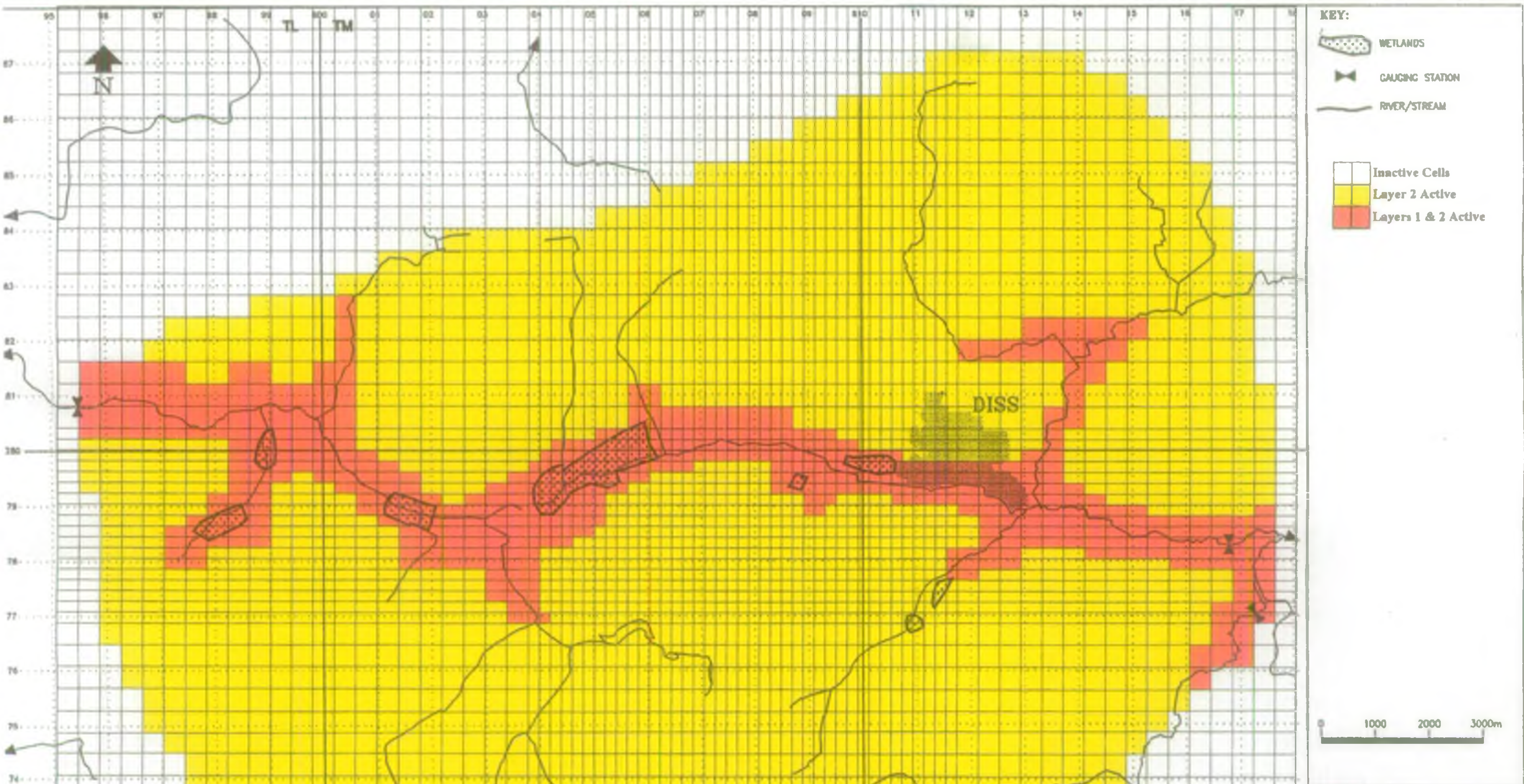

FIGURE 3.1
STAGE II MODEL GRID AND ACTIVE LAYER DISTRIBUTION

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Date: MAY 1995

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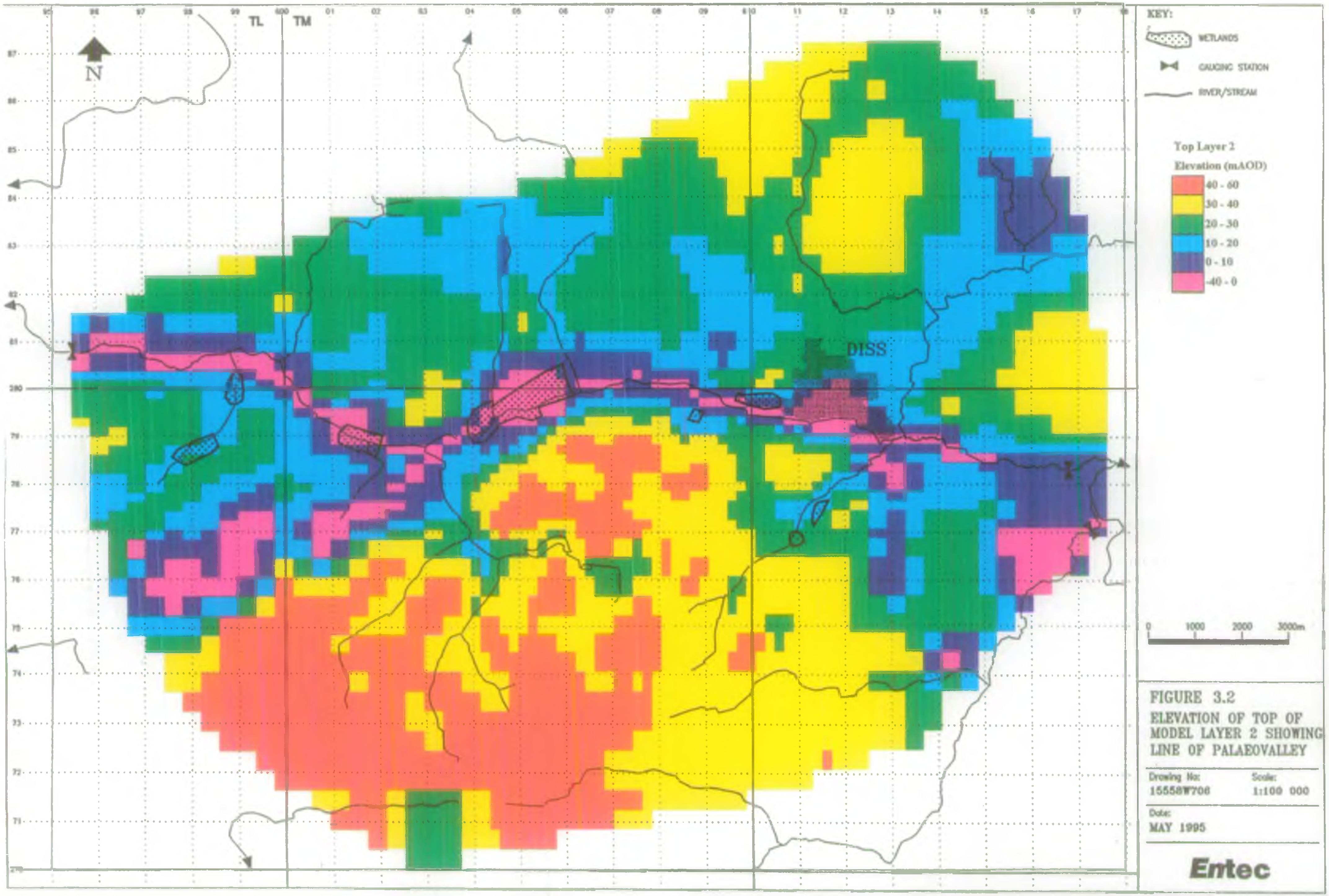

FIGURE 3.2
ELEVATION OF TOP OF MODEL LAYER 2 SHOWING LINE OF PALAEOVALLEY

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Date: MAY 1995

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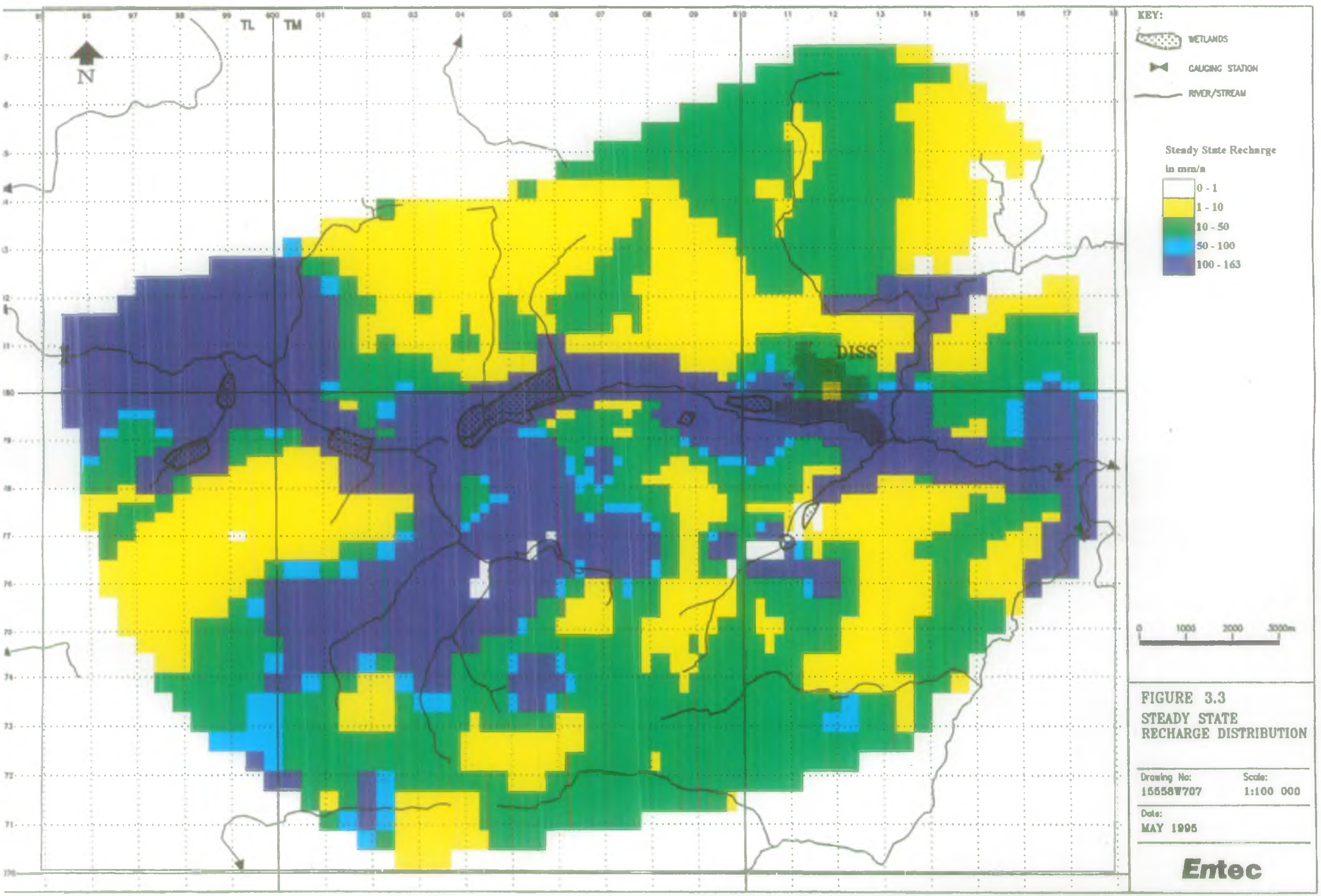

FIGURE 3.3
STEADY STATE RECHARGE DISTRIBUTION

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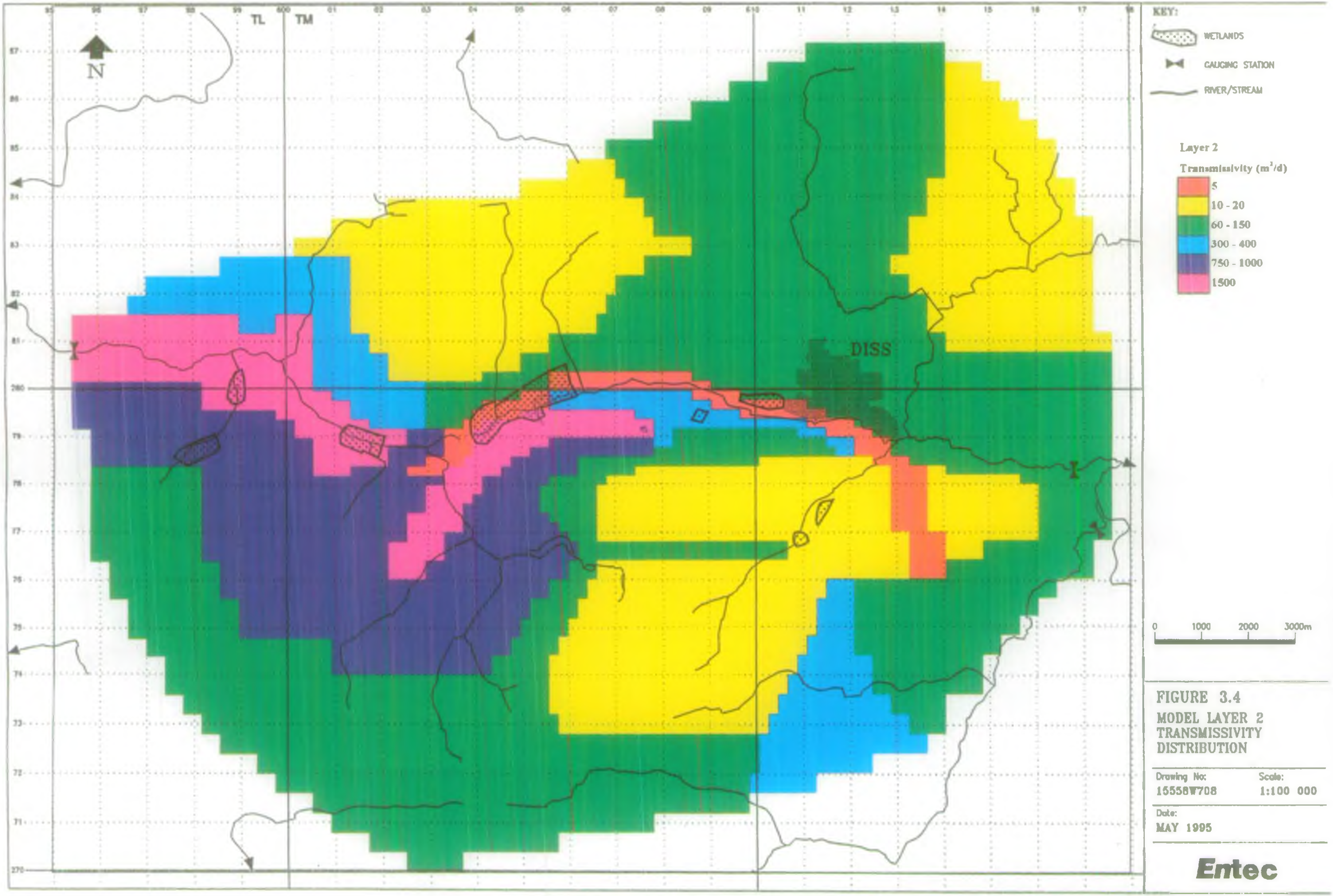

FIGURE 3.4
MODEL LAYER 2 TRANSMISSIVITY DISTRIBUTION

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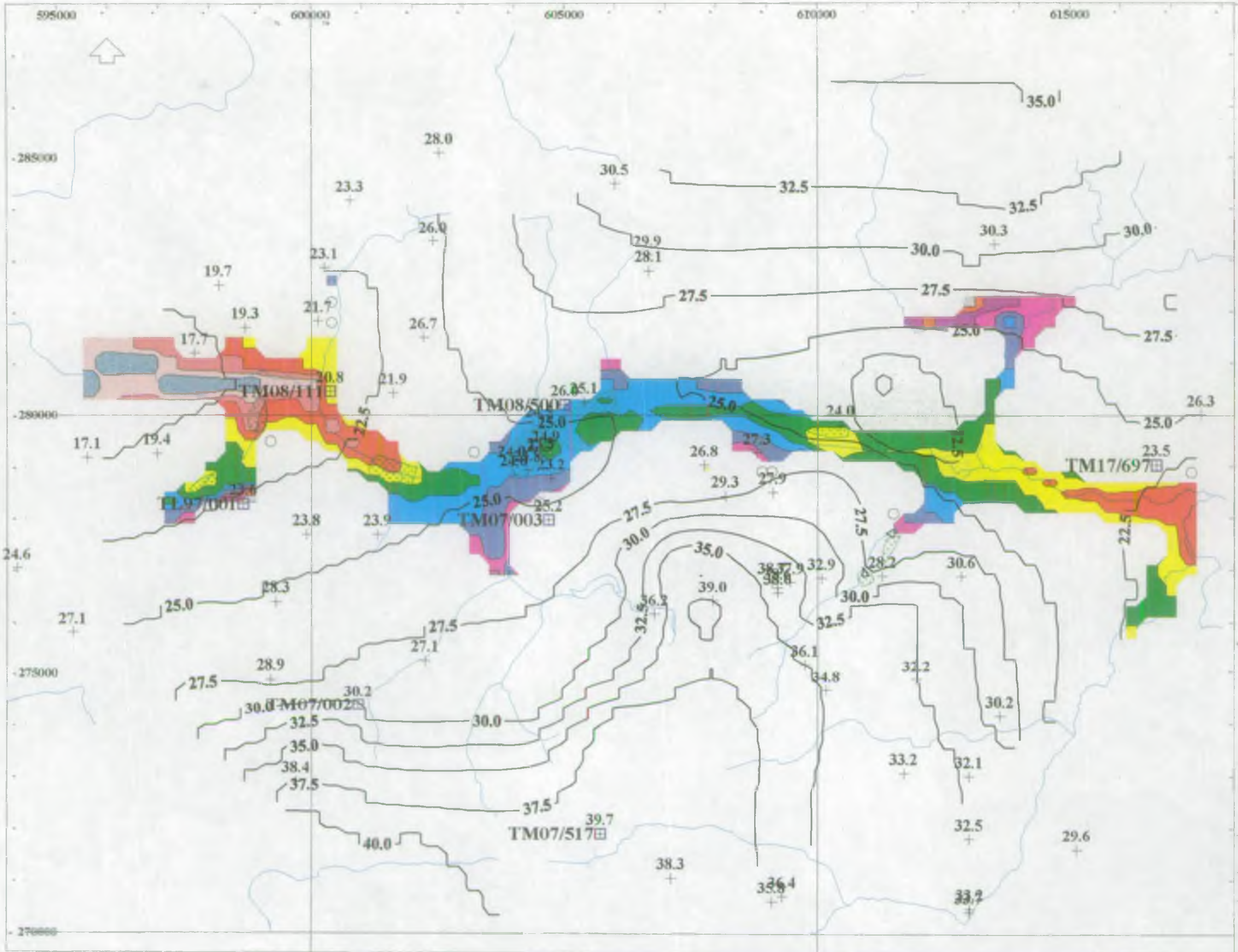

FIGURE 3.5
HISTORICAL CALIBRATION STEADY STATE (RUN 145A) AND OBSERVED AVERAGE HEADS

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MAY 1996

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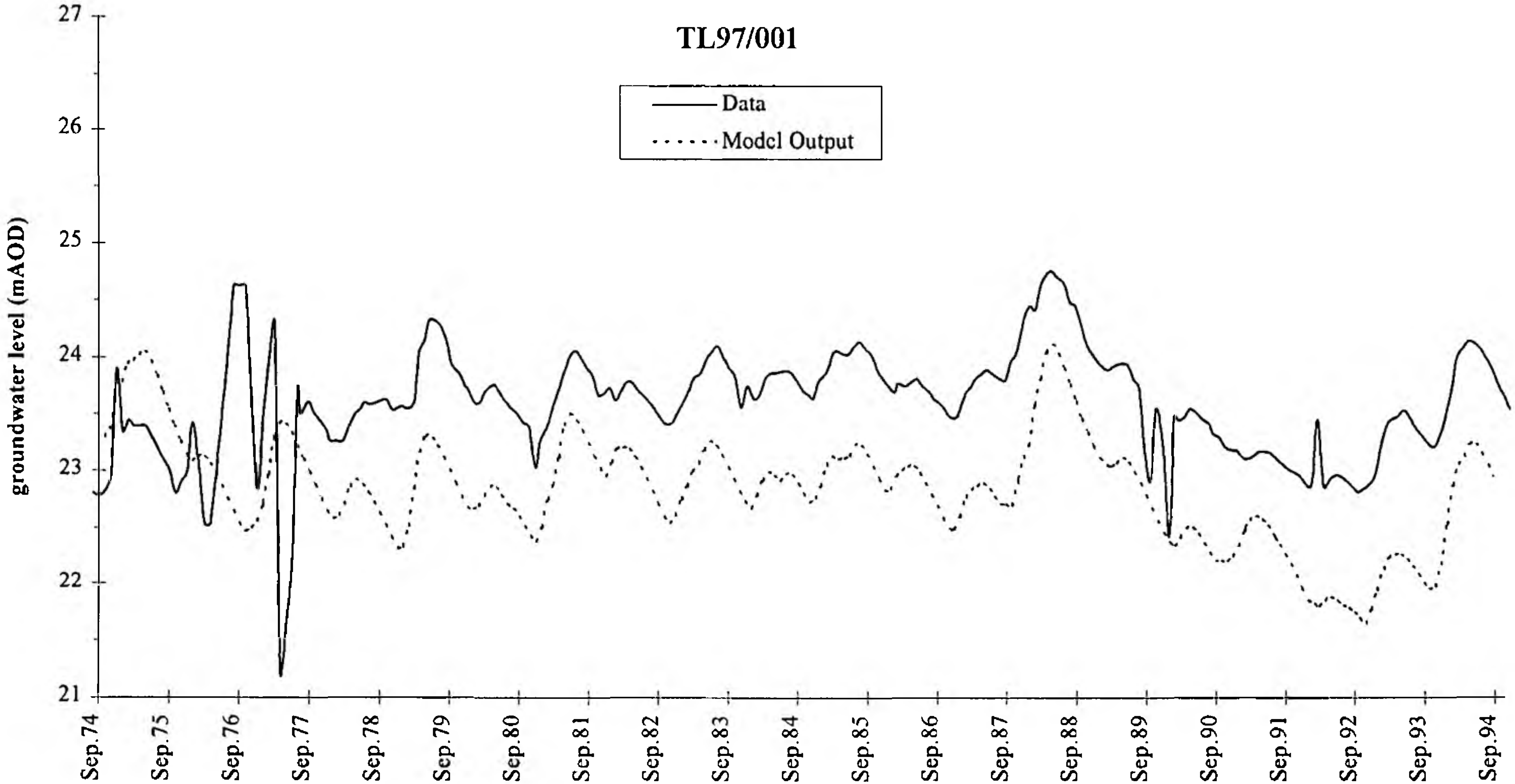

FIGURE 3.6 OBSERVED AND MODELLED GROUNDWATER HEADS TL97/001

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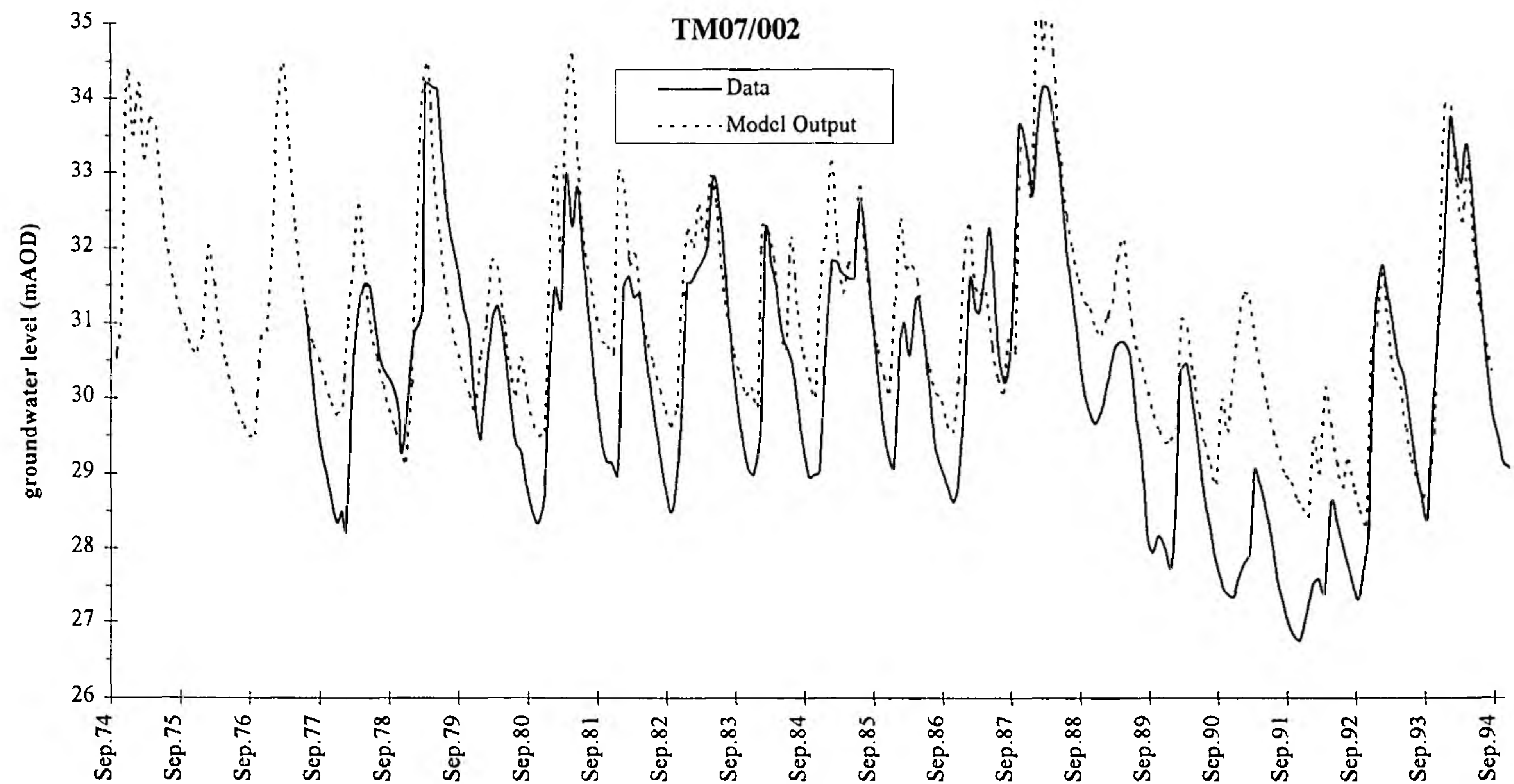

FIGURE 3.7 OBSERVED AND MODELLED GROUNDWATER HEADS TM07/002

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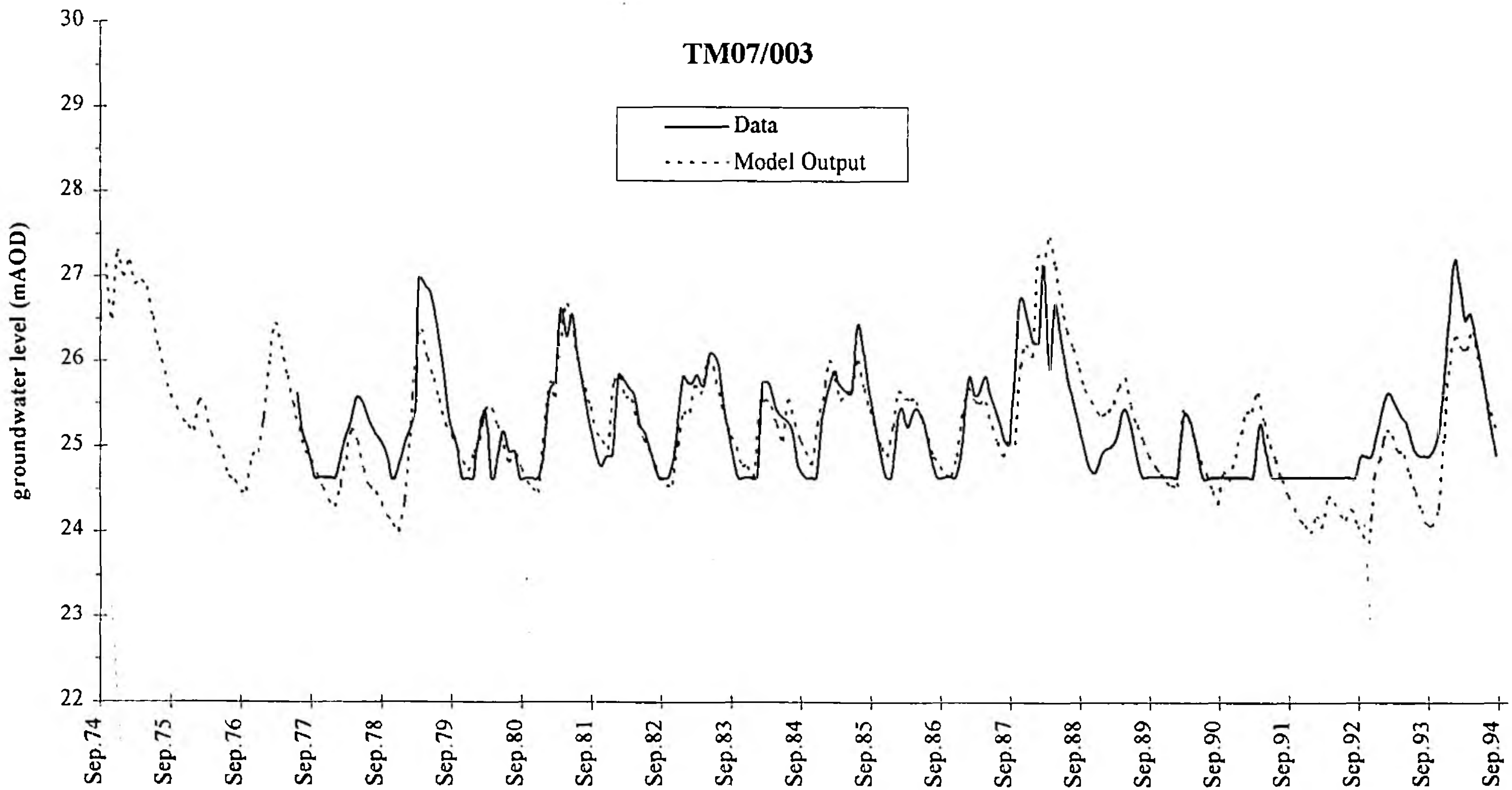

FIGURE 3.8 OBSERVED AND MODELLED GROUNDWATER HEADS TM07/003

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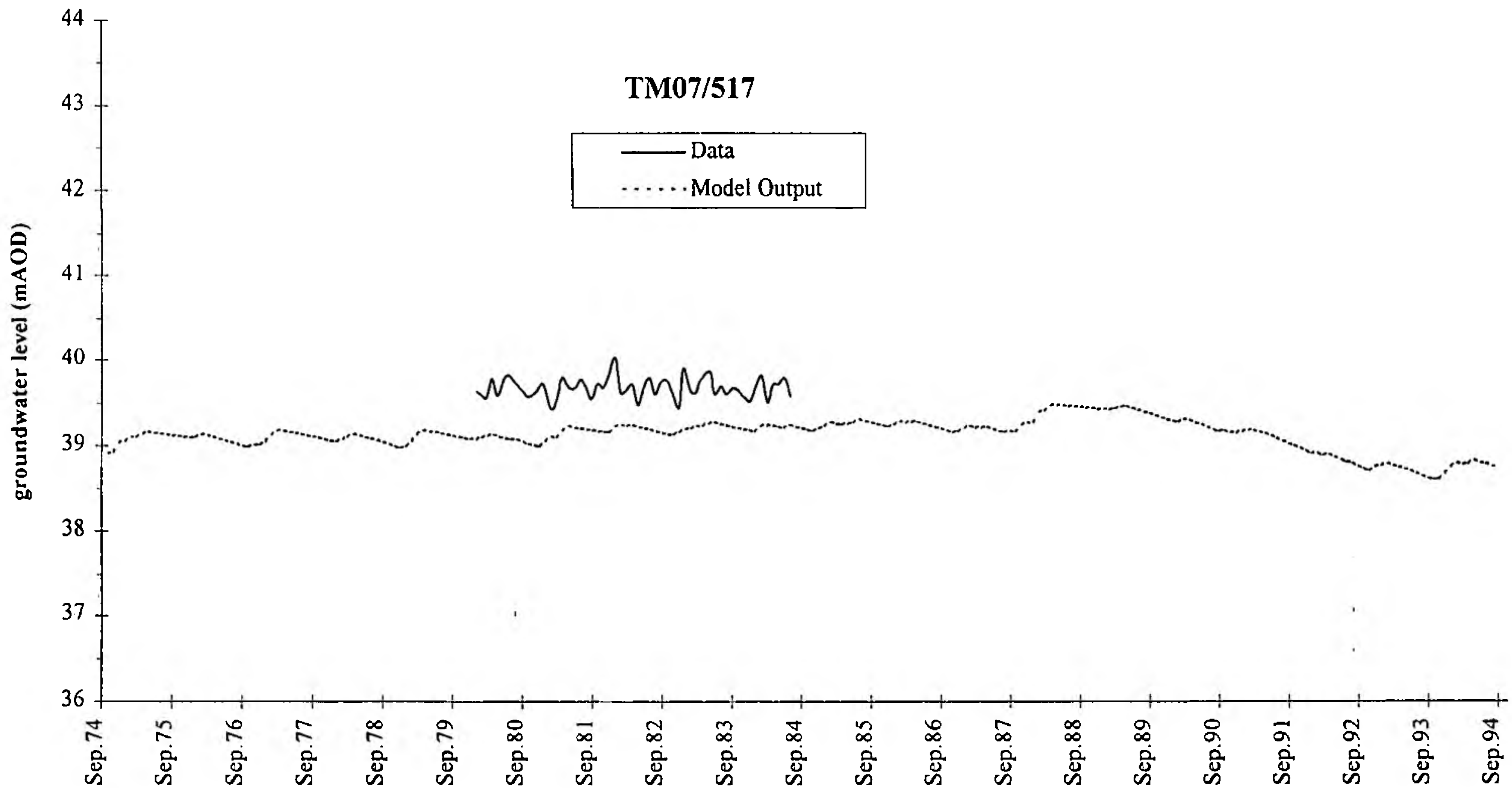

FIGURE 3.9 OBSERVED AND MODELLED GROUNDWATER HEADS TM07/517

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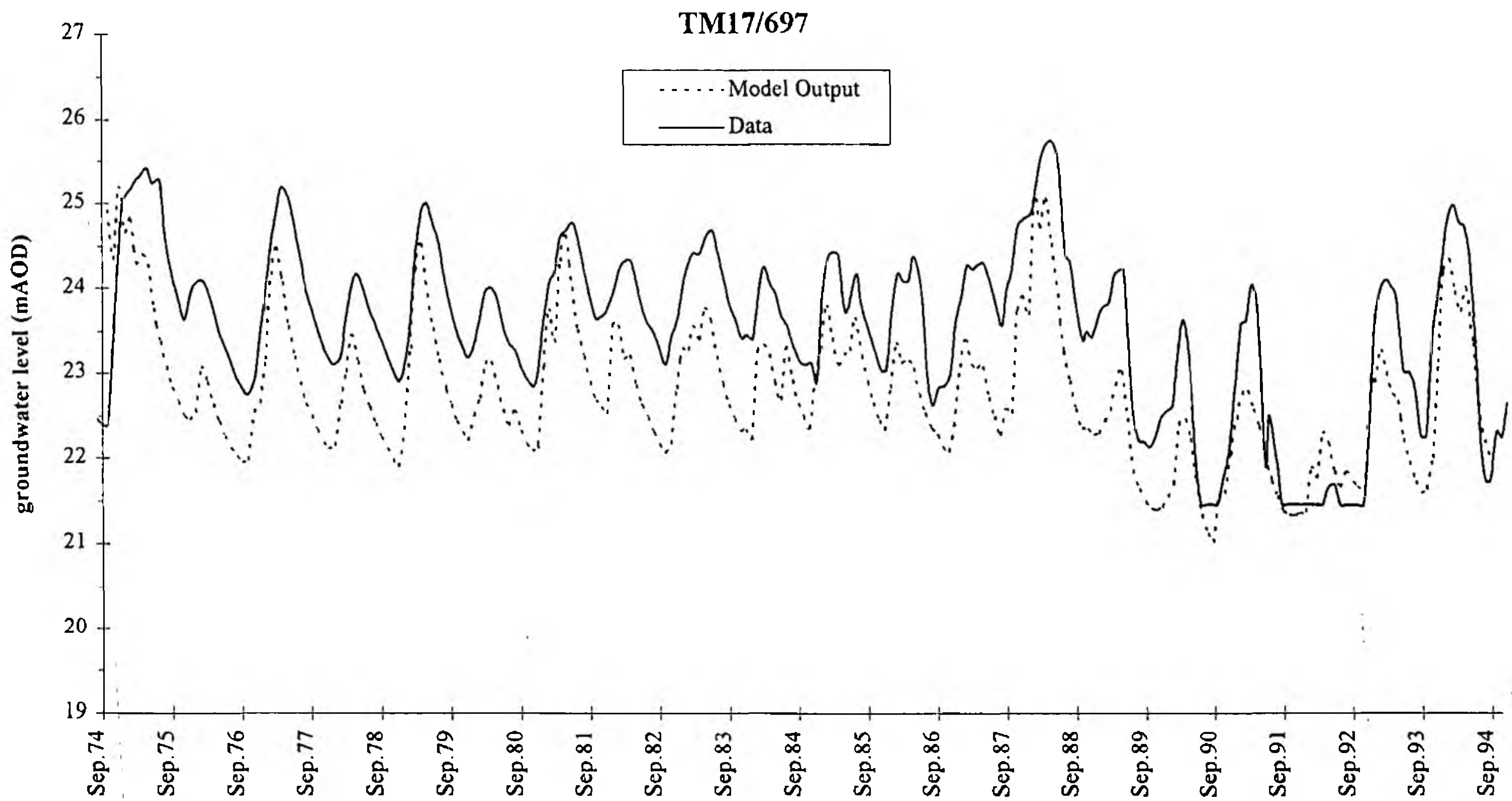

FIGURE 3.10 OBSERVED AND MODELLED GROUNDWATER HEADS TM17/697

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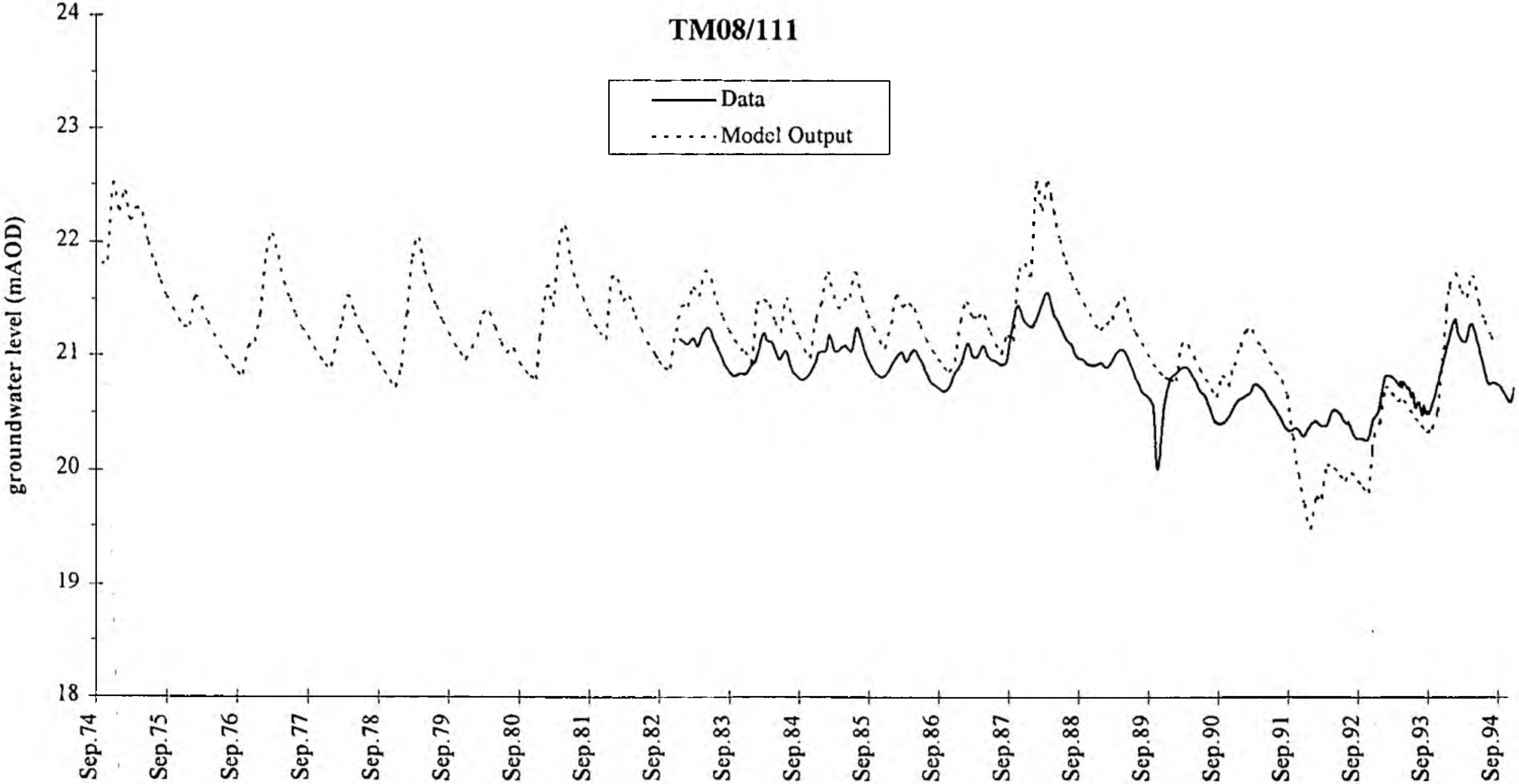

FIGURE 3.11 OBSERVED AND MODELLED GROUNDWATER HEADS TM08/111

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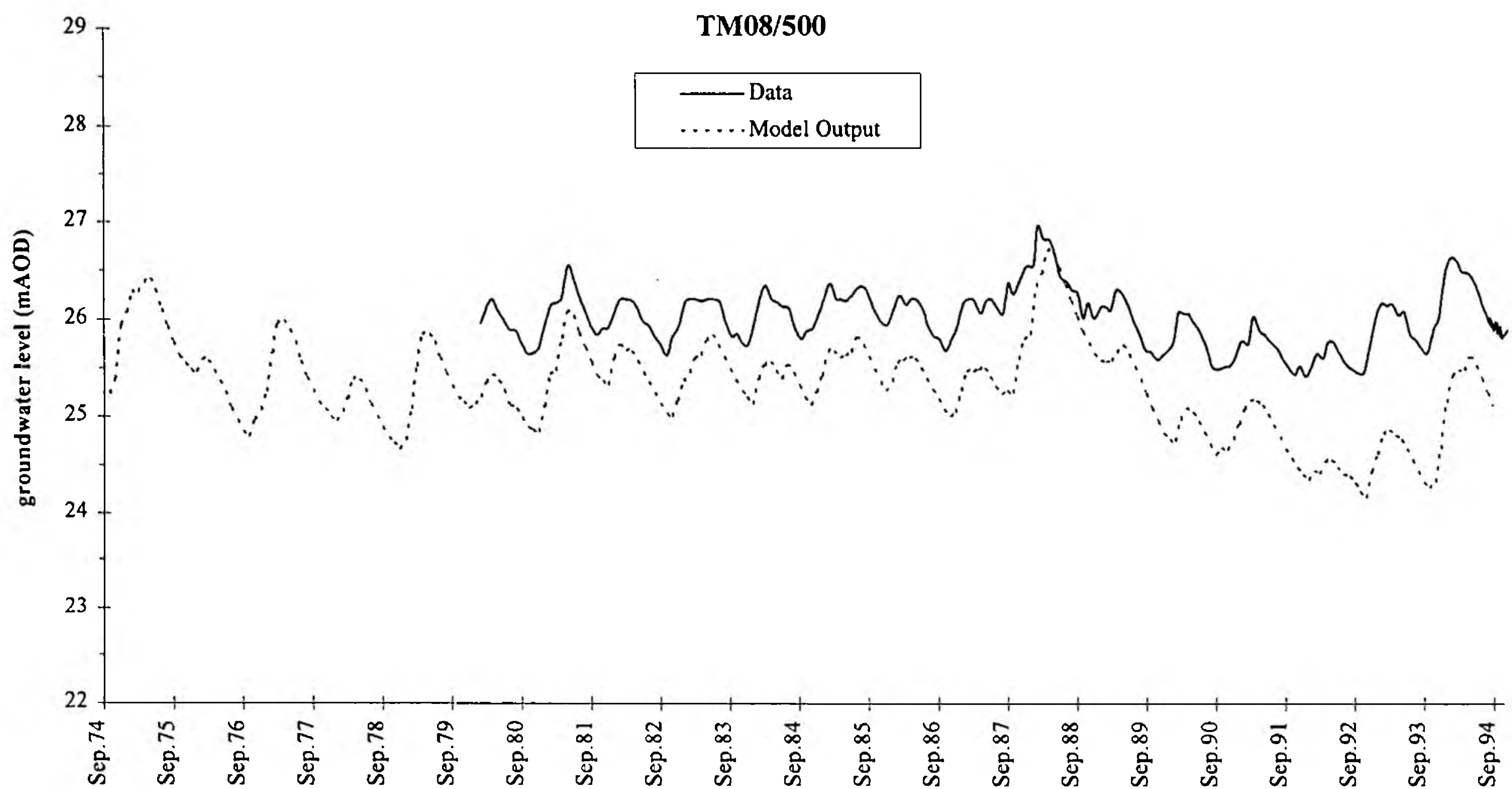

FIGURE 3.12 OBSERVED AND MODELLED GROUNDWATER HEADS TM08/500

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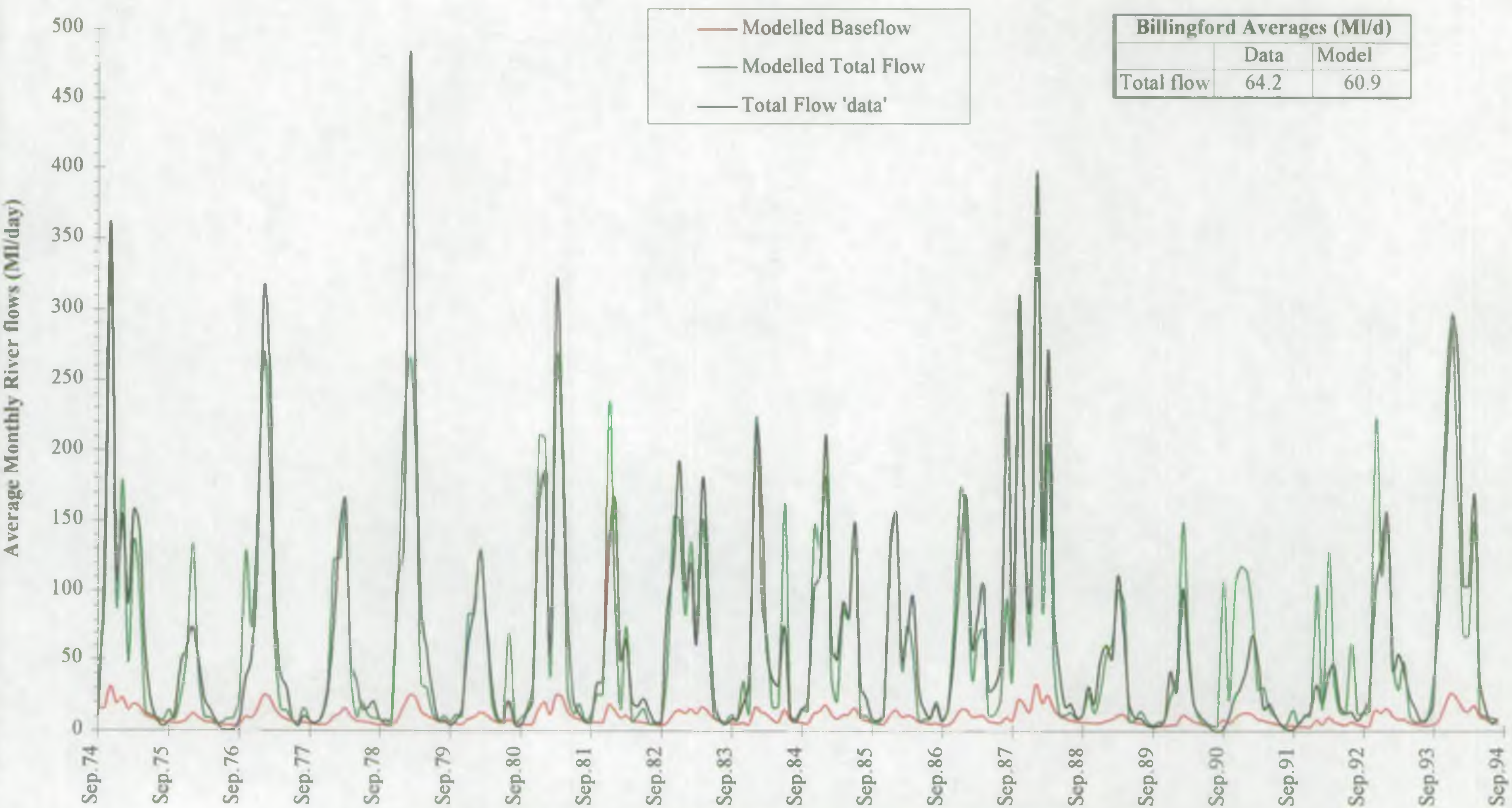

Billingford Averages (Ml/d)		
	Data	Model
Total flow	64.2	60.9

FIGURE 3.13 DYNAMIC MODELLED FLOWS AT BILLINGFORD COMPARED WITH MEASURED FLOWS

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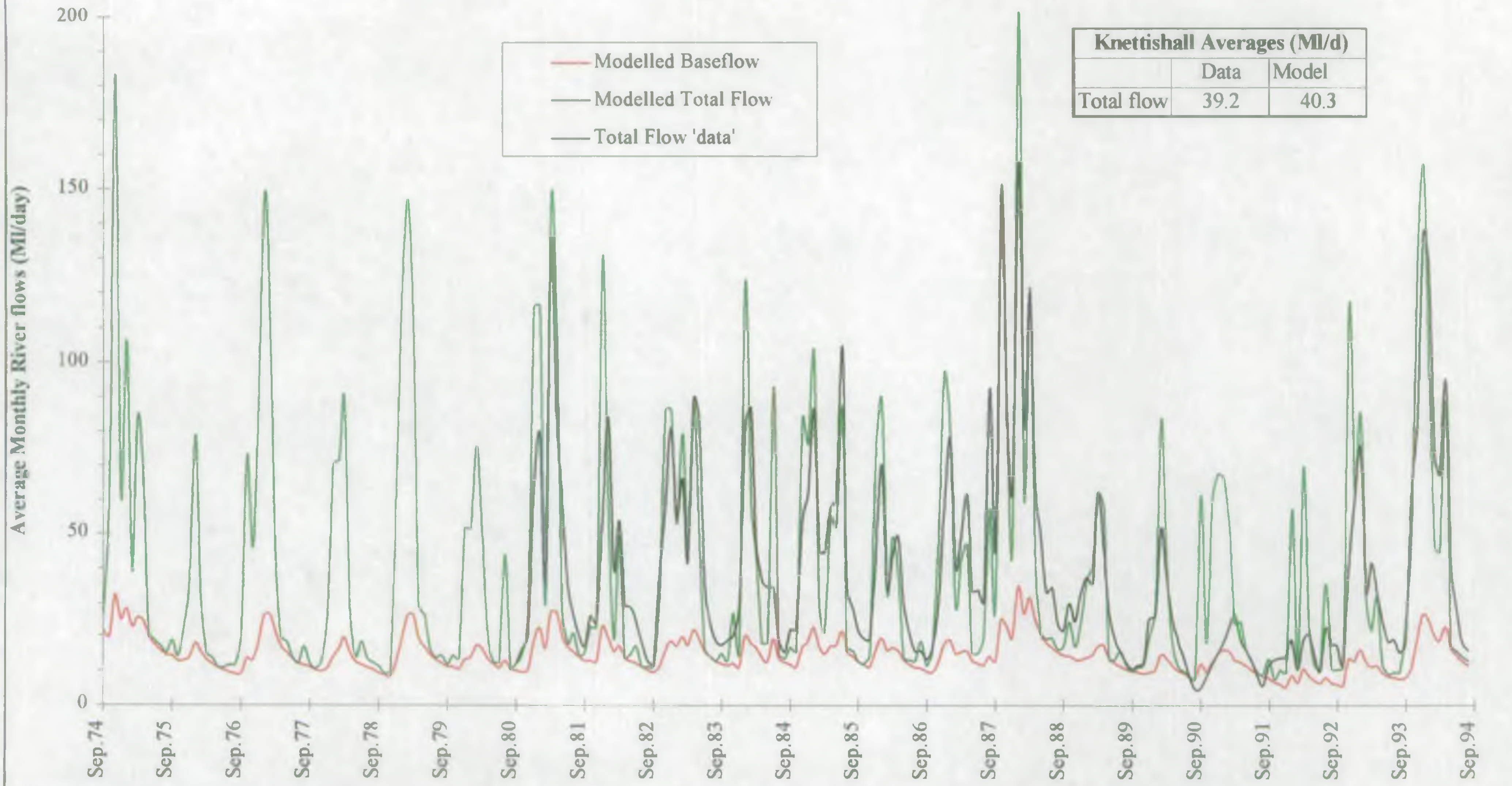

FIGURE 3.14 DYNAMIC MODELLED FLOWS AT KNETTISHALL COMPARED WITH MEASURED FLOWS

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Drawing No : **15558W704** Date: **MAY 1996** Scale: **AS SHOWN**